EXPANDING GIS ANALYSES TO MONITOR AND ASSESS NORTH AMERICAN MOOSE DISTRIBUTION AND DENSITY

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ABSTRACT: Development of long-term geographic information system (GIS) databases of species densities and distributions, combined with biological, ecological, and management-related metrics, can help guide research and management strategies. Here we summarize 3 decades of North American moose (*Alces alces)* population and harvest densities collected at the management unit scale for the years 1980, 1990, 2000, and 2010. A summary analysis of these data indicates that moose have both expanded and contracted along their southern range boundary in recent decades - including the Prairie Provinces and states, and a portion of the northeastern United States. A narrow band of relatively stable and high-density moose populations extends from central Alaska across the Prairie Provinces and east to the Maritime Provinces and upper northeastern states. Distributions in 2010 indicate that moose now occupy an area > 9,492,000 km^2 in North America. We also identified that a core range of boreal habitat, only 30% of the occupied range across the continent, supports 89% of the estimated 1 million moose in North America. Time-series analyses can offer a simple and cost-effective approach to monitor the status of moose populations in North America, and might be particularly insightful given the current and predicted future influences of climate change on moose. Other analyses might address population dynamics, habitat, environmental constraints, and harvest management, among other issues. We encourage jurisdictions to cooperate strategically in implementing and coordinating GIS analyses to monitor, assess, and manage the North American moose population.

ALCES VOL. 54:45–54 (2018)

Key words: *Alces alces*, moose, North America, distribution, population density, harvest density, GIS, long-term datasets, Canada, United States of America.

The value of "big data" and long-term datasets for mammalian research has received a great deal of attention in recent years (Hampton et al. 2013, Schradin and Hayes 2017). Long-term studies, particularly those involving marked ungulates, often require access to unique study sites and agency commitment to financial support (Festa-Bianchet et al. 2017). Long-term research of moose (*Alces alces*) is not common, with the notable exceptions of captive animal research at Alaska's Kenai Moose Research Center and on Isle Royale (Peterson et al. 2014). Arguably, time-series analyses of combined data collected at the jurisdictional level has much potential to help address biological, management, and conservation questions that are difficult to tease apart in short-term, local research (Christie et al. 2015, Ciuti et al. 2015).

As species management questions reach landscape levels, research projects will necessarily rely on collaborative sharing of datasets. Geographic information systems (GIS) offer a wide range of research opportunities for analyzing and displaying information about species on landscape scales. Range layers have been developed using GIS for several species of big game in North America including mule deer (*Odocoileus hemionus*; Luce et al. 2005), white-tailed deer (*Odocoileus virginianus*; Adams et al. 2009), and pronghorn antelope (*Antilocapra americanus*; Jensen et al. 2004). The objective of this project was to assimilate compatible data for moose into GIS layers on a continental scale. We collected 4 decades of moose distribution and density data from survey and harvest records at the management unit scale, and subsequently described these data at the continental scale. We compiled these data from provincial, state, and federal agencies responsible for managing lands with free-ranging moose populations. There were disparities in methodology, types of data, and quality of information available, yet broad patterns emerged when summarizing these long-term, continental-scale data.

METHODS

We contacted wildlife professionals in each state and province in North America (Table 1) with free-ranging populations of moose to obtain population estimates and harvest rates, by management unit, for the decadal years of 1980, 1990, 2000, and 2010. Either a representative wildlife professional from the state or province entered their data directly into an electronic spreadsheet, or we entered data from available sources; all data were double-checked for accuracy. We used data from the closest available year when population estimates and harvest data were not available for an exact decadal year. The size and scale of management units, as well as methods for determining population estimates varied by jurisdiction (e.g., various survey methods, statistical software packages, and license sales). Where GIS data were unavailable, management unit boundaries were digitized (ArcGIS ArcMap 10.4.1, ESRI, Inc., Redland, California) from available paper maps. When jurisdictions did not have hunting seasons and management units, we used county boundaries to delineate surrogate spatial units. Moose population and harvest densities (per km^2) for each management unit were subsequently calculated. Density estimates within each management unit were made under the assumption that animals were evenly and randomly distributed. Attribute information associated with each data record included: source of information, unit name or identification number, unit area (km^2), and "reliability" of the data. Reliability of population estimates ranged from "best guess" to statistically valid, systematic surveys. Estimates of hunter harvest varied with respect to whether or not they included or excluded categories of subsistence hunting. We ranked management units by density, and for display purposes, categorized them into 5 ordinal groups of equal unit counts. We estimated 2 characterizations of the primary range of moose in North America for each decade by selecting only units with values at or above the 50th percentile for 1) moose density and 2) harvest density. We further divided this subset of the highest 50th percentile of units into 5 groups of equal unit counts to display variation in density explicitly within the primary range alone.

