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# Design of ecoregional monitoring in conservation areas of high-latitude ecosystems under contemporary climate change

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ABSTRACT

Land ownership in Alaska includes a mosaic of federally managed units. Within its agency's context, each unit has its own management strategy, authority, and resources of conservation concern, many of which are migratory animals. Though some units are geographically isolated, many are nevertheless linked by paths of abiotic and biotic flows, such as rivers, air masses, flyways, and terrestrial and aquatic migration routes. Furthermore, individual land units exist within the context of a larger landscape pattern of shifting conditions, requiring managers to understand at larger spatial scales the status and trends in the synchrony and spatial concurrence of species and associated suitable habitats. Results of these changes will determine the ability of Alaska lands to continue to: provide habitat for local and migratory species; absorb species whose ranges are shifting northward; and experience mitigation or exacerbation of climate change through positive and negative atmospheric feedbacks. We discuss the geographic and statutory contexts that influence development of ecological monitoring; argue for the inclusion of significant amounts of broad-scale monitoring; discuss the importance of defining clear programmatic and monitoring objectives; and draw from lessons learned from existing long-term, broad-scale monitoring programs to apply to the specific contexts relevant to high-latitude protected areas such as those in Alaska. Such areas are distinguished by their: marked seasonality; relatively large magnitudes of contemporary change in climatic parameters; and relative inaccessibility due to broad spatial extent, very low (or zero) road density, and steep and glaciated areas. For ecological monitoring to effectively support management decisions in high-latitude areas such as Alaska, a monitoring program ideally would be structured to address the actual spatial and temporal scales of relevant processes, rather than the artificial boundaries of individual land-management units. Heuristic models provide a means by which to integrate understanding of ecosystem structure, composition, and function, in the midst of numerous ecosystem drivers.

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## 1. Introduction and background

Given that effects of contemporary climate change on climatic and abiotic conditions have been and are predicted to remain of greatest magnitude in far-northern latitudes (ACIA, 2005; Chapin et al., 2005, 2006; IPCC, 2007; Barber et al., 2009), there is urgent need to achieve a robust understanding of the status and trend of natural resources in the region, through monitoring (e.g., Table 1). Furthermore, the large uncertainties associated with this rapid change further underscore the importance of monitoring for informing management decisions (Suffling and Scott, 2002; USFWS, 2010). Juxtaposed with this great change and uncertainty, lands within Alaska and northern North America have natural resources that are widely renowned for their abundance and condition, and they act as a critical life-history stop for species that range widely (e.g., birds migrating from five continents via various flyways, caribou {*Rangifer tarandus*} herds numbering in the hundreds of thousands) (Barber et al., 2009).

In the midst of this, natural-resource managers of protected areas in the state of Alaska, USA face a distinctive mix of infrastructural, legal, socio-economic, and topographic conditions that shape their programs for monitoring resources. As is the case for many high-latitude areas, human settlement across Alaska is sparse. Although influence of various anthropogenic activities extends well beyond the infrastructural footprint of the cities, towns, and villages in the state, natural processes remain the predominant drivers of ecosystem composition, structure, and function in ecosystems of Alaska.

Here, we discuss the geographic and statutory contexts that influence development of monitoring; argue for the inclusion of significant broad-scale monitoring; discuss the importance of defining clear programmatic and monitoring objectives; and draw

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**Table 1**
Consequences of contemporary climate change of greatest concern to land managers within each of four ecoregions within Alaska. Prioritized lists were created by natural-resource managers and scientists participating in the April 2009 Forum on Ecoregional Monitoring.

| Polar | Bering Coast | Interior Alaska | North Pacific Coast |
|---|---|---|---|
| Altered management of harvested species | Change in plant and animal community composition and structure | Altered fire regimes | Altered phenology (better understood in terrestrial ecosystems) |
| Altered distribution of invasive species (relating to detection and control) | Drying of wetlands | Changes in invasive species diversity and distribution | Water quality, especially melting of glaciers, surface water flow, water chemistry, and timing and quantity of fresh water entering marine systems (and consequent local effects on salinity) |
| Altered water quality and quantity | Changes in amount and timing of precipitation | Altered subsistence management (population sizes, reproduction, and demography; harvest regulations; phenology) | Altered animal community dynamics (terrestrial and marine), due to species' differential responses to climate change |
| Effects on biological diversity (and legal and statutory ramifications) | Alterations to terrestrial hydrology | Effects on rare and declining species and habitats (identify losses, determine conservation actions needed) | Changes in ocean dynamics (upwellings, acidification, altered currents, impacts on marine food webs, nutrient flows, effects on seabirds) |
| | Changes in the types, levels, and spatial distribution of anthropogenic activities | Alterations to water quality and quantity (including management of upstream activities) | Change in plant community composition and structure |
| | | Effects on species covered by treaties (for which broad-scale coordination is essential) | Alterations to migratory and invasive species |

from lessons learned from existing long-term, broad-scale monitoring programs. We describe how the Alaska context informs the process of developing multi-faceted monitoring that supports inference and has implications beyond individual management units, and balances monitoring objectives related to resource conservation with those related to numerous active-management decisions. We focus on the characteristics of, and theoretical and pragmatic lessons learned from, large-scale monitoring programs from around the northern hemisphere (Table 2) that were featured in a Forum on Ecoregional Monitoring in April 2009 (http://alaska.usgs.gov/science/biology/ecomonitoring/index.html). These programs include: Parks Canada Agency (PCA), US National Park Service Inventory & Monitoring (NPS I&M), Circumpolar Biodiversity Monitoring Program (CBMP), US Forest Service Inventory & Analysis Program (FIA), Kenai National Wildlife Refuge's Long-Term Ecological Monitoring Project (LTEMP; Morton et al., 2009), Great Britain's Countryside Inventory (CI), Norway's 3Q Agriculture monitoring, National Aquatic Resource Surveys (NARS), US Environmental Protection Agency Environmental Monitoring & Assessment Program (EMAP), Environmental Monitoring & Assessment Network (EMAN), and Bonanza Creek Long-term Ecological Research site. We use this focus and these examples to consider how broad-scale monitoring in northern latitudes will inform adaptation to contemporary climate change, which is shifting baseline conditions; increasing uncertainty in the amount, distribution, and timing of ecosystem goods and services; and changing the dynamics of spatially integrative resources (e.g., long rivers, migratory ungulates).

All monitoring programs reflect the suite of statutory, logistical, legal, and natural-resource conditions that provide context for and guide their development. In Alaska, the land-use pattern consists of a patchwork of many large, federally managed areas (Fig. 1). Lands managed by four federal agencies (i.e., USFWS, BLM, NPS, and USFS) span 89.1 million ha, and collectively constitute 52.5% of the Alaskan land base (Table 3). The importance of these lands for the four respective agencies is substantial, because they constitute up to 81% of each agency's land holdings, nationally (Table 3). Among these four agencies, notable differences in mandate and management philosophy exist; differences can be greater still, however, between these and other non-federal landholders in the state. Difficulty in finding shared monitoring objectives and indicators across jurisdictions also reflects the agencies' constituencies and the historical legacy of how lands were allocated to meet agency mandates: national forests were established in heavily timbered areas, wildlife refuges encompass waterfowl-supporting wetlands and connecting low-elevation habitats, and national parks typically protect areas having unique geology, history, or often-mountainous scenic beauty (Fig. 1).

Logistical implementation of monitoring faces several challenges in Alaska. Road density is very low in the state – 0.0023 km of major highway per square km of Alaskan land, and 0.14 km of paved roads (including urban areas) per square km. This implies that: (a) all of the ecological effects associated with roads (Trombulak and Frissell, 2000; Havlick, 2002) are very limited in scope, across Alaska (though effects of ORV use can be locally pronounced), and (b) transportation costs to sampling sites can constitute >85% of monitoring-program budgets. Logistics in Alaska are further complicated by the fact that crevassed glaciers, dangerously steep slopes, and nearly impassable areas (e.g., deep bogs, dense forests) can increase travel time and costs. The time available for fieldwork is typically shorter than in more-southern latitudes due to the region's marked seasonality and snow cover that can prevail for 8 months of each year in some areas.

