

THE IMPACT OF CLIMATE CHANGE ON MAMMAL DIVERSITY IN CANADA

JEREMY KERR* and LAURENCE PACKER

Department of Biology, York University, 4700 Keele St., North York, ON, M3J 1P3, Canada.

E-mail: jtkerr@YorkU.CA

(Received 9 July 1997)

Abstract. Current large-scale mammalian diversity patterns in Canada can be accurately explained using various measurements of heat energy. Unfortunately, climatic change is predicted to alter the fundamental climatic basis for contemporary diversity gradients, with the expected consequence that much of the Canadian biota will need to migrate in order to remain within climatically suitable regions. We make predictions regarding future mammal diversity patterns in Canada, and therefore provide a preliminary indication of where management intervention should be directed in order to conserve mammal diversity as climate changes. We also examine the current distributions of individual mammal species in Canada in order to determine which taxa cannot migrate farther north because of the Arctic Ocean barrier. Of the 25 species that fall into this category, we examine the predicted loss of habitat in one keystone species – *Dicrostonyx groenlandicus*, the collared lemming – and find that this taxon is likely to lose approximately 60% of its habitat with unpredictable but likely detrimental consequences for the arctic biota. We discuss the implications of our findings briefly.

Key words: biodiversity, climate change, latitudinal gradients, mammal species richness

1. Introduction

One of the great ironies of the twentieth century may be that we have only begun to appreciate biological diversity after having lost or doomed a substantial proportion of it to extinction (Raven, 1988; Wilson, 1988; Kerr and Currie, 1995). Climate change looms large on the horizon of anthropogenic impacts that are likely to cause massive future extinctions (Peters, 1987; Dobson *et al.*, 1989; Myers, 1992; Soulé, 1992; Quinn and Karr, 1993). Scientists now agree that humanity has committed itself to some climatic warming, regardless of the actions that the international community now takes. If the detrimental effects of climate change are to be reduced, it will be necessary to investigate how biodiversity is likely to respond to alteration of the climatic regime. Large-scale approaches, in particular, are likely to provide valuable insight into the potential responses of biological communities to perturbation due to climatic change (Pace, 1993).

Fortunately, ecologists have developed at least some of the tools necessary to make basic predictions regarding the biodiversity impacts of climate change. In particular, it is now clear that most of the variability in geographical patterns of vertebrate and tree species richness in Canada can be attributed to variation in energy availability (see Figure 1), as measured by potential evapotranspiration or

* Author to whom correspondence should be addressed.

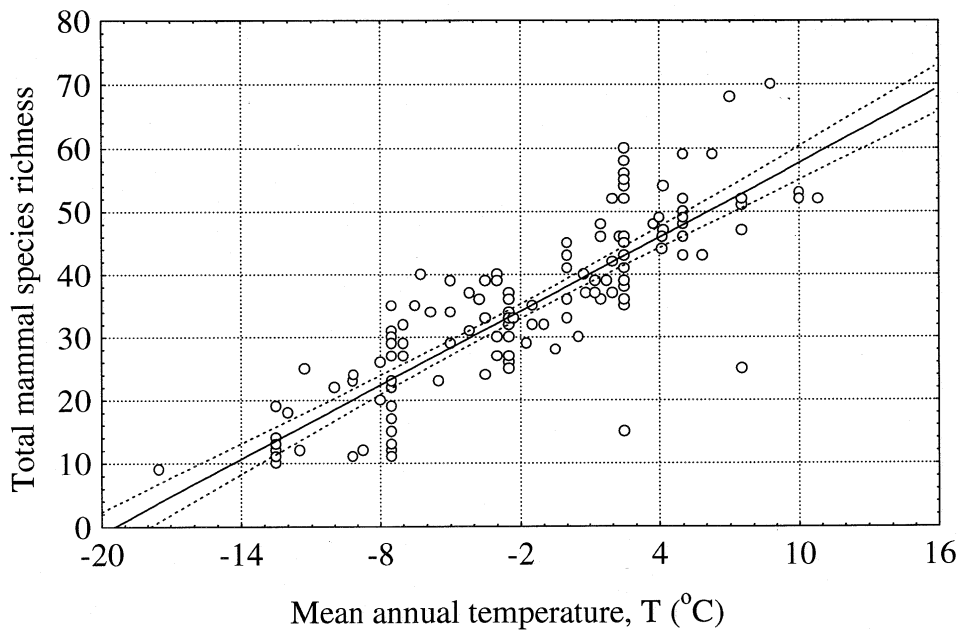


Figure 1. The relationship between contemporary mammal species richness patterns in Canada and average annual temperature.

