United States
Department of
Agriculture

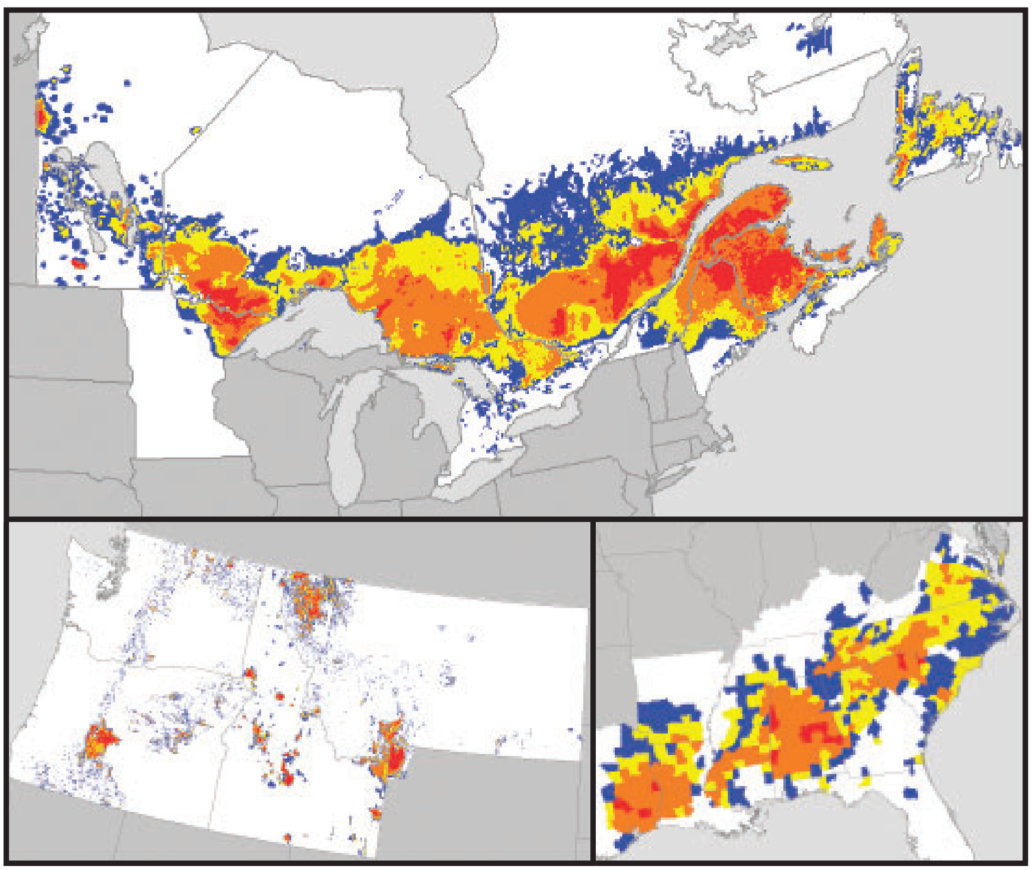
Forest Service

**Northeastern
Research Station**

General Technical
Report NE-308

Historical Patterns of Spruce Budworm Defoliation and Bark Beetle Outbreaks in North American Conifer Forests: An Atlas and Description of Digital Maps

David W. Williams
Richard A. Birdsey



Abstract

This atlas provides maps of historical defoliation by the eastern and western spruce budworms and historical outbreaks of the mountain and southern pine beetles during the past half century. The maps encompass various regions of the conterminous United States and eastern Canada. The publication also serves as documentation for an extended set of digital maps, which are available on our website. The digital maps are useful for investigating spatial dynamics of insect populations and for providing pest disturbance inputs to spatially explicit forest simulation models.

The Authors

DAVID W. WILLIAMS is a research entomologist with the Northeastern Research Station and RICHARD A. BIRDSEY is the program manager for the Northern Global Change Research Program. Both authors are located at station headquarters in Newtown Square, PA.