In addition to these natural attributes that affect monitoring, several legislative, legal, and socio-economic contexts also figure heavily in design considerations for broad-scale monitoring in the region. At the broadest ideological level, resource conservation in Alaska and northern Canada is much more comprehensive, compared to wildlife refuges or reserves in the contiguous USA and southern Canada within the same agency. To date, active management of habitats (which would permit manipulative experiments in an adaptive-management context) has occurred much less frequently in conservation areas of Alaska than in more-developed portions of the globe. In contrast, however, wildlife-population management is relatively common, as evidenced by the greater prominence of subsistence and sport harvest for meat (of ungulates, other furbearers, and fishes) in Alaska and northern Canada, relative to most of the contiguous USA or southern Canada. Another distinctive wrinkle to land management is that within conservation areas, private landholdings constitute legacies of past settlement patterns, and can locally affect resource dynamics. For example, the state's 16 USFWS national wildlife refuges contain

**Table 2**
Characteristics of seven broad-scale monitoring programs featured in a Forum on Ecoregional Monitoring, held in Anchorage, Alaska in April 2009.

| Program name, design | Goals | Organization | Components monitored | Data types | Study area (extent and stratification) | Scale of results |
|---|---|---|---|---|---|---|
| **Parks Canada Agency (PCA)** Independent units; core national staff | Trends in ecosystem integrity to evaluate management, increase understanding, identify research needs, and provide a baseline | National guidance for core indicators; conducted by park staff | Plant and animal diversity, ecosystem functions, stressors | Primarily *in situ* | National parks of Canada | Core indicators at national and bioregional scale; others at park scale |
| **US National Park Service Inventory & Monitoring (NPS I&M)** Independent units, core national staff | Status and trends of indicators of park ecosystem condition; others similar to Parks Canada | National guidance on administration; network-level authority for monitoring decisions; funded by national agency | Vital Signs – biotic and abiotic ecosystem components or processes | Variety of types, spatial scales, and sampling frequencies | US NPS units; often sampled independently | Primarily park unit |
| **Circumpolar Biodiversity Monitoring Program (CBMP)** Independent units | Coordinating entity for: existing arctic biodiversity monitoring programs; identifying gaps in knowledge; integrating and analyzing data; gathering and communicating results | Staff funded by Environment Canada; consists of scientists in all eight arctic countries; linked to other monitoring programs, who largely conduct the monitoring | Integrated-ecosystem approach (terrestrial, freshwater, marine): species composition; ecosystem structure, functions, and services; habitat extent and quality; human health and well-being | Do not do any monitoring themselves, but partners use remote sensing, *in situ* measurements, etc. | Varies by indicator; up to all 8 countries defined as arctic by Conservation of Arctic Flora & Fauna (CAFF) | Indicator-specific; ranges from individual management units to Arctic-wide |
| **USFS Forest Inventory & Analysis Program (FIA)** Standard protocol | Assess status and trend of US forests (e.g., forest health and sustainability, forest ownership and use); analyze current issues (e.g., fire risk, C sequestration) | Funded and conducted by national agency; standard regional protocol | Tree characteristics, physical environment; intensity of other vegetation monitoring varies with scale | *In situ* sampling; systematic grid | Forested lands of United States | State, region, national |
| **Kenai NWR LTEMP** Standard protocol | Status, trends, and distribution of biodiversity | Funded and conducted by Kenai NWR; augments FIA data | Vascular and non-vascular plants, insects, birds | *In situ* sampling | Kenai NWR, FIA plots | Refuge |
| **Countryside Inventory (CI)** Standard protocol; nested design | Extent and change of broad habitats; inform policy (especially land-use) | Conducted by independent public-sector research center; funded by variety of government bodies | Landscape/habitat mapping, vegetation, soil, freshwater, birds | Field mapping, *in situ* sampling, satellite imagery | Great Britain, by land class and nation (England, Scotland, Wales) | National |
| **3Q Agriculture Monitoring** Standard protocol | Changes in agricultural landscapes; inform policy (especially agricultural) | Conducted by independent research institute; funded primarily by Ministry of Agriculture & Food | Land cover, vascular plants, birds, cultural heritage elements | Aerial photos, selected *in situ* sampling | Norway, agricultural land-uses only | National |
| **National Aquatic Resource Surveys (NARS)** Standard protocol; nested | Describe condition and trend of US waters; promote collaboration across jurisdictional boundaries in assessing water quality | Funded and conducted by a national agency, working with states, tribes, and other partners | Water-quality metrics (e.g., indicators of ecological integrity, nutrients, chemical and physical measures, shoreline habitat) | *In situ* samples, automated recorders, supplemented with remotely sensed data | 30 US states (as of Jan. 2008); monitoring divided into coastal, wadeable-stream, river, lake, and wetland ecosystems | State, regional (multi-state), and national; some metrics at basin and smaller resolutions |
| **Environmental Monitoring & Assessment Program (EMAP)** | Status of ecological resources | Conducted and funded by national government agency | Surface waters and estuaries; biotic and physical components | *In situ* sampling | United States: projects by region and resource type | Region |
| **Ecological Monitoring and Assessment Network (EMAN)** Independent units | Provide environmental 'early warnings'; inform policy | Various networks of monitoring sites; coordinated by national government agency | Varies by network; includes water, air, temperature, substrate, genetic, species, community and landscape | Primarily *in situ* sampling | Networks scattered across Canada | Qualitative national summary |
| **Bonanza Creek LTER** Reference site | Improve understanding of long-term consequences of changing climate and disturbance regimes in Alaskan boreal forest | Funding by federal and university research grants | Biogeochemistry, vegetation, weather, soils, vertebrates, invertebrates, fire | Remote sensing, *in situ* measurements | Varies by study; most in a Research Watershed (10,400 ha) or Experimental Forest (5053 ha) | Mostly small-scale (plot to within two focal units); some across taiga ecosystems or statewide |

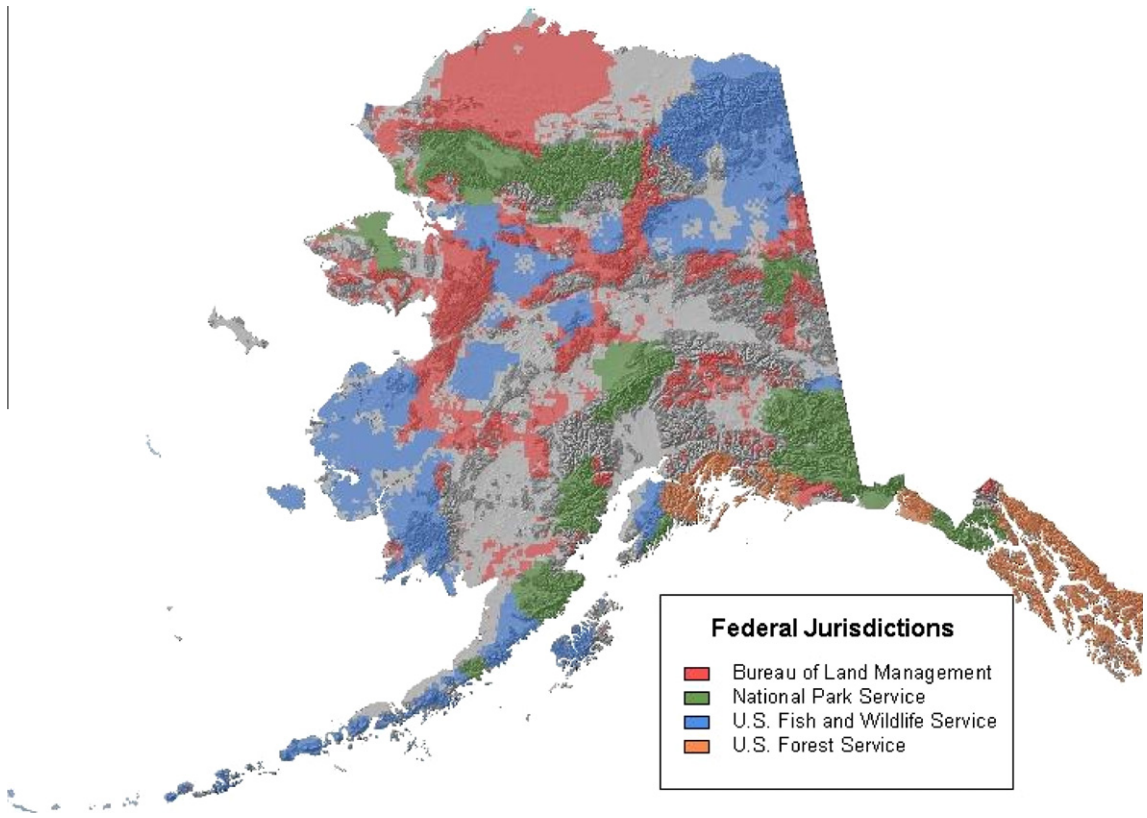


**Fig. 1.** Relationship among four federal jurisdictions and mountainous areas across Alaska. Landforms were mapped following procedures of Gallant et al. (2005), with the slope-gradient threshold set at 2%. From these results, all areas coded as continuous hills, high hills, and low and high mountains in the Hammond scheme were reclassified as "mountainous" (dark-grey shading), and all other pixels as "non-mountainous" (light-grey areas).

**Table 3**
Quantification of land managed by each of four US Department of Interior land-management agencies, within Alaska, USA.

| | US Fish & Wildlife Service | US National Park Service | Bureau of Land Management | US Forest Service | Totals |
|---|---|---|---|---|---|
| Number of management units | 16 refuges | 15 parks | ⩾13 areas | 13 districts | ⩾57 units |
| Amount of area (ha) managed | 28.1 million | 21. 8 million | 30.3 million | 8.9 million | 89.1 million |
| Percentage of Alaskan land base | 16.6% | 12.9% | 17.9% | 5.2% | 52.5% |
| Percentage of agency's holdings, nationally | 81% | 65% | 30% | 14% | $\bar{x}$=47.5% |
| Amount of area (ha) as wilderness, in Alaska | 7.56 million | 13.55 million | 0 | 2.33 million | 23.44 million |

over 90 villages and thousands of private inholdings that cover millions of ha (D. Jerry, USFWS Division of Realty and Resources, *personal communication*).