annual mean temperature (Currie and Paquin, 1987; Adams and Woodward, 1989; Currie, 1991; Wright *et al.*, 1993; Kerr and Parker, 1997). Richness is defined here as the number of distinctive species found within a given region. At a regional scale, therefore, it is possible to accurately predict the number of vertebrate or tree species that are present given information on regional energy balance alone. No large-scale hypothesis has been proposed that provides as statistically powerful an explanation for known diversity patterns as the species-energy model. Very little work has been done on invertebrates at this scale, though preliminary results for subgroups of Lepidoptera (butterflies and moths) and Hymenoptera (ants, bees, wasps, and relatives; Kerr *et al.*, submitted) suggest that a similar energy-dependent relationship exists. How can the species-energy hypothesis be used to improve understanding of the impacts of climate change?

If species' distributions shift in response to climatic alteration, then, based on the species-energy hypothesis, it is possible to use forecasted changes in temperature patterns to predict the future distribution of biological diversity. There are many well-documented precedents for shifts in species ranges in response to gradual climatic change (Peters, 1992). For example, the distribution of the collared lemming (*Dicrostonyx* spp.) shifted more than 1600 km north following the glacial retreat at the end of the Wisconsinan period (Graham, 1992). A dung beetle species (*Aphodius hodereri*), however, was unable to shift its range quickly enough during

the post-Wisconsinan climatic warming, and is now extinct save for a remnant population in the high Tibetan plateau (Cox and Moore, 1985).

There are two purposes in this paper. First, using the species-energy relationship, we make projections regarding future regional mammal biodiversity patterns that will be observed based on a widely accepted climate change model and knowledge of the principal predictors of contemporary diversity patterns. While no model can reasonably predict the specific mammal community composition following climatic change in the next century, providing predictions of where diversity is likely to change the most will facilitate management efforts. The second purpose of this paper is to determine which mammal taxa are most likely to undergo substantial range contraction because their current distributions are limited in the north by the Arctic Ocean. A keystone species, *Dicrostonyx groenlandicus* (the collared lemming), is used to illustrate this phenomenon.

2. Methods

We gathered data on the ranges of all mammal species in Canada (based on Currie, 1991) and tallied species richness scores in 154 quadrats covering mainland Canada. Mean annual temperature values were then collected for each quadrat (also based on Currie 1991). The relationship between mammal species richness and average temperature is summarized in the following regression equation ($F = 422$, $R^2 = 0.736$, $p << 0.0001$; Figure 1):

$$\text{Mammal species richness} = 1.960 (\text{Mean annual temperature}) + 38.1 + \varepsilon,$$

where ε is the residual variance for each data point for which the regression equation does not account.

We then collected information on projected changes in mean annual temperature in Canada based on a well known general circulation model (GCM) developed at the Goddard Institute of Space Sciences (GISS; Russell *et al.*, 1996) for the International Panel on Climate Change. The GISS GCM has provided the basis for current international scientific consensus regarding future climatic change (Houghton *et al.*, 1995). This model geographically varied levels of climatic warming for Canada over a 75 yr time period based on 1% annual CO₂ increase. Using projected temperature increases per quadrat and the species richness-temperature equation (above), we calculated expected future increases in regional mammal species richness. We then constructed a contour map of Canada showing the geographical distribution of diversity changes (Figure 2).

We separated from the main database all taxa that are partially or extensively limited to the north by the Arctic Ocean. While most taxa are likely to undergo some range contraction as a consequence of the temperature increases along the southern portions of their ranges, taxa that are currently limited in the north as well are likely to be most severely affected in the long term (Table I). In order to provide