RESULTS

Data from some jurisdictions were digitized directly by agency personnel (Alberta, British Columbia, Idaho, Maine, Minnesota, Montana, New Brunswick, North Dakota, New Hampshire, New York, Ontario, Quebec, Saskatchewan, Vermont, Wyoming, Yukon Territory), while for the remainder of jurisdictions we entered data from available

Table 1. A summary of information sources obtained for 1980-2010 GIS mapping of North American moose range distribution and densities.

State or Province	Information Source
Alaska, USA	Harper (2010)
Alberta, CA	Jim Castle, Cassandra Hardie, and Michelle Founier, AB Environment and Parks
British Columbia, CA	Gerry Kuzyk and Diana DeMarchi, Min. of Environment
Colorado, USA	CO Parks and Wildlife Website
Connecticut, USA	CT Dept. of Energy & Environ. Protection website, and Wattles and DeStefano (2011)
Idaho, USA	Steve Nadeau, ID Dept. of Fish and Game, and Timmermann (2003)
Labrador and Newfoundland, CA	Timmermann (2003)
Maine, USA	Lee Kantar, ME Agriculture, Conservation and Forestry
Manitoba, CA	Hank Hristienko, Manitoba Sustainable Development
Massachusetts, USA	Wattles and DeStefano (2011)
Michigan, USA	Isle Royale NP Website, Beyer et al. (2011)
Minnesota, USA	Michelle Carstensen and Tyler Obermoller, MN Dept. of Natural Resources
Montana, USA	Nick DeCesare, MT Fish, Wildlife and Parks
New Brunswick, CA	Dwayne Sabine, Natural Resources, NB
New Hampshire, USA	Kristine Rines, NH Fish and Game Dept.
New York, USA	Ed Reed, Dept. of Environmental Conservation
North Dakota, USA	William Jensen and Jason Smith, ND Game and Fish Dept.
Northwest Territories, CA	Timmermann (2003)
Nova Scotia, CA	NS Min. of Natural Resources Website
Nunavut, CA	Mathieu Dumond, NU Dept. of Environment
Ontario, CA	Art Rodgers and Ed Iwachewski, ON Min. of Natural Resources and Forestry
Oregon, USA	OR Dept. of Fish and Wildlife Website
Quebec, CA	Sebastien Lefort, Min. des Forets, de la Faune et des Parcs
Saskatchewan, CA	Robert Tether, SK Min. of Environment
Utah, USA	UT Dept. of Natural Resources Website
Vermont, USA	Cedric Alexander, VT Fish and Wildlife
Washington, USA	Richard Harris, WA Dept. of Fish and Wildlife
Wisconsin, USA	Jane Wiedenhoeft, WI Dept. of Natural Resources
Wyoming, USA	Grant Frost, WY Game and Fish Commission Yellowstone National Park Website
Yukon, CA	Susan Westover, Environment YK

reports and publications (Alaska, Colorado, Connecticut, Massachusetts, Manitoba, Michigan, Newfoundland, Northwest Territories, Nova Scotia, Nunavut, Oregon, Utah, Washington, Wisconsin). Individual moose management units (n = 938), where and when available, were mapped for 4 decadal years (1980, 1990, 2000, 2010) in all 30 states and provinces with free-ranging moose populations. We provide written summaries of our results by decade, but provide maps only for the 2010 data.

1980: We compiled estimates of the population density from 173 individual management units within 10 jurisdictions, and estimates of the harvest density from 98 units within 8 jurisdictions (Table 2). The estimated population density

Table 2. Summary of states and provinces that provided information on moose population and harvest density estimates, by management unit, for each decade (N/A = Not Applicable for states without hunting seasons).