Importantly, monitoring that happens within an agency across broad scales in Alaska must also interface with that agency's national monitoring program, and may additionally seek to improve effectiveness and cost-efficiency by interfacing with other monitoring entities in the region. Although land-management units of BLM and NPS in Alaska have broad autonomy over indicator selection and sample frames within national-level monitoring programs, the relationship of Alaska national wildlife refuges to the national monitoring program of USFWS has not yet been determined. Given that: (1) agencies and other monitoring entities have different missions and objectives for their lands both nationally and locally, and (2) objectives drive monitoring designs and methods, there may be challenges to integrating monitoring across agencies. These may be resolved through compromises or implementation of hybrid methods for which some metrics are broadly comparable, yet other metrics meet individual-agency objectives (e.g., Johnson et al., 2008).

Effects of contemporary climate changes in Alaska are but one of several stimuli that have led to consideration by the USFWS of bolstering monitoring at scales broader than that of individual management units, including collaboration with other agencies. Broad-scale monitoring is also attractive because: (a) contrary to local monitoring, it is able to distinguish between local anomalies and broad-scale patterns; (b) it allows greater area of inference and domain of applicability; (c) when using consistent methods, it achieves greater collective sample size, higher statistical power, and thus greater sensitivity to detect any changes that may be occurring; (d) it can detect phenomena such as thresholds, nonlinear dynamics, synergies, and cross-scale and hierarchical dynamics; and (e) many processes are best monitored and interpreted at broader spatial resolutions. Examples of broad-scale processes include fire regime that affects the availability of forage for migratory ungulates; storm seasonality relative to sea-ice melt, which in turn affects coastal erosion; and the shifting mosaic of wetlands as some regions dry and others experience thawing permafrost.

Land-management agencies within Alaska are at various stages in the process of supplementing existing, largely local-scale

(individual-unit) monitoring with broader-scale monitoring. Landscape Conservation Cooperatives and the US's first Regional Climate Science Center will begin work in 2010, as will fieldwork for one NPS I&M network; meanwhile, other NPS networks have been performing field monitoring for several years. The magnitude of contemporary climate change underscores the need for a broader-scale perspective for monitoring (Suffling and Scott, 2002; Barber et al., 2009). Development of the agencies' broad-scale monitoring programs will reflect numerous constraints, criteria, and contexts: legislation and statutes, the state of natural resources, available internal and extramural funding, technical capacity internally and that can be engaged extramurally, and the ability to leverage or complement efforts on adjacent jurisdictions and from other programs within the same agency. Our objectives in this paper, intended for application to both terrestrial and freshwater ecosystems, are threefold. First, we seek to learn from other broad-scale, comprehensive monitoring programs, regarding critical elements of program structure, monitoring designs, and implementation (see Table 2). Second, we strive to highlight aspects for consideration for broad-scale ecological monitoring programs for high-latitude protected areas within Alaska and Canadian partners by juxtaposing those against: (1) the ecological, monitoring, and arctic literatures; (2) conceptual models of individual refuges and the ecoregions; and (3) existing constraints (e.g., current data availability). Finally, we discuss some potential pitfalls in application, and relate alternative solutions that may be applicable.

## 2. Objective-setting for broad-scale monitoring

Monitoring-program development in the context of natural-resource-management or conservation must be guided by identification of clearly defined objectives (Olsen et al., 1999; Noon et al., 1999; Noon, 2003; Beever, 2006). At finer organizational levels, tight, clear expression of objectives provides guidance for subsequent steps of the process, thereby vastly reducing uncertainty about alternative options of design, field methods, analytical method, and interpretation of monitoring results. For complex, multi-scaled programs (e.g., see Table 2 or Olsen et al., 1999), objectives must be resolved at numerous hierarchical levels of the monitoring organization (compare dynamics in Figs. 2a and 2b), and often must be iteratively re-visited and refined throughout the initial years of program development. Alaskan protected areas are generally assumed to contain intact ecosystems, and to fulfill a benchmark role against which trends in other, more-altered portions of the landscape can be compared. Possible overarching programmatic objectives that could be used to guide development of broad-scale monitoring across conservation areas in high-northern-latitude ecosystems, such as those in Alaska, include:

(a) Understand the demographic, population-size, distributional, and (occasionally) genetic status and trends of species that: (1) are widely used for subsistence, or (2) relate to existing international treaties; (3) connect or integrate distant portions of the landscape (e.g., migratory species); (4) are broadly distributed within Alaska, and localized difference in trend could indicate broader pattern; or (5) are otherwise of broad interest.
(b) Inform and support decisions for meeting statutory and legislative mandates related to natural-resource conservation, subsistence use, and recreational activities.
(c) Document and begin to interpret broad-scale alterations in ecological communities due to contemporary climate change.
(d) Better understand distinction between anthropogenically induced and endogenous ('natural') variation.

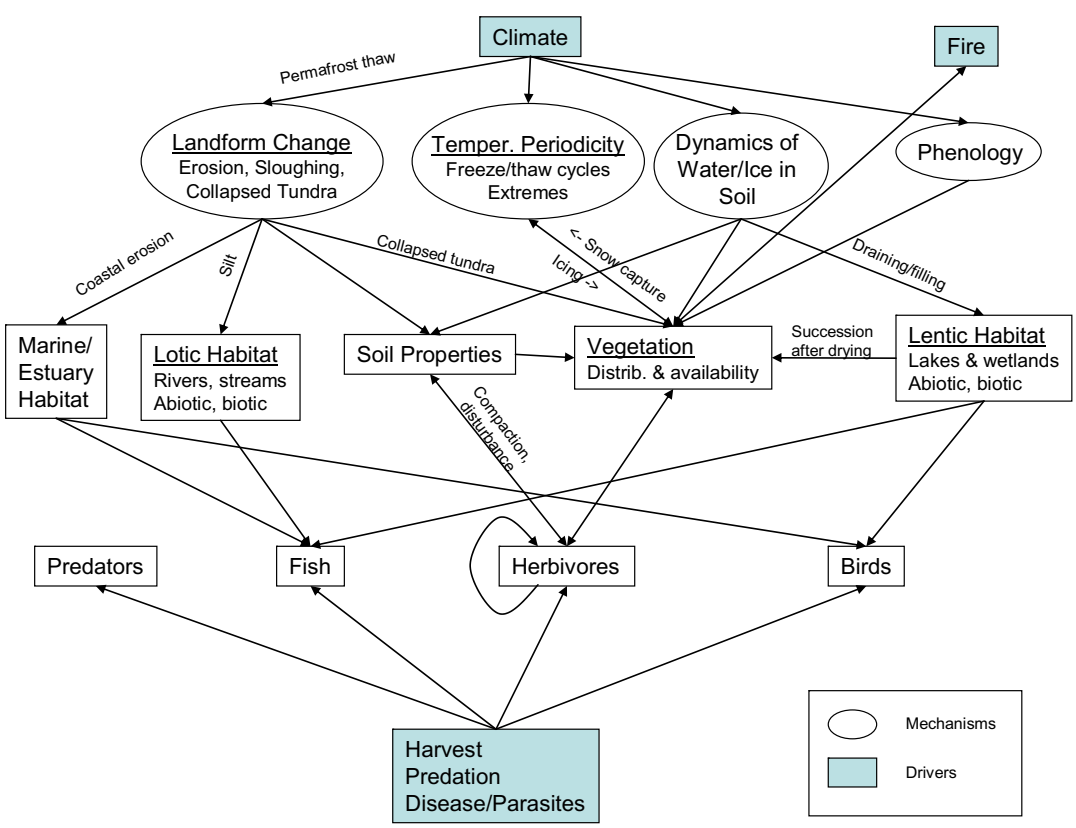


**Fig. 2a.** Conceptual model of Selawik National Wildlife Refuge, created by staff of the Refuge. Labels along connecting arrows typically describe processes, whereas white rectangles constitute ecosystem components.