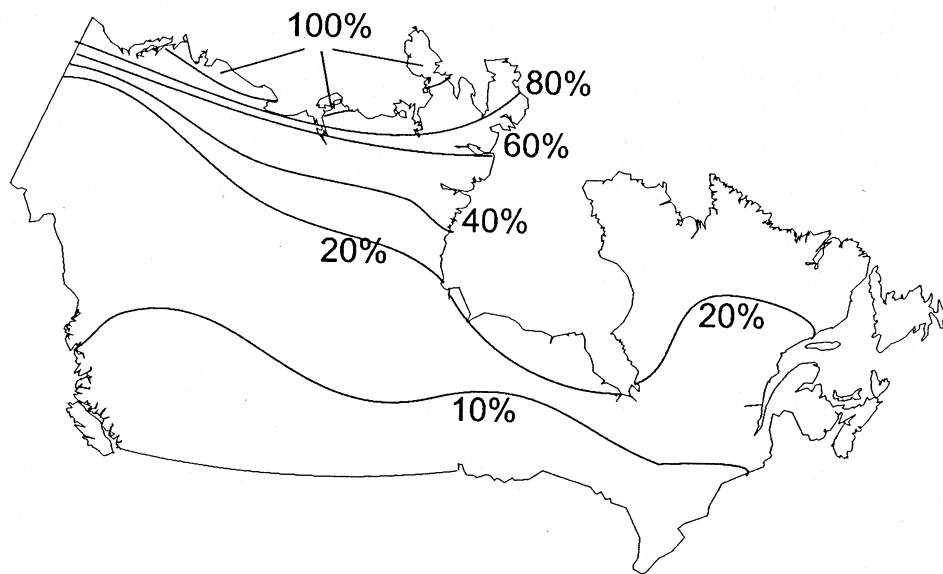


Figure 2. Contour map showing percent increases in mammal diversity predicted by the species-energy model and assuming that all taxa will be able to migrate fast enough to track shifting climatic zones. This figure shows which regions will undergo the most severe changes relative to current conditions, and that should, therefore, receive the greatest management attention.

a specific example, we modelled the impact of a 4 °C temperature increase on the mainland distribution of a northern species, *Dicrostonyx groenlandicus* (Table II). This species exhibits very high population densities, and is an important prey item for many mammal and bird taxa (Forsyth, 1985). Due to this and the heavy impact that lemming grazing can have on vegetation, lemmings can be considered a keystone species in arctic ecosystems. Substantial reductions in the distribution of *Dicrostonyx* would therefore be expected to have a major impact on the success of lemming predators, such as snowy owls, and arctic foxes. This species may provide particular insight since it is known to have migrated in response to gradual climatic change since the last glacial period (Graham and Grimm, 1990).

3. Where will the Diversity of Today go in the Warmer World of Tomorrow?

There is considerable geographical variability in the predicted response of mammal diversity patterns in Canada. The arctic is expected to undergo the largest proportional changes, as much as 111%, assuming that organisms are able to track their shifting climatic zones despite anthropogenic and natural barriers (Peters, 1992; Figure 2). The magnitude of biotic response declines toward the southern regions of Canada, corresponding with smaller predicted temperature changes.

Table I

Terrestrial mammal species whose northern distributions are bounded, at least partially, by the Arctic Ocean (Forsythe, 1985)

Mammal species	Common name
<i>Rangifer tarandus</i>	Caribou
<i>Alces alces</i>	Moose
<i>Ovis dalli</i>	Dall's sheep
<i>Ovibos moschatus</i>	Muskox
<i>Canis lupus</i>	Grey wolf
<i>Canis latrans</i>	Coyote
<i>Alopex lagopus</i>	Arctic fox
<i>Vulpes vulpes</i>	Red fox
<i>Ursus arctos</i>	Grizzly bear
<i>Ursus americanus</i>	Black bear
<i>Ursus maritimus</i>	Polar bear
<i>Gulo gulo</i>	Wolverine
<i>Mustela erminea</i>	Ermine
<i>Mustela nivalis</i>	Least weasel
<i>Lynx canadensis</i>	Lynx
<i>Spermophilus parryii</i>	Arctic ground squirrel
<i>Dicrostonyx groenlandicus</i>	Collared lemming
<i>Lemmus sibiricus</i>	Brown lemming
<i>Microtus miurus</i>	Singing vole
<i>Microtus oeconomus</i>	Root vole
<i>Microtus xanthognathus</i>	Yellow-cheeked vole
<i>Microtus pennsylvanicus</i>	Meadow vole
<i>Lepus arcticus</i>	Arctic hare
<i>Sorex monticolus</i>	Dusky shrew
<i>Sorex tundrensis</i>	Tundra shrew

Indeed, the species-energy model suggests that arctic communities in particular are likely to be fundamentally altered in the next 75 yr, as a massive influx of species from the south sweeps northward. Thus, taxa whose distributions are already limited by the barrier of the Arctic Ocean may face a bleak future indeed. While most authors agree that communities will not remain intact due to species-specific migration rates (Davis, 1989; Graham and Grimm, 1990; Pacala and Hurtt, 1993), it is not yet possible to confidently predict the community composition after 75 yr of climate change. This is perhaps where the species-energy approach can make its most valuable contribution to global change research - by providing an indication of the size, rather than species composition, of communities, it becomes possible to direct management efforts to those regions which are likely to undergo the largest changes.