STATES/PROVINCES	1980	1980	1990	1990	2000	2000	2010	2010
	Pop.	Harv.	Pop.	Harv.	Pop.	Harv.	Pop.	Harv.
Alaska, USA					X	X	X	X
Alberta, CA			X		X	X	X	X
British Columbia, CA	X	X	X	X	X	X	X	X
Colorado, USA							X	X
Connecticut, USA						X	N/A	
Idaho, USA				X[1]	X[2]	X[1]	X[2]	X[1]
Labrador & Newfoundland, CA					X[2]	X[2]	X[2]	X[2]
Maine, USA							X	X
Manitoba, CA			X		X		X	
Massachusetts, USA							X	N/A
Michigan, USA	X		X		X		X	N/A
Minnesota, USA	X	X	X	X	X	X	X	X
Montana, USA							X	X
New Brunswick, CA					X	X	X	X
New Hampshire, USA			X	X	X	X	X	X
New York, USA	X		X		X		X	N/A
North Dakota, USA	X	X	X	X	X	X	X	X
Northwest Territories, CA					X[2]	X[2]	X[2]	X[2]
Nova Scotia, CA							X	X
Nunavut, CA							X	X
Ontario, CA	X	X	X	X	X	X	X	X
Oregon, USA			X		X		X	N/A
Quebec, CA			X	X	X	X	X	X
Saskatchewan, CA	X	X	X	X	X	X	X	X
Utah, USA	X	X						
Vermont, USA	X	X	X	X	X	X	X	X
Washington, USA							X	N/A
Wisconsin, USA					X		X	N/A
Wyoming, USA	X	X	X	X	X	X	X	X
Yukon, CA	X	X	X	X	X	X	X	X
Total	10	8	15	11	21	16	30	22

[1] Source: Idaho Department of Fish and Game
[2] Source: Timmermann (2003): State or Province-wide estimates

for the primary range was between 0.12 and 1.79 moose/km^2. The estimated harvest density in the primary range was between 0.005 and 0.12 moose/km^2. The units with highest population density were Isle Royale and Unit 2 in Minnesota; the Jackson Herd Unit (M0103) in Wyoming had the highest harvest density.

1990: We compiled estimates of population density from 326 individual management units within 15 jurisdictions, and estimates of harvest density from 256 units within 11 jurisdictions (Table 2). The estimated population density in the primary range was between 0.15 and 6.20 moose/km^2. The estimated harvest density in the primary range was between 0.008 and 0.19 moose/km^2. The units with the highest population density were Isle Royale and Newfoundland; Newfoundland had the highest harvest density.

2000: We compiled estimates of population density from 422 individual moose management units within 21 jurisdictions, and estimates of harvest density from 403 units within 16 jurisdictions (Table 2). The estimated population density in the primary range was between 0.17 and 4.33 moose/km^2. The estimated harvest density in the primary range was between 0.009 and 0.23 moose/km^2. The units with the highest reported density were Isle Royale and Unit 14A (Matanuska Valley) in Alaska; the Cooking Lakes District in Alberta had the highest harvest density.

2010: We compiled estimates of population density from 649 individual moose management units within all 30 jurisdictions queried (Fig. 1a, Table 2), and estimates of harvest density from 569 units within 22 jurisdictions (Fig. 2a, Table 2). The estimated population density in the primary range was between 0.11 and 4.34 moose/km^2 (Fig. 1b). The estimated harvest density in the primary range was between 0.01 and 0.82 moose/km^2 (Fig. 2b). The units with the highest reported density were Unit 1 in Nova Scotia and Unit 4 in Maine; the Connecticut Lakes Region in New Hampshire had the highest harvest density.

DISCUSSION

Population and harvest estimates from 1980 were limited, whereas information collected on distribution and abundance between 1990 and 2010 revealed distinct patterns and trends. Moose density along the northern range boundary has been low, but relatively stable, although known harvest rates were well below 0.01 moose/km^2. More recently, increasing density at these latitudes and in shrub habitat in the high Arctic are linked to climate change (Tape et al. 2016). Moose distribution across the southern range has also expanded in recent decades (Fig. 1a, 2a), particularly in the Prairie Provinces of Alberta and Saskatchewan. Range expansion has provided for new moose hunting units and increased harvest rates on the prairies of Manitoba, North Dakota, and Saskatchewan. That said, harvest rates along much of the southern range boundary are also well below 0.01 moose per km^2, with a few pockets of higher rates in Idaho, Wyoming, Utah, Colorado, New Hampshire, and Vermont. It is recognized that harvest rates are often allocated conservatively in jurisdictions where moose hunting is relatively new. Additionally, reported harvest rates may or may not include First Nations/tribal subsistence hunting.