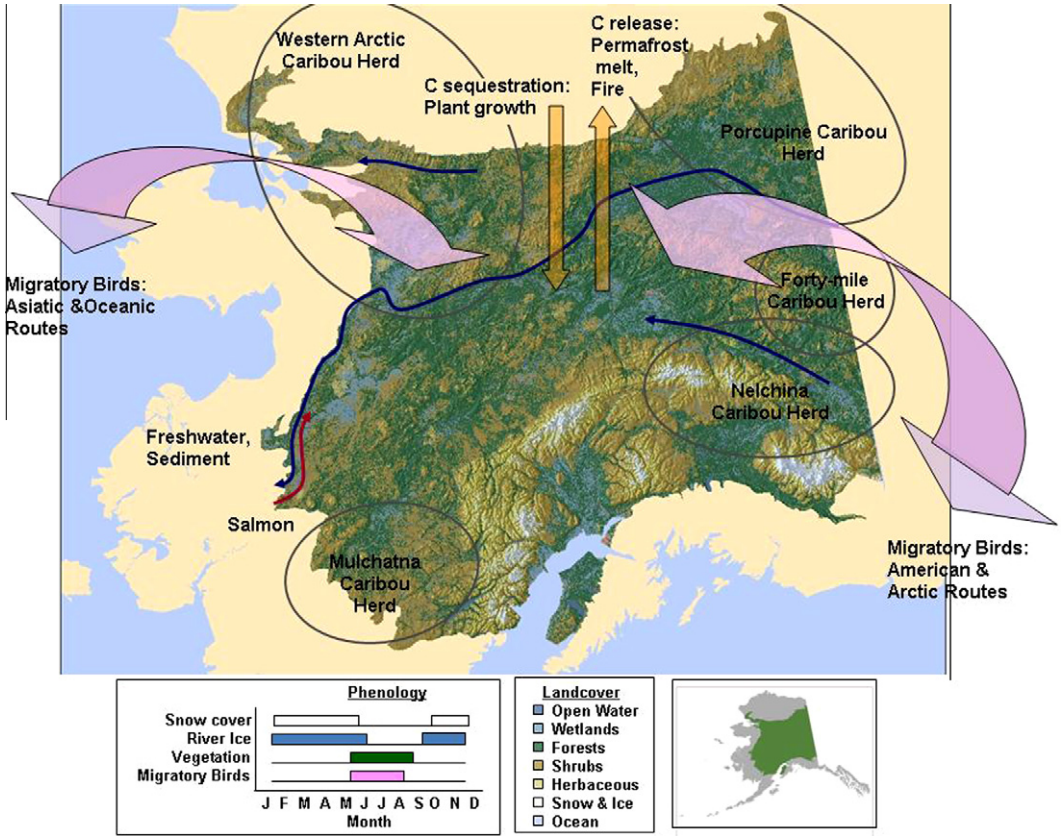


**Fig. 2b.** Conceptual model of the Interior Alaska ecoregion, illustrating ecological processes and components that operate at scales larger than individual refuges. The model depicts the spatial pattern of land cover and temporal pattern of phenology, which constitute the ecoregional environmental template. Model elements overlaying the template include ecoregional components and processes that require and impact large areas, rather than those that are widely distributed (e.g., arctic ground squirrel {*Spermophilus parryii*}, gray wolf {*Canis lupus*}, common raven {*Corvus corax*}). The model represents one of several possible ways to represent the ecoregion. Locations of elements on the map are symbolic rather than geographically precise.

(e) Facilitate proactive assessment of broad-scale landscape condition, by providing early warning of impending ecological challenges.

## 3. Structure of broad-scale monitoring: considerations from previous efforts

### 3.1. Strategic decisions about resource allocation

Ultimately, structure of the monitoring program reflects decisions about how to allocate resources (both staff time and monitoring funds) along several continuous dimensions, which are not necessarily independent. Results of these decisions reflect philosophical and theoretical preferences, and also the objectives, capacities, and contexts of the monitoring organization. For example, although most monitoring by land-management agencies seeks to inform management decisions (PCA, 2008; Fancy et al., 2009; USFWS, 2010), monitoring may be tied specifically to particular active-management actions or may instead characterize ecosystem status and thus inform non-manipulative management as well as detect unexpected responses. Assessing success of a management action involves monitoring to compare the consequences with the objective, whereas assessing success of protection involves characterizing ecosystem status. Monitoring programs that assess ecosystem status (sometimes called 'surveillance' monitoring) have been criticized for not being tied to management decisions (Nichols and Williams, 2006). However, if managers set quantitative thresholds to indicate when indicators are within acceptable bounds, success or failure of protective management can be clearly understood (PCA, 2008). Given the logistical, legal, and socio-economic realities of Alaska, non-manipulative ("passive") management is currently more prominent there than in the rest of the continent, though climate change may increase the need for active management (e.g., use of prescribed fires).

Organizationally, a spatially extensive monitoring program may focus on a core suite of questions and indicators that are monitored consistently across a broad domain (e.g., FIA and NARS in Table 2), or foster local autonomy by addressing questions of greatest interest to each individual management unit (e.g., PCA and NPS I&M in Table 2). "Consistent" monitoring implies constancy of questions, metrics measured, sampling designs, and field and analytical methods. The more of these that differ, the greater is the loss in strength of analytical method – from increased number of true replicates in the sample and thus greater statistical power (when all are consistent), to tests that simply analyze the counts of the number of positive and negative trends. Within Alaska, coordinated monitoring across jurisdictions on resources for which agencies' mandates and objectives differ dramatically (e.g., waterfowl) may have to resort to low-power tests. Although broad consistency permits wider understanding, it can sometimes be more difficult to obtain management-unit-level support and investment, if not including locally relevant indicators.

Philosophically and through its sampling designs, a monitoring program may seek primarily to document status and trend in resources across space and time (e.g., NPS I&M in Table 2). Alternatively (e.g., NARS and EMAP in Table 2), it may seek also to elucidate possible causes behind any observed 'effects' in monitoring indicators – albeit not unequivocally (Sokal and Rohlf, 1995),

given that monitoring is rarely experimental. Spatially, monitoring may focus on areas that are already altered, sensitive, or appear to be changing, or alternatively anticipate changes due to broad-scale stressors (Table 2). Analogously, monitoring may spatially focus only on one domain (e.g., water bodies for NARS, forested ecosystems for FIA, agricultural lands for 3Q, easily-accessible strata; Table 2) or instead track a more-comprehensive scope or domain (e.g., EMAN, CS; Table 2). Focusing on one stratum (or domain) can reduce noise and process variation in an indicator, thus increasing power to detect trend (Burnham et al., 1987). However, many managers prefer to track dynamics in more than just one subset of the landscape, and statistical advantages of stratification evaporate if stratum membership of sample points shifts through time (e.g., vegetation types may shift distributions over time). Given the staff investment in monitoring that already or soon will exist within Alaska, agencies leaning towards the former seems likely (though expansion of the scope of indicators could lead to contracted specialist teams). Biologically, a program may focus on vulnerable ecosystem elements (thus seeking an 'early-warning' system; e.g., NPS I&M in Table 2); focus on more-common elements whose greater numbers may provide greater power; or focus on keystone, umbrella, flagship, or focal species (summarized in Table 1 of Beever (2006)). In many cases, these characterizations are not mutually exclusive, such that a single species can fit numerous designations. In high-latitude areas, 'early-warning' indicators seem attractive given the expectation of relatively rapid ecological changes due to climate change; however, resources that are tied to ecosystem services (Daily et al., 1997) or are less noisy in their signal may be more efficient, interpretable, and insightful indicators. We acknowledge, however, that in some instances, monitoring of variation can be an explicit goal (Carpenter and Brock, 2006).

Temporally, a program may make a strategic decision to deem long-term continuity its highest priority (e.g., NPS I&M, FIA; Table 2), or instead foster tactical flexibility through time by addressing a number of specific applied questions that are most

**Table 4**
A sample list of indicators that could be considered for monitoring in northern-latitude conservation areas, at each of three spatial scales, as well as examples of monitoring designs and temporal re-visit strategies that could be employed to accomplish such monitoring.

| Indicator(s) | Monitoring design | Temporal (re-visit) strategy |
|---|---|---|
| *State-wide extent* | | |
| Climate | Collection of index sites with time series of varying antiquity and continuity | Continuous data collection (recorded or summarized sub-hourly, hourly, sub-daily, daily, monthly, seasonally, and annually) |
| Air quality, precipitation chemistry | Collection of index sites with time series of varying antiquity and continuity | Continuous data collection (recorded or summarized sub-daily, daily, monthly, seasonally, and annually) |
| Land cover | Patchwork of strips of locally censused area; re-sample across years at several index strips (randomly selected, initially), to quantify inter-annual effects | State divided into 5–7 randomly selected samples of strips; rotating-panel design |
| Phenology | Varies by attribute; probably a collection of volunteer locations, for many attributes; most sites likely to be in easily-accessible locations, for easy re-visits | Re-visits daily or weekly, within range of target date (varying by indicator); more-frequent surveillance, with remote cameras |
| Water quality and quantity | Gage stations are a network of index sites; seasonal chemistry should be sampled across gradients of remoteness | Continuous data collection (recorded or summarized sub-hourly, hourly, sub-daily, daily, monthly, seasonally, and annually) |
| Deformities and contaminants in organisms | Opportunistic, in the midst of other research and monitoring projects | Contingent upon existing study designs |
| *Ecoregional extent* | | |
| Habitat mosaics | Obtain landsat or other remotely sensed imagery; supplement with ground-based sampling or finer-resolution imagery (e.g., SPOT, LiDAR, IKONOS), to validate | Ecoregion (or interested management units) divided into 5–7 randomly (or systematically) selected samples of strips; rotating-panel design |
| Migratory species | Across gradients of remoteness (at least occasionally); maintenance of existing BBS-route time series | Annually, within target season(s) (migrant arrival, breeding/rutting, pre-migration) |
| Permafrost-related events and resources | Opportunistic, in the midst of other research and monitoring projects; use these to inform subsequent monitoring designs; stratified random sampling across gradients at least several km away from big population centers (i.e., heat sources); sample across elevations and aspects; use remotely sensed imagery as a coarse-resolution census | Opportunistic sampling varies by project; Censuses: ecoregions divided into 5–7 randomly selected samples of strips; rotating-panel design |
| Shoreline changes | Stratified random sampling | Split-panel design (to balance understanding of status and trend) |
| Invasive species | Divided effort: smaller effort in systematic or random sampling (stratified by accessibility); greater effort at most-likely vectors (e.g., trailheads) of invasion and known population sites | Annually, within target season |
| Other landscape processes | Opportunistic, depending on where events occur (mapping) | Annually, within target season; split-panel design (to balance understanding of status and trend) |
| *Management-unit extent* | | |
| Subsistence resources | Most effort at most-likely locations (e.g., near population centers, trailheads, roadsides) of likely and known harvest or collecting sites | Annually, within target season; split-panel design |
| Ecological keystones, ecosystem engineers, or key landscape modifiers | Varies by indicator | Varies by indicator |
| Local stressors and responses | Most effort at most-likely locations (e.g., near population centers, trailheads, roadsides) of likely and known transportation corridors and recreation sites | Annually, within target season |
| Refuge-significant species not covered at ecoregional extent | Varies by indicator | Varies by indicator |
| Special plant and animal communities | Varies by indicator | Split-panel design (to balance understanding of status and trend) |