Table II

Predicted reduction in mainland distribution of *Dicrostonyx groenlandicus*, the collared lemming, as a function of three predicted changes in average annual temperature by 2070

Increase in annual temperature ^a	Area of species distribution (km ²)	Decline in area occupied (km ²)	% decrease relative to current area occupied
2 °C	315 000.00	195 000.00	38%
4 °C	205 000.00	305 000.00	60%
6 °C	115 000.00	395 000.00	78%
Current climatic conditions	510 000.00	n/a	n/a

^a The predicted temperature increase in the regions currently occupied by *Dicrostonyx groenlandicus* ranges from 2 to 6 °C by 2070 (IPCC, 1994).

4. The Species with Nowhere to go

There are 25 mammal species that are caught between the Arctic Ocean in the north (Table I) and that are likely to face pressure from species that are migrating from the south. All terrestrial mammal orders are represented in this list except Chiroptera (the bats), which has no arctic species, and Marsupialia, which has only one southern species in North America. Some of these taxa, such as *Ursus americanus*, the black bear, are widespread in North America, and are not likely to become extinct or even rare with substantial climate change. The black bear, however, consists of several different subspecies with distinct characteristics (Hall and Kelson, 1981), and may be in a state of relatively rapid speciation. Such evolutionary processes may be inhibited or even reversed if climate change leads to increased mixing among the subspecies. Other taxa with fewer distinctive races may not be threatened with extinction, but may still be seriously disturbed due to significant changes in biotic and abiotic interactions (Melillo *et al.*, 1991). A further possibility is that synergistic interactions with other environmental perturbations, such as habitat fragmentation (Peters, 1987) and increasing UV radiation, may lead to increased likelihood of extinction for some species (Myers, 1992). In general, however, taxa that are limited by the Arctic Ocean in their ability to disperse northward (listed in Table I) are likely to undergo significant losses of habitat, and may eventually require management intervention.

Range reductions in some taxa, such as *Dicrostonyx groenlandicus*, are likely to be severe, and the consequences that this will have on arctic ecology are also likely to be substantial. Indeed, given a 4 °C increase in temperature throughout the current mainland range of the *Dicrostonyx*, the area that this species occupies is projected to decline from approximately 510 000 to 205 000 km², a reduction of about 60% (based on generally observed temperature changes with latitude

established by MacArthur, 1972; Table II). Continued warming up to 6 °C could further reduce the species range to 115 000 km², to about a fifth of its current mainland area.

What will happen as a consequence of the rapid removal of a keystone prey species from such a large proportion of its range? Will other small prey species expand to occupy niches left behind by the collared lemming? Will predators be able to switch their hunting tactics to accommodate new prey species, or will they need to follow shifting prey distributions as well as climatic zones? Which species will require human intervention to migrate, and which can do so without aid? While these important ecological questions urgently require attention, incomplete scientific knowledge is a poor reason for national and international governments to continue to postpone preventive treatment of the global problem of climate change. By the time the data have been gathered and the obvious research implications explored, it may be too late to accomplish the main conservation objective: to sustain biodiversity in the face of unprecedented environmental perturbation.

Acknowledgements

This research was supported by an NSERC PGS-B Doctoral fellowship to JTK, and a research grant to LP. Thanks also to Don McQueen and Laura Kerr for insightful discussion. David Currie generously provided the main database.

References

- Adams, J. M. and Woodward, F. I.: 1989, Patterns in tree species richness as a test of the glacial extinction hypothesis, *Nature* **339**, 699.
- Cox, B. C. and Moore, P. D.: 1985, *Biogeography: An Ecological and Evolutionary Approach*, Blackwell Scientific, Oxford, U.K.
- Currie, D. J.: 1991, Energy and large-scale patterns of animal and plant species richness, *Am. Nat.* **137**, 27.
- Currie, D. J. and Paquin, V.: 1987, Large-scale biogeographic patterns of species richness of trees, *Nature* **329**, 326.
- Davis, M. B.: 1990, Biology and paleobiology of global climate change: Introduction, *TREE* **5**, 269.
- Dobson, A., Jolly, A. and Rubenstein, D.: 1990, The greenhouse effect and biological diversity, *TREE* **4**, 64.
- Forsyth, A.: 1985, *Mammals of the Canadian Wild*, Camden East Publishing, Camden East, Ontario.
- Graham, R. W.: 1992, Late Pleistocene Faunal Changes as a Guide to Understanding Effects of Greenhouse Warming on the Mammalian Fauna of North America, in: R. L. Peters and T. E. Lovejoy (eds.), *Global Warming and Biological Diversity*, Yale University Press, New Haven, Connecticut, pp. 76–87.
- Graham, R. W. and Grimm, E. C.: 1990, Effects of global climate change on patterns of terrestrial biological communities, *TREE* **5**, 289.
- Hall, E. R. and Kelson, K. R.: 1981, *The Mammals of North America*, John Wiley & Sons, Toronto, Canada.
- Houghton, J. T., Meira Filho, L. G., Bruce, J., Hoesung Lee, Callander, B. A., Haites, E., Harris, N. and Maskell, K.: Climate Change 1994: Radiative forcing of climate change and an evaluation