From 1980 through 2010, the highest moose densities and harvest rates remained within a band of primary range 300–750 km wide that stretched from central Alaska across the Prairie Provinces, through southern Ontario and Quebec, to northern Maine, New Brunswick, and Newfoundland; a narrower band extended down the Rocky Mountain range (Fig. 1a, 2a). This band of high moose density is strikingly similar to the distribution of moose when at their lowest numbers in the late 1800s (Canada 1888, as cited in Peterson 1955). In 2010, North American moose range encompassed a total area of >9,492,400 km^2; however, the relatively narrow band of primary range comprises just 30% of the total range. Based upon 2010 densities in units within the primary range, this narrow band of boreal habitat supports >890,700 moose, or ~89% of the North American population (Timmermann 2003, Timmermann and Rodgers 2017).

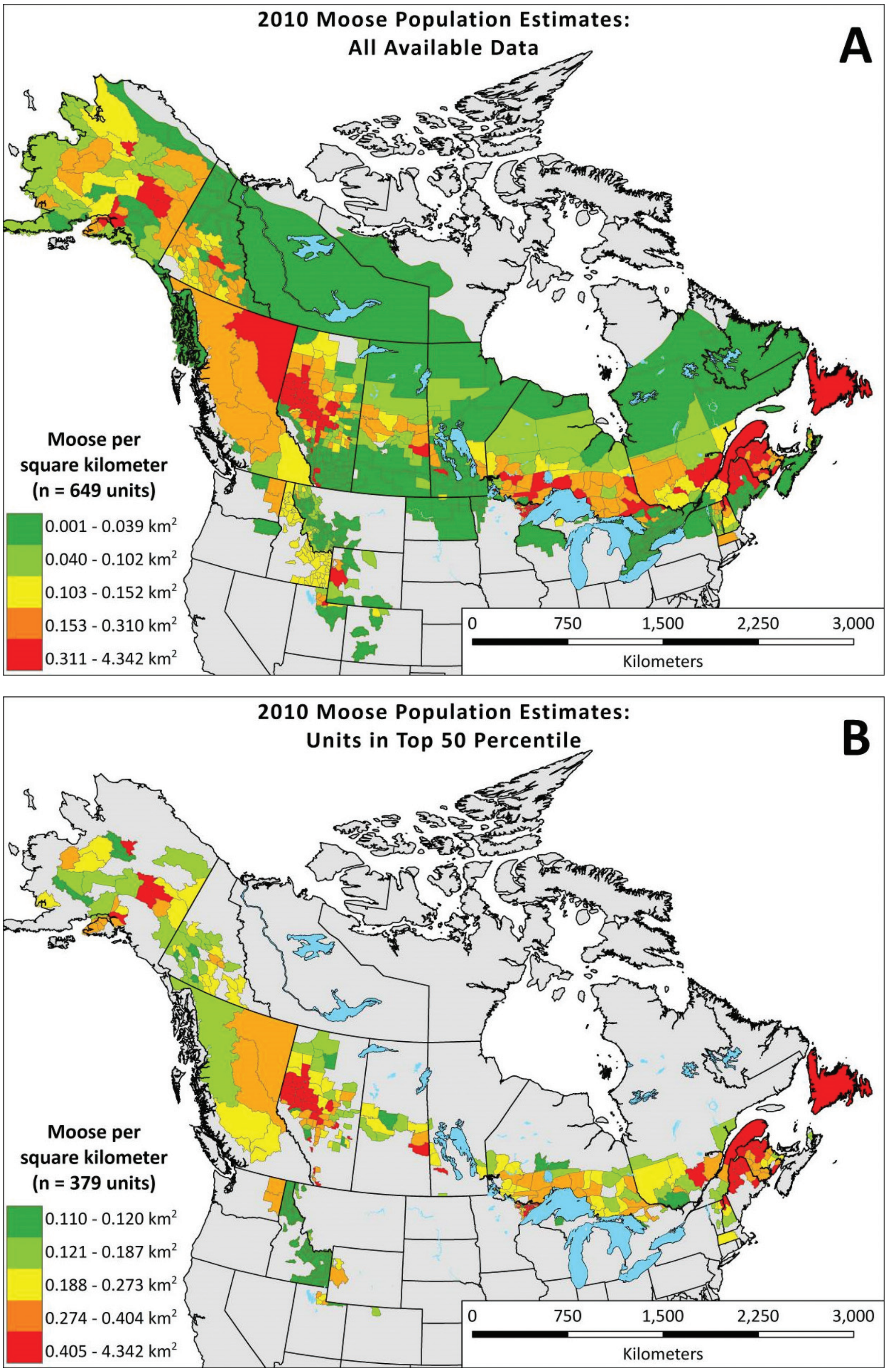

Fig. 1. Moose population density estimates, by management unit, for North America (ca. 2010). Panel A represents all available management unit data (n = 649). Panel B represents moose population density estimates, by management unit, for the top 50^{th} percentile (379 of 649 units) of the management units with the highest population densities.