immediately relevant, through a series of short-term hypothesis tests. An additional alternative is that monitoring frequency or intensity can vary through time, as a function of resource condition (e.g., as a function of uncertainty in the estimate of population density, or proximity to a population-abundance threshold; Hauser et al., 2006). Long data series have enabled some of the most-powerful understanding of natural phenomena (e.g., Johnson et al., 2000); however, some individuals feel strongly that extreme programmatic rigidity can mean missed opportunities (Ringold et al., 1996). Landscapes in high northern latitudes paradoxically seem to justify both of these philosophies, given: (a) the relative rapidity of landscape change, and (b) the unpredictability of the nature and direction of some changes.

Pragmatically, a program may involve collecting all data with existing staff, solely use data collected by others (e.g., CBMP in Table 2; citizen-science efforts such as the National Phenological Network; incorporation of traditional ecological knowledge), or utilize some combination thereof. Financially and philosophically, a program may decide to do a few things well by investing in a small number of indicators that are sampled thoroughly, or instead use the 'weight of evidence' (i.e., concordance) provided by results from numerous indicators sampled less intensively.

Although we have described most of these as dichotomous choices, they are in fact continua. In practice, most broad-ranging programs have a mix of values along many dimensions, when assessed collectively across indicators (Table 2). A program can seek a compromise by allocating some resources to each strategy. Several fundamentally different monitoring foci, and monitoring designs appropriate for each, appear in Table 2 of Beever (2006). A diverse, multi-scale list of potential indicators and relevant sampling designs for protected areas of Alaska appears below, in Table 4.

### 3.2. Conceptual models as tools for understanding system dynamics

Development of many multi-faceted monitoring and research programs proceeds from *conceptual models* that illustrate how the system is understood and the dynamics it contains. Conceptual models play an integral role in the development of a monitoring program, in part because they aid in framing useful questions and selecting relevant indicators (e.g., see Tables 1 and 5; National Research Council, 1995; Noon et al., 1999; Boutin et al., 2001; Noon, 2003). In effect, conceptual models represent working hypotheses about ecosystem organization, function, and inter-relationships (Huggett, 1993; Manley et al., 2000). Specifically, conceptual models inform the development of a monitoring program in several ways (modified from Maddox et al., 1999):

**Table 5**
List of indicators that may be valuable for monitoring, by ecoregion. The list derives from ecoregional-scale conceptual models that featured ecosystem components and processes that span broad spatial extents, and thus would have organization and interpretation of monitoring occur most meaningfully at broad resolutions.

| Terrestrial ecoregions | | | |
|---|---|---|---|
| Polar | Bering Coast | Interior Alaska | North Pacific Coast |
| *Air and climate* | | | |
| Climate (terrestrial, nearshore) | Climate (terrestrial, nearshore) | Climate (terrestrial, nearshore) | Climate (terrestrial, nearshore) |
| Shorefast- and sea-ice distribution, phenology | Shorefast- and sea-ice distribution, phenology | | Sea-ice distribution, phenology |
| Beaufort Gyre | Ocean currents; marine climate | | North Pacific current |
| | | $CO_2$ levels (release by melting permafrost, fires; sequestration by plant growth) | |
| *Geology and soils* | | | |
| | Marine-derived nutrients (chemistry) | Marine-derived nutrients (chemistry) | Marine-derived nutrients (chemistry) |
| Maximum active-layer depths of permafrost (spatial pattern of trends) | | Permafrost distribution and thawing | Isostatic rebound |
| | | | Volcanism |
| *Water quality and quantity* | | | |
| Freshwater (water quality, hydrograph characteristics) | Aspects of Kuskokwim, Yukon, and Kobuk River waters | Riverflow and flood risk; river-ice breakup | |
| Pattern of lake drying, creation | | | |
| Marine conditions | Marine conditions | | Marine conditions (pollutants, acidification, climatic influence) |
| *Biological integrity* | | | |
| | Beluga whales *(Delphinapterus leucas)* and other migratory large marine mammals | | Whales, Northern fur seals *(Callorhinus ursinus)*, and other migratory large marine mammals |
| Migratory birds | Migratory birds | Migratory birds | Marine food web |
| | Anadromous fishes | Anadromous fishes | |
| Caribou herds (Western Arctic, Central Arctic, Porcupine) | Caribou {*Rangifer tarandus*} herds (Western Arctic, Mulchatna) | Caribou herds (Western Arctic, Forty mile, Porcupine, Mulchatna) | |
| Phenology (insects, sea ice, vegetation green-up, migratory birds) | Phenology (ice, vegetation, migratory birds) | Phenology (insects, river ice, vegetation green-up, migratory birds, fire season) | Phenology (whale migrations, vegetation green-up, migratory birds) |
| *Anthropogenic stressors (human use)* | | | |
| Harvest of migratory animals | Harvest of migratory animals | Harvest of migratory animals | Harvest of migratory animals (marine, terrestrial) |
| Fire management | Fire management | Fire management | Fire management |
| Industrial activities | | | Oil and gas development |

- Models summarize the most important ecosystem descriptors, spatial and temporal scales of major biological processes, and current and potential threats to the system (see Fig. 2a). They provide feedback to, and help formulate, goals, objectives, indicators, management strategies, results, and research needs. Models facilitate discussion and debate about the nature of the system and important management issues and questions.
- Conceptual ecosystem models play an important role in determining indicators (components, processes, or relationships) for monitoring that may be considered for measurement (Figs. 2a and 2b).
- Conceptual models can provide a useful tool to help interpret monitoring results and explore alternative courses of management (Fig. 2a). Monitoring results should be used to iteratively update and improve the ecological model, as the model is developed, tested, and informed by new data and knowledge.
- Models offer templates for assessing possible alternative management strategies. Models may be useful for understanding the impacts of various management actions, natural ecological variability, and human-influenced change.

Particularly for supplementing a suite of existing local-scale monitoring efforts in Alaska and other northern-latitude protected areas, conceptual models can also: (a) broaden thinking beyond specific land-management units or species to a landscape level, by illustrating broader-scale integration and context (Fig. 2b); (b) identify 'gaps' (i.e., discrepancies between what is currently being monitored and how land managers conceive ecosystems (Figs. 2a and 2b)); (c) identify monitoring priorities and identify which new inventories may be most informative (Tables 1 and 5); and (d) serve as a key element for adaptive management, by providing the means by which to assess alternative management strategies, and human and natural changes (Fig. 2a).

Examples of a management-unit-level and an ecoregional-level conceptual model are provided in Figs. 2a and 2b. Fig. 2a not only provides testable hypotheses about how certain aspects of ecosystem structure, composition, and function may change with contemporary climatic changes, but also postulates mechanisms by which each of numerous changes may occur. Fig. 2a also illustrates how changes in climate will impose both direct and indirect effects on ecosystems. Note also that conceptual models can work jointly across multiple spatial scales (Figs. 2a and 2b). For example, although the relationship of birds to their habitats appears in both models, the finer-scale model implies narrower, more-mechanistic relationships. In contrast, the ecoregional model suggests that spatial distribution of waterbirds may shift with contemporary climate change, as the patterns of wetland drying (Riordan et al., 2006) and permafrost thawing (Jorgenson et al., 2001) alter availability of water bodies across broad spatial scales, in far-northern latitudes.

### 3.3. Monitoring fieldwork in the broader organizational context

There will inevitably be insufficient funds to field-sample all indicators of interest across the entire domain of a monitoring program. In fact, many monitoring programs have found that information obtained from field sampling can have its value better leveraged when the monitoring fieldwork is part of a larger suite of program activities (e.g., Table 6). In this section, we outline a number of such complementary activities that may be particularly relevant for Alaska, and briefly describe the utility of each, for broad-scale monitoring. Often, to inform selection of indicators and development of the sampling designs, monitoring is preceded by *inventories* that both 'fill out' species lists and improve understanding of species' distributions within the sampling domains. In an extreme (albeit simplistic) view, monitoring can be considered simply a temporally repeated series of inventories. Such inventories could also characterize abiotic resources within the domain (e.g., topography, bathymetry, soils, hydrography), which could be used both in sampling designs (e.g., as stratifying factors) and to help interpret sampling results. In similar fashion, comprehensive samples of entire domains (or a subset thereof), via *remote sensing or aerial photography*, can provide information on landscape composition and structure, and may inform any stratification. National parks have begun to complete numerous inventories of high-priority resources within park units across Alaska, whereas USFWS refuges are lacking many digital coverages (of critical resources) that would aid interpretation of broad-scale monitoring data (USFWS 2004).