Published by:

USDA FOREST SERVICE
11 CAMPUS BLVD SUITE 200
NEWTOWN SQUARE PA 19073-3294

July 2003

For additional copies:

USDA Forest Service
Publications Distribution
359 Main Road
Delaware, OH 43015-8640
Fax: (740)368-0152

Visit our homepage at: **http://www.fs.fed.us/ne**

Introduction

Recent developments in geographic information system (GIS) software and the availability of increasingly powerful hardware to run it have facilitated interests in the spatial aspects of forest ecology (Liebhold and Barrett 1993). Moreover, the increasing availability of high-quality, remotely sensed imagery has provided abundant data for mapping forests and the various environmental factors affecting them (Zhu and Evans 1994, Gutman et al. 1997). Accurate digital maps of forests have obvious utility for the routine management of resources. In addition, they are useful for anticipating altered spatial distributions of forest species and stands under global climate change (Iverson and Prasad 1998, Iverson et al. 1999).

Beyond the sheer acquisition, manipulation, and analysis of spatial data on forests, there are the recent developments of spatially explicit vegetation models (Aber and Federer 1992, Neilson 1995). Such models facilitate the extrapolation of basic ecosystem processes to the landscape and regional levels and permit the simulation of forest dynamics under changing environmental conditions (Aber et al. 1993, 1997; Pan et al. 2003). Recently, vegetation models have incorporated the effects of large-scale environmental disturbances, most notably fire (Bachelet et al. 2001, Thonicke et al. 2001). But biotic disturbances, such as insect outbreaks, generally are not yet considered in those modeling efforts (Williams et al. 2000). Because vegetation models are evolving to include disturbance effects, the time is ripe to compile and make available archived maps of insect outbreaks. Historical data are critical for the development of spatially explicit models of disturbance for inclusion in vegetation models.

Here we describe maps of historical damage by four native species of forest insects that cause extensive disturbances in North American forests. We present an atlas of previously unpublished maps for the species and reference the more extensive set of digital coverages available at www.fs.fed.us/ne/global/products. These pests of conifer forests include two defoliators, the eastern spruce budworm (*Choristoneura fumiferana*) and the western spruce budworm (*Choristoneura occidentalis*), and two bark beetles, the southern pine beetle (*Dendroctonus frontalis*) and the mountain pine beetle (*Dendroctonus ponderosae*). The maps have been used previously in studies of potential effects of climate change on the geographical ranges of the species (Williams and Liebhold 1995, 1997, 2002; Williams et al. 2000) and of the spatial dynamics of their populations at the regional level (Williams and Liebhold 2000a, b; Peltonen et al. 2002). We make them available now for their obvious utility in simulating pest disturbances in spatially explicit forest models. We describe the pest maps and their development and explore ways in which they may be applied. A similar set of maps of historical defoliation by gypsy moth (*Lymantria dispar*), a devastating exotic invasive insect attacking oak forests in the eastern United States, is described in Liebhold et al. (1997) and available at www.fs.fed.us/ne/morgantown/4557/gmoth.

Map Development

Maps of defoliation and damage were developed using the Idrisi (Eastman 1999) and GRASS (U.S. Army Corps of Engineers 1993) GIS. Both systems are raster-based GIS, in which the smallest map units (i.e., rasters) are square grid cells.

With the exception of the southern pine beetle maps, GIS coverages were created from paper maps. The paper maps were assembled from individual state and province maps that, in turn, were developed from aerial sketch maps of defoliation or tree mortality (McConnell et al. 2000). For the budworms, areas depicted as defoliated on sketch maps had defoliation visible from the air, which was generally greater than 30 percent canopy loss (Webb et al. 1961). Bark beetle damage was reported as “spots” that were observed in aerial surveys. A spot is a cluster of attacked, fading trees (Coulson 1980). The minimum spot size is typically five to ten trees in state monitoring programs (Price et al. 1998).

Damage areas indicated on the paper maps were traced onto transparent mylar film, along with a variable number of georeference points located on well-defined political and natural boundaries. The transparencies then were digitized using a digital scanner at 300 dots per inch to produce binary tagged image format (TIF) files, which were converted to byte-binary format files for use in the GIS.