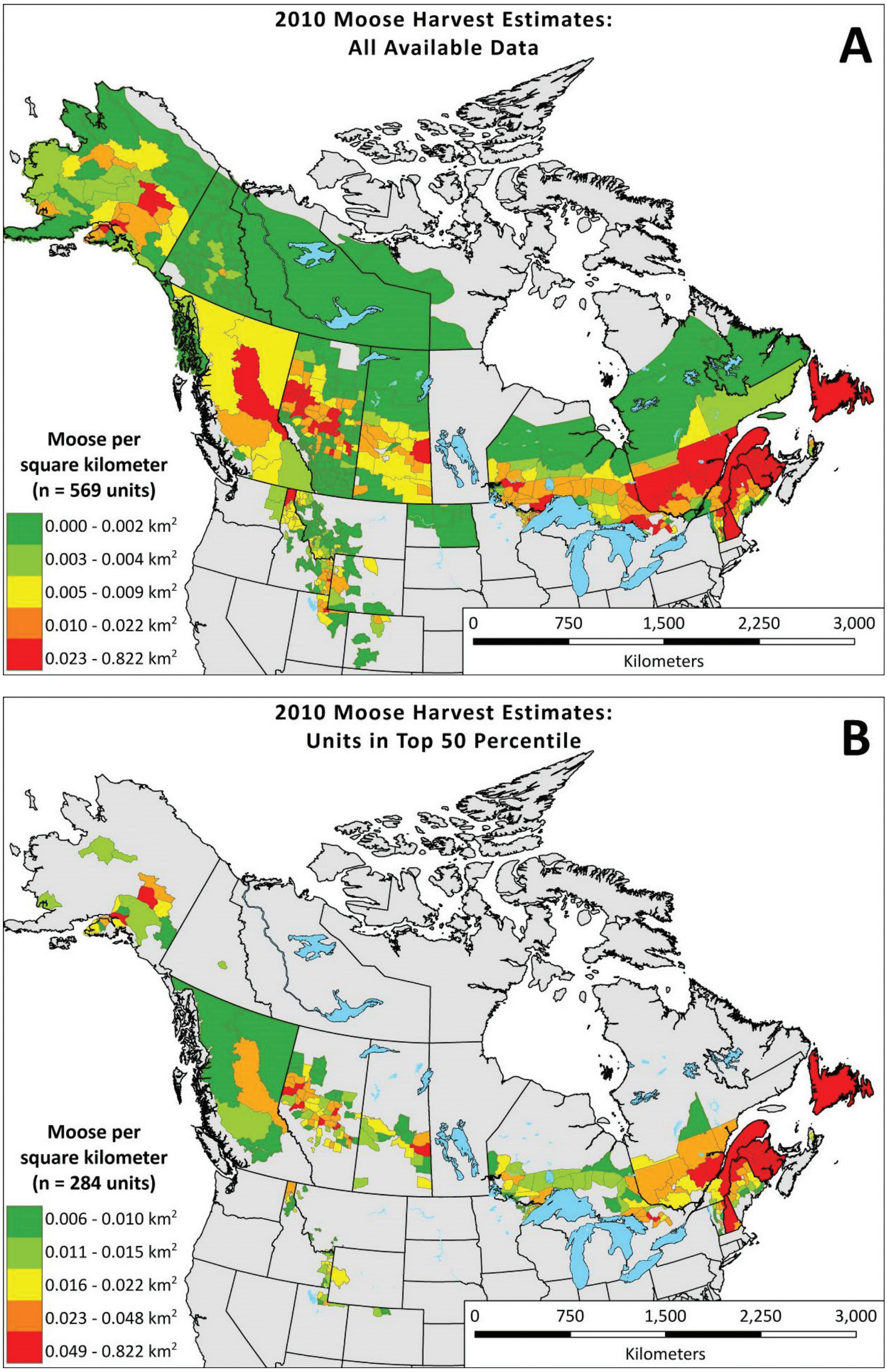

Fig. 2. Moose harvest density estimates, by management unit, for North America (ca. 2010). Panel A represents all available management unit data (n = 569). Panel B represents moose population density estimates, by management unit, for the top 50th percentile (284 of 569 units) of the management units with the highest harvest densities.

While there may be local exceptions, range-wide patterns of moose demography and regional population pulses most likely reflect the importance of underlying biological and ecological changes in community structure (e.g., predators, parasites, and disease), land use management strategies (e.g., fire suppression and logging practices), and environmental variation and climate change, not specific management and harvest strategies implemented by agencies.

The 2010 moose distribution and relative density maps (Fig. 1, 2) reiterate several key points raised by Karns (1998) and others, including: 1) the importance of boreal forest ecoregions, 2) the influences of natural barriers such as major rivers and mountains, 3) the location of small, isolated remnant and/or vulnerable populations (e.g., southern Rocky Mountains, Michigan, Nunavut), and 4) continued expansion of moose in Alaska, British Columbia, Washington, prairie states and southern provinces, Maritime provinces, and the northeastern United States.

We advocate for continued examination into climate change impacts, including influence of snow cover in spring and autumn on parasites such as winter ticks (*Dermacentor albipictus*; Lankester and Samuel 1998, Musante et al. 2010), and range expansion of white-tailed deer (*Odocoileus virginianus*) and parasites they host (e.g., *Parelaphostrongylosis tenuis* and *Fascioloides magna*; Lankester and Samuel 1998, Lankester 2018). Other demographic parameters that would enhance this broad-scale assessment are estimates of survival, pregnancy and twinning rates, and accurate estimates of subsistence harvest. Given continuous biological and ecological measurements by state and provincial agencies, such data should prove useful to identify environmental factors and other influences that affect moose on a range-wide basis including climate change, fire suppression, forest management, habitat fragmentation, and the impacts of harvest strategies.