**Table 6**
An approximately sequential list of activities that are typically accomplished in the development of an integrative, long-term program of monitoring natural resources across broad spatial scales.

| Activity | Typical duration |
|---|---|
| Perform inventories of resources present in management area (especially within target domains) | One to several years |
| Amalgamate information from existing monitoring programs within the sphere of influence of the target domain(s) | 6–24 months |
| Begin to hire staff for broad-scale monitoring: coordinator, data manager | 4–15 months |
| Summarize resources, processes, drivers, and gradients existing within focal area | 9–18 months |
| Create conceptual models that link prominent resources, processes, structure, and stressors via defined interactions/links | 6–12 months |
| Develop and refine objectives for the monitoring center (and other levels, as appropriate) | 1–6 months |
| Identification of more-comprehensive list of potential indicators | 1–4 months |
| Decide upon method to prioritize indicators; obtain input on priorities from researchers and managers | 3–9 months |
| Make initial list of indicators to be monitored in short and longer terms (tiered, to accommodate various funding levels) | 2–6 months |
| Hire disciplinary specialists to lead monitoring program(s) for related indicator(s) | 6–15 months |
| Develop objectives/questions for each indicator | 1–2 months |
| Develop sampling design and protocols for each indicator | 6–18 months |
| External peer-review of objectives/questions, sampling design, and protocols | 3–6 months |
| Pilot testing of methods and protocol; protocol revision | 1–4 years |
| *Begin full implementation of monitoring* | |
| Reflect and review progress of monitoring for each indicator | Every 3–5 years |
| Produce report of each year's monitoring | Every year |
| Synthesize, interpret, and communicate findings of monitoring; may need multiple reporting formats, to address different audiences | Every 5–7 years |

Various types of modeling can also be informative. *Ecological forecasts* (Clark et al., 2001) and *futures modeling* can help bound expectations about magnitudes of possible change and identify areas where particular attention may be focused, to provide early warning of landscape or distributional change. In protected areas of Alaska, this has been performed on hydrological parameters by the Wilderness Society and collaborators (O'Brien et al., submitted for publication), on biome shifts using downscaled vegetation and climate projections by the SNAP program (Calef et al., 2005), and for individual wildlife species' distributions (e.g., Magness et al., 2008; Booms et al., 2010). Especially in light of climate change, *vulnerability assessments* that account for life-history variables such as vagility, reproductive capacity, degree of commensalism with humans, and breadth of habitat niche and bioclimatic envelope, may point to species that may be early-responders to contemporary climate change (e.g., Lexer and Seidl, 2009). *Spatial modeling*

may clarify species-habitat relationships, predict vulnerability to future climate change, and provide testable predictions that can be iteratively refined with subsequent data collection. *Simulation modeling* and *sensitivity analyses* can help clarify the robustness of observed dynamics, and identify which factors appear to be having the greatest effect on indicator status.

*Manipulative experiments* (especially for plants or invertebrates) provide strong tests of these assessments, and could clarify the limits of the thermoneutral zone, among many other phenomena (Dunne et al., 2004). Monitoring for understanding status and trends of resources can also be supplemented by *implementation monitoring* (i.e., evaluation of compliance with standards and guidelines), *validation monitoring* (i.e., testing cause-effect relationships in indicators), and *effectiveness monitoring* (i.e., testing the effect of a particular conservation strategy or management action on indicators) (Mulder and Palmer, 1999).

## 4. Other lessons learned from other broad-scale monitoring programs

Whereas Section 3.1 identified how monitoring programs might structure their program, in this section, we provide overarching principles that will likely apply across a range of program conditions and philosophies within high northern latitudes. Table 2 summarizes a number of the salient program characteristics from numerous broad-scale ecological monitoring programs. As mentioned above, leaders of broad-scale monitoring programs continually stressed the importance of *clearly defined goals and objectives*, because all subsequent steps in program development reflect those definitions. Once objectives are crafted down to the level of individual indicators, *appropriate sampling designs* must be chosen to match the specific questions and constraints involved (Cochran, 1977; Underwood, 1994; Hayek and Buzas, 1997; Yoccoz et al., 2001). Program leaders, as well as numerous authors in the literature (e.g., Stevens et al., 2007), generally agree that probabilistic designs are worthwhile in most monitoring contexts, given that they apply to all (or a definable subset) of particular management unit(s) and are least likely to produce bias (Hayek and Buzas, 1997; Manly, 2001). Probabilistic designs do not *de facto* mean that costs must be unapproachably high. In high-northern-latitude areas such as Alaska, options to keep costs manageable with a probabilistic design include using accessibility strata (in which increasingly remote areas have increasingly small – but non-zero – chance of being selected) or limiting the entire domain to more-accessible areas (e.g., areas within 30 km of existing infrastructure) (Thompson et al., submitted for publication). A balancing consideration is that designs that are extremely complex will continually require outside analysts to properly interpret monitoring results, which weakens self-sufficiency. When sample sites are fixed through time, such complex designs also can become inefficient or even force interruption of the time series of data, as values of stratification factors at sites drift over the years.

Programmatic organization of monitoring through time can greatly influence a program's ability to accurately quantify and interpret status and trends of resources within the domain(s) of interest. For example, *implementing a program hierarchically* (e.g., FIA and NARS, in Table 2; also compare dynamics in Figs. 2a and 2b) allows for inference at multiple spatial scales (Noss, 1990; Niemi and McDonald, 2004), and seems an optimal balance between the desires to: (a) have greatest consistency and statistical power at broadest spatial scales, yet (b) increase local investment, by having sampling that produces locally relevant results that are statistically powerful enough to be pragmatically reliable. Understanding the scales at which indicators vary most strongly and predictably will inform which scales are most meaningful to measure at (Beever, 2006).

Experience suggests that a *tiered monitoring program*, consisting of a minimal core set of compulsory measurements and one or more sets of optional measurements, provides a reasonable balance between long-term continuity of monitoring and flexibility to adapt to fiscal and logistical vagaries (e.g., low funding, bad weather). An alternative source of flexibility is *adaptive monitoring* (Ringold et al., 1996), in which one or more aspects of the monitoring process are iteratively adjusted through time.

Most program leaders recommend as much *protocol standardization* (e.g., Oakley et al., 2003) as possible, balanced against the possibility of differing objectives. Program leaders agree that *data management, analysis, and reporting* must be timely (to maintain support and credibility among constituencies, through time), and that they will consume a significant part of the monitoring budget – up to fully one-third of the entire operating budget. They further suggest that *contemporary climate change* should be *explicitly incorporated into the selection of indicators* (either as a sensitivity criterion for prioritizing indicators, as indicators themselves, or both) *and in the choice of monitoring designs*, because any biotic strata based on current mosaics will undoubtedly morph through time.

Finally, *linking monitoring to management decisions* has been advocated not only in the literature (e.g., Ringold et al., 1996; Noon et al., 1999; Noon, 2003; Nichols and Williams, 2006), but also by monitoring-program leadership (Table 2). For northern-latitude protected areas, an *adaptive-management* rubric could be employed for some questions and indicators, and a *surveillance-monitoring* approach for more-conservation-oriented objectives (e.g., "conserving fish and wildlife populations and habitats in their natural diversity"; USFWS, 1980) that are focused and hypothesis-driven (Nichols and Williams, 2006). Broad-scale monitoring can be particularly informative in an adaptive-management context, because on average it should distinguish local anomalies from broader-scale trends. Adaptive management typically involves iterative refinement of (active-) management actions through time, by explicitly considering management actions as ecological experiments that can be learned from (Holling, 1978). In contrast, passive management typically does not employ management actions (e.g., habitat manipulation, removal of exotic vertebrates), but instead uses protective regulation (e.g., restriction of use of off-road vehicles) to achieve objectives. Conservation monitoring can be linked to management through creation of objectives, formulation of models and hypotheses about system dynamics, evaluation of alternative management actions, and monitoring that allows discrimination among competing hypotheses or models by describing the system's status and trend (Nichols and Williams, 2006).

## 5. Additional pragmatic considerations in an adaptive-monitoring process

Of over-riding importance for long-term and broad-scale monitoring is *repeatability*, which can be achieved by adopting published methods or by creating protocols and standard operating procedures (Oakley et al., 2003). *Observer bias*, which has been documented to account for up to 50% of the variability in an indicator, introduces noise into the monitoring 'signal' and thus reduces the ability of the monitoring to detect trends that actually exist (Burnham et al., 1987; Beever et al., 2005; Udevitz et al., 2005). One approach to minimize observer bias is by using *pilot testing* of sampling designs and methods, which allows assessment of which methods will be logistically and fiscally feasible, yet still meet program objectives (e.g., see Thompson et al., submitted for publication; Reynolds et al., submitted for publication). Pilot testing has been used extensively by NPS for protocol development across

Alaska; given the number and magnitude of logistical constraints, pilot testing will likely remain equally or more prominent in high-latitude protected areas than for lower-latitude programs. Although it may not figure prominently into documents communicated to public decision-makers at the highest levels, *uncertainty* should be explicitly characterized and quantified, to indicate the confidence in the results (Noss, 1990).