The map layers for three of the four species, western spruce budworm, mountain pine beetle, and southern pine beetle, were georeferenced to a vector line coverage of the conterminous United States referenced to the Lambert Azimuthal Equal-Area projection. Those for the fourth species, eastern spruce budworm, were georeferenced to a vector coverage of eastern North America, including southern Canada and the northern United States, referenced to the Albers Equal-Area Conic projection. Equal area projections were used because they equalize surface areas across the geographical range of the coverage, facilitating analysis and modeling. Common georeference points were identified on the various map layers and the reference map, and the map layers were transformed to the resolution and projection of the reference map through "rubber-sheeting." Rubber-sheeting is a process by which one map is transformed mathematically to fit a reference map given a set of common georeference points defined on both maps (Antenucci et al. 1991). The rubber-sheeting of most maps used a second-order polynomial transformation (U.S. Army Corps of Engineers 1993).

Resolutions of 2 km or 5 km were used because they represented the smallest resolution reliable for the defoliation maps given various sources of mapping error. Errors may have occurred in four processes of map production: aerial sketch mapping, replotting of sketch maps to produce regional coverages, tracing, and scanning. The first two processes were beyond our control, so we cannot estimate errors associated with them. However, potential errors in aerial sketch mapping are well-documented (Van Sickle 1995). The coarse grid cell sizes that we used probably minimized the effects of such errors. The paper maps that we traced came at a wide variety of scales, as described below. Although we exercised great care in tracing, error was possible because the pen width represented nearly 2 km on some of the maps traced. Scanning error was likely to have been minimal because each scanned dot represented less than 1 km^2, given the map scales and scanner resolution.

Sources of Map Sets

Eastern spruce budworm. Most of the defoliation maps were developed from maps published in Hardy et al. (1986), which included annual maps of spruce budworm defoliation during 1938-1980 in southeastern Canada and the northeastern United States at a scale of 1:11,000,000. Because maps were unavailable for some states and provinces early in the series, we only used maps from 1954 to 1980. Maps for the period 1981-1988 were assembled from defoliation maps published in the series of annual insect and disease conditions reports of individual provinces and states, including Manitoba at a scale of 1:10,000,000 (e.g., Cerezke and Emond 1989), Minnesota at 1:4,400,000[1], Ontario at 1:7,000,000 (e.g., Howse and Applejohn 1988), Quebec at 1:6,000,000 (e.g., Bordeleau et al. 1989), Maine at 1:2,000,000 (e.g., Trial 1989), the Maritime Provinces at 1:4,000,000 (e.g., Magasi 1989), and Newfoundland and Labrador at 1:3,500,000 and 1:20,000,000, respectively (e.g., Clarke and Carew 1987). The resolution for the eastern spruce budworm maps was set at 5 km.

Western spruce budworm and mountain pine beetle. Maps of defoliation by western spruce budworm in the states of Washington and Oregon from 1947 to 1979 were developed from an atlas by Dolph (1980), in which maps were at a scale of 1:3,500,000. Defoliation maps for 1980-1994 for the same states, as well as maps of mountain pine beetle outbreaks, were

---

[1]Albers, J. Regional Forest Pest Specialist, Minnesota Department of Natural Resources, 1201 East Highway 2, Grand Rapids, MN 55744. Personal communication.

converted to raster coverages from digital vector maps.[2] These recent maps were digitized from aerial sketch maps at scales of 1:126,720 for Oregon and 1:100,000 for Washington (Sheehan 1996). They are available at www.fs.fed.us/r6/nr/fid/data.shtml. Maps of budworm defoliation and mountain pine beetle outbreaks for the states of Idaho and Montana (including Yellowstone National Park) for the years 1977-1996 and 1980-1995, respectively, were developed from maps published in annual pest conditions reports at scales of 1:2,000,000 and 1:3,500,000, respectively (e.g., Beckman et al. 1996, McConnell 1996). The resolution for the western spruce budworm defoliation maps in Washington, Oregon, Idaho, and Montana was set at 5 km, and that for the mountain pine beetle outbreak maps across the same area was set at 2 km.