- of the IPCC IS92 Emission Scenarios, published for the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, U.K.
- Kerr, J. T. and Currie, D. J.: 1995, Effects of human activity on global extinction risk, *Conservation Biology* **9**, 1528.
- Kerr, J. T. and Packer, L.: 1997, Habitat heterogeneity as a determinant of mammal species richness in high energy regions, *Nature* **385**, 252.
- MacArthur, R. H.: 1972, *Geographical Ecology*, Harper and Row, New York, New York.
- Melillo, J. M., Callaghan, T. V., Woodward, F. I., Salati, E. and Sinha, S. K.: 1991, in: J. T. Houghton, G. J. Jenkins and J. J. Ephraums, (eds.), *Climate Change: The IPCC Scientific Assessment*. Cambridge University Press, New York, New York, pp. 283–310.
- Myers, N.: 1992, Synergisms: Joint Effects of Climate Change and Other Forms of Habitat Destruction, in: R. L. Peters and T. E. Lovejoy (eds.), *Global Warming and Biological Diversity*, Yale University Press, New Haven, Connecticut, pp. 344–354.
- Pacala, S. W. and Hurtt, G. C.: 1993, Terrestrial Vegetation and Climate Change: Integrating Models and Experiments, in: P. M. Kareiva, J. G. Kingsolver and R. B. Huey (eds.), *Biotic Interactions and Global Change*. Sinauer Associates, Sunderland, Massachusetts, pp. 57–74.
- Pace, M. L.: 1993, Forecasting Ecological Responses to Global Change: The Need for Large-Scale Comparative Studies, in: P. M. Kareiva, J. G. Kingsolver and R. B. Huey (eds.), *Biotic Interactions and Global Change*, Sinauer Associates, Sunderland, Massachusetts, pp. 356–365.
- Peters, R. L.: 1987, Effects of Global Warming on Biological Diversity: An Overview, in: *Proceedings of the First North American Conference on Preparing for Climate Change: A Cooperative Approach*, Government Institutes, Inc. Washington, D.C., pp. 169–185.
- Peters, R. L.: 1992, Conservation of Biological Diversity in the Face of Climate Change, in: R. L. Peters and T. E. Lovejoy (eds.), *Global Warming and Biological Diversity*, Yale University Press, New Haven, Connecticut, pp. 15–26.
- Peters, R. L. and Darling, J. D.: 1985, The greenhouse effect and nature reserves, *BioScience* **35**, 707.
- Quinn, J. F. and Karr, J. R.: 1993, Habitat Fragmentation and Global Change, in: P. M. Kareiva, J. G. Kingsolver and R. B. Huey (eds.), *Biotic Interactions and Global Change*, Sinauer Associates, Sunderland, Massachusetts, pp. 451–465.
- Raven, P. H.: 1988, Our Diminishing Tropical Forests, in: E. O. Wilson (ed.), *Biodiversity*, National Academy Press, Washington, D.C., pp. 119–122.
- Russell, G. L., Miller, J. R. and Rind, D.: 1996, A coupled atmosphere-ocean model for transient climate change studies, *Atmos. Ocean* **33**, 683.
- Soulé, M. E.: 1992, Foreword: The Wrong Time for Climate Change, in: R. L. Peters and T. E. Lovejoy (eds.), *Global Warming and Biological Diversity*, Yale University Press, New Haven, Connecticut. pp. xiii-xv.
- Wilson, E. O.: 1988, The Current State of Biological Diversity, in: Edward O. Wilson (ed.), *Biodiversity*, National Academy Press, Washington, D.C., pp. 3–17.