As with all good scientific endeavors, robust monitoring programs will *consider hypotheses alternative to the preferred* 'pet' hypotheses (Noss, 1990). Because the distributions of biotic and abiotic resources rarely correspond with administrative boundaries, monitoring of resources that cross boundaries will be best informed when *integrating the relevant portions of the surrounding matrix* landscape (e.g., the remainder of a watershed). A priori *power analyses or simulations* can be used to determine what level of change that a certain sample size can detect over time with a given level of confidence, thus indicating that some monitoring programs should perhaps never be started, if sample size will remain meager (Steidl et al., 1997; Di Stefano, 2001; Reynolds et al., submitted for publication). Given all the benefits of broad-scale monitoring mentioned above, and given the non-trivial savings achieved by adopting existing protocols, *coordination with existing monitoring efforts* can not only leverage an organization's fiscal investment in monitoring, but also provide more information useful for interpreting the sampling (e.g., comparison with indicator values from surrounding areas). An excellent example of cross-agency collaboration is the LTEMP program from Kenai NWR allying itself with the FIA national-level program of forest monitoring (Morton et al., 2009; Table 2). Although the refuge increased sampling density by supplementing existing FIA points (in order to provide statistically powerful results at the refuge scale), the refuge was able to capitalize on existing FIA protocols and database structure.

Ecosystems are defined not solely by their composition (at various levels of biological organization), but also in terms of their structure and function (Franklin et al., 1981; Noss, 1990; Niemi and McDonald, 2004). Accordingly, monitoring programs should include indicators from each of these aspects of ecosystems.

Beever (2006) outlined five theoretical and five practical challenges to monitoring. The former included: (a) ecologists' incomplete understanding of ecosystems; (b) the difficulty in separating noise from signal, and (c) the lack of information for setting a target range for an indicator. The last is especially important for high-latitude areas, given the frequent lack of data from little-studied ecological communities, and the fact that climate change will mean that targets will usually shift through time. The latter included: (a) the limited time, personnel, and money available; (b) effects of changes in leadership or data collectors; and (c) uncertain and dynamic funding. Beever (2006) suggested a suite of design or analytical approaches that can address each challenge, or at least ameliorate their effects; these included replication, adaptive monitoring, use of confidence intervals, indicator species analysis, prioritization processes, and linkages with existing programs, among others.

## 6. Conclusions

Creation of a multi-scale, multi-disciplinary monitoring program is an exacting and arduous process, and although efficiencies can be achieved by not 're-inventing the wheel', many broad-scale programs have required over a decade to develop from creation to full functionality (S. Fancy, A.R. Olsen, D. McLennan, *personal communication*; Olsen et al., 1999; Busch and Trexler, 2003). Such programs in northern latitudes can benefit from critical review and input from community ecologists, geologists, climatologists, wildlife and conservation biologists, landscape ecologists, hydrologists, sociologists, economists, and decision-makers. Participants in the development of monitoring programs should be aware of the limitations of monitoring. Specifically, by itself, monitoring cannot: (a) decide how much change is acceptable; (b) decide threshold values in indicators that trigger management response; (c) unequivocally determine the cause of any observed change; or (d) inform scientists about the status of unmonitored ecosystem components, by inference from monitored components (Landres, 1992) (for additional limitations, see Beever, 2006). In spite of all the challenges and limitations, an honest appraisal of the current possibility of broad-scale monitoring in high northern latitudes may conclude: (a) now is an opportune time to fully engage in such effort, given the wealth of new analytical tools and sampling technologies available; (b) the importance of having information as soon as possible on indicators to provide benchmarks against which to compare future values cannot be underestimated, given the anticipated changes; and (c) although a far-reaching monitoring program seems dauntingly expensive, the alternative may ultimately be more costly, in terms of lost understanding and cost of incompletely informed decisions, especially given the specter of contemporary climate change. Thoughtfully designed broad-scale monitoring can maximize learning about the status and trend of natural resources in far-northern-latitude protected areas, as well as understand the consequences of various management actions.

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## References

Arctic Climate Impact Assessment (ACIA), 2005. Impacts of a Warming Arctic: Arctic Climate Impacts Assessment. Cambridge University Press, Cambridge, UK, 1042 pp.

Barber, V.A., Juday, G.P., D'Arrigo, R., Berg, E., Buckley, B., Huntington, H., Jorgensen, T., McGuire, A.D., Osterkamp, T., Riordan, B., Whiting, A., Wiles, G., Wilmking, M., 2009. A synthesis of recent climate warming effects on terrestrial ecosystems in Alaska. In: Wagner, F. (Ed.), Future Climate Change: Implications for Western Environments. University of Utah Press, Salt Lake City, Utah, pp. 110–139.

Beever, E.A., 2006. Monitoring biological diversity: strategies, tools, limitations, and challenges. Northwestern Naturalist 87, 66–79.

Beever, E.A., Pyke, D.A., Chambers, J.C., Landau, F., Smith, S.D., 2005. Monitoring temporal change in riparian vegetation of Great Basin National Park. Western North American Naturalist 65, 382–402.

Booms, T.L., Huettmann, F., Schempf, P.F., 2010. Gyrfalcon nest distribution in Alaska based on a predictive GIS model. Polar Biology 33, 347–358.

Boutin, S., Krebs, C.H., Nams, V.O., Sinclair, A.R.E., Boonstra, R., O'Donoghue, M., Doyle, C., 2001. Experimental design and practical problems of implementation. In: Krebs, C.J., Boutin, S., Boonstra, R. (Eds.), Ecosystem Dynamics of the Boreal Forest: The Kluane Project. Oxford University Press, New York, pp. 49–66.

Burnham, K.P., Anderson, D.R., White, G.C., Brownie C., Pollock., K.H. 1987. Design and analysis of fish survival experiments based on release-recapture data. American Fisheries Society Monograph, vol. 5. American Fisheries Society, Bethesda, Maryland, pp. 1–437.

Busch, D.E., Trexler, J.C. (Eds.), 2003. Monitoring Ecosystems: Interdisciplinary Approaches for Evaluating Ecoregional Initiatives. Island Press, Covelo, California, p. 447.

Calef, M.P., McGuire, A.D., Epstein, H.E., Rupp, T.S., Shugart, H.H., 2005. Analysis of vegetation distribution in interior Alaska and sensitivity to climate change using a logistic regression approach. Journal of Biogeography 32, 863–878.

Carpenter, S.R., Brock, W.A., 2006. Rising variance. A leading indicator of ecological transition. Ecology Letters 9, 311–318.

Chapin, F.S., Sturm, M., Serreze, M.C., McFadden, J.P., Key, J.R., Lloyd, A.H., McGuire, A.D., Rupp, T.S., Lynch, A.H., Schimel, J.P., Beringer, J., Chapman, W.L., Epstein, H.E., Euskirchen, E.S., Hinzman, L.D., Jia, G., Ping, C.L., Tape, K.D., Thompson, C.D.C., Walker, D.A., Welker, J.M., 2005. Role of land-surface changes in Arctic summer warming. Science 310, 657–660.

Chapin III, F.S., Berman, M., Callaghan, T.V., Convey, P., Crepin, A.-S., Danell, K., Ducklow, H., Forbes, B., Kofinas, G., McGuire, A.D., Nuttall, M., Virginia, R., Young, O.R., Zimov, S., 2006. Polar systems. In: Fitzharris, B., Shrestha, K. (Eds.), Millennium Ecosystem Assessment: Current State and Trends. Island Press, Covelo, CA, pp. 719–743.

Clark, J.S., Carpenter, S.R., Barber, M., Collins, S., Dobson, A., Foley, J.A., Lodge, D.M., Pascual, M., Pascual, M., Pielke Jr., R., Pizer, W., Pringle, C., Reid, W.V., Rose, K.A., Sala, O., Schlesinger, W.H., Wall, D.H., Wear, D., 2001. Ecological forecasts: an emerging imperative. Science 293, 657–660.

Cochran, W.G., 1977. Sampling Techniques, third ed. John Wiley and Sons, New York.

Daily, G.C., Alexander, S., Ehrlich, P.R., Goulder, L., Lubchenco, J., Matson, P.A., Mooney, H.A., Postel, S., Schneider, S.H., Tilman, D., Woodwell, G.M., 1997. Ecosystem services: benefits supplied to human societies by natural ecosystems. Issues in Ecology 2, 1–18.

Di Stefano, J., 2001. Power analysis and sustainable forest management. Forest Ecology and Management 154, 141–153.

Dunne, J.A., Saleska, S.R., Fischer, M.L., Harte, J., 2004. Integrating experimental and gradient methods in ecological climate change research. Ecology 85, 904–916.

Fancy, S.G., Gross, J.E., Carter, S.L., 2009. Monitoring the condition of natural resources in US national parks. Environmental Monitoring and Assessment 151, 161–174.

Franklin, J.F., Cromack, K., Denison, W., McKee, A., Maser, C., Swanson, F., Juday, G., 1981. Ecological characteristics of old-growth Douglas-fir forests. USDA Forest Service, Pacific Northwest Research Station, Portland, OR. General Technical Report GTR-PNW-118, pp. 1–48.