Southern pine beetle. Maps of southern pine beetle outbreaks in the southeastern United States (i.e., Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas, and Virginia) over the period 1960-1994 at a scale of about 1:12,000,000 have been published in an atlas by Price et al. (1998). These maps are now part of the USDA Forest Service Southern Forest Health Atlas and may be viewed at fhpr8.srs.fs.fed.us/atlas/spb/spb.html. The maps on our website were provided by the USDA Forest Service, Forest Health Protection.[3] It must be noted that 1973 was the first year for which outbreak data were available for all 11 states.

The southern pine beetle maps are very different from the others. They depict outbreaks at the spatial scale of a county (i.e., as opposed to a grid cell). A county is defined to be in outbreak status in a given year if it contains one spot (see definition above) or more per 1,000 acres (405 ha) of susceptible forest (Price et al. 1998). Beginning in 1978, a refined classification was introduced that categorized counties into low, medium, and high outbreak states depending upon numbers of spots per 1,000 acres. However, for the sake of simplicity, we decided to retain the original outbreak definition and binary classification in the maps presented. That is, for an individual year, a county is categorized as either in outbreak status (1) or not (0).

Insect Damage Maps

We include in this atlas only maps that have not been published previously. Maps of eastern spruce budworm defoliation in eastern North America for the years 1981-1988 are shown in Figure 1 a-h. Maps of mountain pine beetle damage in Washington, Oregon, Idaho, Montana, and the northwestern corner of Wyoming for the years 1980-1995 are shown in Figure 2 a-p, and maps of western spruce budworm defoliation over the same area for 1977-1993 are shown in Figure 3 a-q. Figure 4 provides a summary map of the frequency of southern pine beetle outbreaks in the southeastern United States from 1973 to 1994. It must be noted that all of the digitized annual maps use a binomial classification, in which the presence of insect damage in a grid cell or a county is denoted by a value of 1 and its absence is denoted by a value of 0. The full set of digital maps is available at www.fs.fed.us/ne/global/products. The GIS coverages are provided as ArcGrid files or ArcInfo shape files.

Applications of the Insect Damage Maps

Obvious uses of the maps include investigations of insect population dynamics or disturbance inputs to forest simulation models. The basic annual time series of defoliation or damage may be useful in some cases. However, interpretation of pest impact from the defoliation maps is somewhat problematic because the annual maps show only presence of defoliation greater than

---

[2]Johnson, J. GIS Coordinator, Forest Insects and Diseases Group, USDA Forest Service, Pacific Northwest Region, P.O. Box 3623, Portland, OR 97208-3623. Personal communication.

[3]Yockey, E. Forest Health Analyst, Forest Health Protection, USDA Forest Service, Southern Region, 200 Weaver Boulevard, Asheville, NC 28804. Personal communication.

30 percent without any information on its intensity. Moreover, a single year's defoliation usually does not lead to death or severe growth loss of a tree. By contrast, spots on the bark beetle maps indicate areas where many trees are recently dead or moribund.

The summation of all annual maps for a species is used to produce a frequency map (Figs. 1i, 2q, 3r, and 4), which generally is useful to identify "hot spots" or infer areas of differing vulnerability to the pest. Summary maps without frequency classes show areas where a pest was present at least once. As such, they approximate the geographical ranges of outbreaks of the pest species, and such maps are useful, among other things, for assessing the potential effects of climate change (Williams and Liebhold 1995, 1997, 2002; Williams et al. 2000).