Although long-term studies of marked individuals can effectively address a multitude of questions, they are usually constrained by cost, time, and logistics (Schradin and Hayes 2017). Conversely, our use of existing long-term population monitoring data demonstrate the potential for using a GIS approach to assess the continental moose population with minimal expense, time, or effort. We used a variety of methods, survey techniques, and software packages to derive continental moose population and harvest estimates. It is important to recognize that each estimate has its own inherent variability, strength, and weakness; as with any large dataset, interpretations and specific and general conclusions require a certain degree of caution. However, we believe the information presented here is the best currently available regarding the unit-by-unit continental density and distribution of moose.

The Western States and Provinces Mule Deer Mapping Project (Luce et al. 2005) can serve as a model for future work along similar lines for moose, such as identification of critical habitat within and across political jurisdictions. Additionally, these maps may be used to inform the general public and managers regarding: 1) realistic expectations of moose densities and harvest rates relative to their location within moose range, 2) estimates of potential density within jurisdictions that are usually not surveyed (e.g., national parks, First Nation Reserves) via comparison with surrounding management units, 3) identification of management units that may be impacted by unregulated harvest, and 4) identification of management units to optimize moose population densities and recreational opportunities through harvest strategies and land management techniques. By probing for patterns and using time-series analysis at the landscape scale, future research may better focus on those factors that principally influence moose populations.

ACKNOWLEDGMENTS

We thank the many biologists and GIS specialists that have assisted us in compiling this dataset. We also thank the reviewers for their editorial suggestions. This project was funded by Federal Aid to Wildlife Restoration administered through North Dakota Game and Fish Department (Project W-67-R-57). Any mention of trade, product, or firm names is for descriptive purposes only, and does not imply endorsement by the U.S. Government.

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