Gallant, A.L., Brown, D.D., Hoffer, R.M., 2005. Automated mapping of Hammond's landforms. IEEE Geoscience and Remote Sensing Letters 2, 384–388.

Hauser, C.E., Pople, A.R., Possingham, H.P., 2006. Should managed populations be monitored every year? Ecological Applications 16, 807–819.

Havlick, D., 2002. No Place Distant: Roads and Motorized Recreation on America's Public Lands. Island Press, Covelo, CA.

Hayek, L.C., Buzas, M.A., 1997. Surveying Natural Populations. Columbia University Press, New York.

Holling, C.S., 1978. Adaptive Environmental Assessment and Management. John Wiley, London, UK.

Huggett, R.J., 1993. Modeling the Human Impact on Nature: Systems Analysis of Environmental Problems. Oxford University Press, New York.

Intergovernmental Panel on Climate Change (IPCC), 2007. Climate Change 2007: The Physical Science Basis. Cambridge University Press, New York.

Johnson, L.C., Shaver, G.R., Cades, D.H., Rastetter, E., Nadelhoffer, K., Giblin, A., Laundre, J., Stanley, A., 2000. Plant carbon-nutrient interactions control $CO_2$ exchange in Alaskan wet sedge tundra ecosystems. Ecology 81, 453–469.

Johnson, S.E., Mudrak, E.L., Beever, E.A., Sanders, S., Waller, D.M., 2008. Comparing power among three sampling methods for monitoring forest vegetation. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 38, 143–156.

Jorgenson, M.T., Racine, C., Walters, J., Osterkamp, T., 2001. Permafrost degradation and ecological changes associated with a warming climate in central Alaska. Climatic Change 48, 551–579.

Landres, P.B., 1992. Ecological indicators: panacea or liability? In: McKenzie, D.H., Hyatt, D.E., McDonald, V.J. (Eds.), Ecological Indicators, vol. 2. Elsevier Applied Scientific Publishers, Amsterdam, pp. 1295–1318.

Lexer, M.J., Seidl, R., 2009. Addressing biodiversity in a stakeholder-driven climate change vulnerability assessment of forest management. Forest Ecology and Management 258, S158–S167.

Maddox, G.D., Poiana, K.E., Unnasch, R.E., 1999. Evaluating management success: using ecological models to ask the right monitoring questions. In: Johnson, N. (Ed.), The Ecological Stewardship Project: A Common Reference for Ecosystem Management (vol. 3). Elsevier Science, Oxford.

Magness, D.R., Huettmann, F., Morton, J.M., 2008. Using random forests to provide predicted species distribution maps as a metric for ecological inventory & monitoring programs. Studies in Computational Intelligence 122, 209–229.

Manley, P.N., Zielinski, W.J., Stuart, C.M., Keane, J.J., Lind, A.J., Brown, C., Plymale, B.L., Napper, C.O., 2000. Monitoring ecosystems in the Sierra Nevada: the conceptual model foundation. Environmental Monitoring and Assessment 64, 139–152.

Manly, B.F.J., 2001. Statistics for Environmental Science and Management. Chapman and Hall/CRC Press, New York.

Morton, J.M., Bowser, M., Berg, E., Magness, D., Eskelin, T., 2009. Long term ecological monitoring program on the Kenai National Wildlife Refuge, Alaska: an FIA adjunct inventory. In: McWilliams, W., Moisen, G., Czaplewski, R. (compilers), Forest Inventory and Analysis (FIA) Symposium 2008 Proceedings, October 21–23, 2008. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, RMRS-P-56CD, pp. 1–17.

Mulder B.S., Palmer, C.J., 1999. Introduction to effectiveness monitoring. In: Mulder, B.S., Noon, B.R., Spies, T.A., Raphael, M.G., Palmer, C.J., Olsen, A.R., Reeves, G.H., Welsh, H.H., (Technical cords.), The Strategy and Design of the Effectiveness Monitoring Program for the Northwest Forest Plan. USDA Forest Service, Pacific Northwest Research Station, Portland, OR. General Technical Report PNW-GTR-437, pp. 1–20.

National Research Council, 1995. Review of EPA's Environmental Monitoring and Assessment Program: Overall Evaluation. National Research Council, National Academy Press, Washington, DC.

Nichols, J.D., Williams, B.K., 2006. Monitoring for conservation. Trends in Ecology & Evolution 21, 668–673.

Niemi, G.J., McDonald, M.E., 2004. Application of ecological indicators. Annual Review of Ecology Evolution and Systematics 35, 89–111.

Noon, B.R, Spies, T.A., Raphael, M.G., 1999., Conceptual basis for designing an effectiveness monitoring program. In: Mulder, B.S., Noon, B.R., Spies, T.A., Raphael, M.G., Palmer, C.J., Olsen, A.R., Reeves, G.H., Welsh, H.H., (Technical cords.), The Strategy and Design of the Effectiveness Monitoring Program for the Northwest Forest Plan. USDA Forest Service, Pacific Northwest Research Station, Portland, OR. General Technical Report PNW-GTR-437, pp. 49–68.

Noon, B.R., 2003. Conceptual issues in monitoring ecological resources. In: Busch, D.E., Trexler, J.C. (Eds.), Monitoring Ecosystems: Interdisciplinary Approaches for Evaluating Ecoregional Initiatives. Island Press, Covelo, CA, pp. 27–72.

Noss, R.F., 1990. Indicators for monitoring biodiversity: a hierarchical approach. Conservation Biology 4, 355–364.

Oakley, K.L., Thomas, L.P., Fancy, S.G., 2003. Guidelines for long-term monitoring protocols. Wildlife Society Bulletin 31, 1000–1003.

O'Brien, B.J., Springsteen, A.L., Rupp, T.S., Loya, W.M., submitted for publication. Future climate change impacts on growing season water availability in Alaska. Climatic Change.

Olsen, A.R., Sedransk, R., Edwards, D., Gotway, C.A., Liggett, W., Rathbun, S., Reckhow, K.H., Young, L.J., 1999. Statistical issues for monitoring ecological and natural resources in the United States. Environmental Monitoring and Assessment 54, 1–45.

Parks Canada Agency (PCA), 2008. The Parks Canada Charter. Parks Canada, Ottawa. <http://www.pc.gc.ca>.

Reynolds, J.H., Thompson, W.L, Russell, B., submitted for publication. Planning for success: identifying effective and efficient monitoring designs. Biological Conservation.

Ringold, P.L., Alegria, J., Czaplewski, R.L., Mulder, B.S., Tolle, T., Burnett, K., 1996. Adaptive monitoring design for ecosystem management. Ecological Applications 6, 745–747.

Riordan, B., Verbyla, D., McGuire, A.D., 2006. Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. Journal of Geophysical Research-Biogeosciences 111, 11.

Sokal, R.R., Rohlf, F.J., 1995. Biometry: The Principles and Practice of Statistics in Biological Research, third ed. W.H. Freeman and Co., New York.

Steidl, R.J., Hayes, J.P., Schauber, E., 1997. Statistical power analysis in wildlife research. Journal of Wildlife Management 61, 270–279.

Stevens Jr., D.L., Larsen, D.P., Olsen, A.R., 2007. The role of sample surveys: why should practitioners consider using a statistical sampling design? In: Johnson, D.H., Shrier, B.M., O'Neal, J.S., Knutzen, J.A., Augerot, X., O'Neil, T.A., Pearsons, T.N. (Eds.), Salmonid Field Protocols Handbook: Techniques for Assessing Status and Trends in Salmon and Trout Populations. American Fisheries Society, Bethesda, Maryland, pp. 11–23.

Suffling, R., Scott, D., 2002. Assessment of climate change effects on Canada's National park system. Environmental Monitoring and Assessment 74, 117–139.

Thompson, W.L., Miller, A.E., Mortenson, D.C., Woodward, A.W., submitted for publication. Developing effective sampling designs for monitoring natural resources in Alaskan national parks: an example using simulations and vegetation data. Biological Conservation.

Trombulak, S.C., Frissell, C.A., 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology 14, 18–30.

Udevitz, M.S., Jay, C.V., Cody, M.B., 2005. Observer variability in pinniped counts: ground-based enumeration of walruses at haul-out sites. Marine Mammal Science 21, 108–120.

Underwood, A.J., 1994. On beyond BACI: sampling designs that might reliably detect environmental disturbances. Ecological Applications 4, 3–15.

US Fish & Wildlife Service (USFWS), 1980. Alaska National Interest Lands Conservation Act of 1980. USFWS, Washington, DC 16 U.S.C. 3101 et esq.

US Fish & Wildlife Service (USFWS), 2004. Baseline Inventory Data Recommendations for National Wildlife Refuges. Fulfilling the Promise Baseline Inventory Team, WH8.1. 33 pp.

US Fish & Wildlife Service (USFWS), 2010. Strategic Plan for Inventories and Monitoring on National Wildlife Refuges: Adapting to Environmental Change. Unpublished document.

Yoccoz, N.G., Nichols, J.D., Boulinier, T., 2001. Monitoring of biological diversity in space and time. Trends in Ecology & Evolution 16, 446–453.