Another way of using the maps, particularly for investigating insect population dynamics, is to create time series of relative abundance (Williams and Liebhold 2000a, b; Peltonen et al. 2002). Estimates of relative abundance are produced by aggregating the pixels of the original annual maps (i.e., having values of either 0 or 1) so as to produce larger pixels that are assigned "population" values equal to the sums of the values of the smaller pixels. For example, a 4 × 4 aggregation of an annual defoliation map yields a map of larger pixels ranging in value from 0 to 16. Concatenating the aggregated annual maps produces a map with a time series of defoliation in each large aggregate pixel. This technique produces satisfactory results for all but the smallest levels of aggregation (i.e., 2 × 2 pixels, in which there is a range of only five possible "population" sizes) (Williams and Liebhold 2000a).

Using the maps to quantify pest disturbances as inputs to forest simulation models requires transformations of the basic damage maps or summarized frequency maps. The goal usually is to estimate rates of tree mortality or growth loss given the number of years that damage is sustained. Information for quantifying relationships between tree loss and time lengths of disturbance impacts is available in the literature for a few common forest pests (e.g., Campbell 1979, MacLean 1980, Davidson et al. 1999, 2001). In this publication, we present a simple model to illustrate a possible use of the data. As an example, we consider the effect of repeated defoliation on mortality in forests susceptible to eastern spruce budworm.

MacLean (1980) reviewed the literature on the vulnerability of host stands to uncontrolled spruce budworm outbreaks and presented a figure (his Fig. 1) relating cumulative percentage of fir mortality to the number of years since the start of an outbreak for several budworm outbreaks. In general, mortality was first observed after about four years and increased approximately linearly, reaching 100 percent by about 10 years. Formulating this relationship mathematically yields the following simple model:

$$\%\ \text{MORTALITY} = \begin{cases} 0.0, & 0 \leq \text{YRS DEFOL} \leq 4 \\ 16.67*(\text{YRS DEFOL}) - 66.67, & 4 < \text{YRS DEFOL} < 10 \\ 100.0, & \text{YRS DEFOL} \geq 10 \end{cases}$$

It was not realistic to apply this model to the frequency map for the entire series of budworm defoliation maps, which includes more than one major outbreak. Instead, we considered a shorter span of defoliation from 1966, at the start of a major outbreak, through 1980, at its peak. We summed the 15 annual maps to produce a frequency map and then applied the mortality function to all pixels. The resulting map (Fig. 1j) is a hypothetical picture of the forested areas in eastern North America that may have been most vulnerable to eastern spruce budworm outbreaks during the 1970s. We stress that this is a simple illustration of a possible use of the data; the results have not been validated on field data. More detailed and more realistic algorithms using the time series of maps could be developed and validated depending upon the needs of the individual modeler.

Clearly these historical series of insect defoliation and damage will be useful in a wide variety of modeling applications.

Acknowledgments

We are grateful to the following individuals for providing maps and publications: Edwin Yockey, USDA Forest Service, Asheville, North Carolina; Katharine Sheehan and Julie Johnson, USDA Forest Service, Portland, Oregon; Kenneth Gibson, USDA Forest Service, Missoula, Montana; R. Ladd Livingston, Idaho Department of Lands, Coeur d'Alene, Idaho; Jana Albers, Minnesota Department of Natural Resources, Grand Rapids, Minnesota; and Henry Trial, Jr., Maine Department of Conservation, Augusta, Maine. We thank Valerie DeFelice, Gregory Bonynge, Eugene Luzader, Heath Holt, and Jason Frederick for their technical assistance in developing the digital coverages and Kevin McCullough for his expertise with the web site. We are grateful to Louis Iverson, Andrew Liebhold, and Ronald Neilson for their thoughtful comments on the manuscript. Development of the digital maps was funded by the Northern Global Change Research Program of the USDA Forest Service.

Literature Cited

Aber, J.D.; Federer, C.A. 1992. **A generalized, lumped-parameter model of photosynthesis, evapotranspiration and net primary production in temperate and boreal forest ecosystems.** Oecologia. 92: 463-474.

Aber, J.D.; Driscoll, C.T.; Federer, C.A. [et al.]. 1993. **A strategy for the regional analysis of the effects of physical and chemical climate change on the biogeochemical cycles in northeastern (U.S.) forests.** Ecological Modelling. 67: 37-47.

Aber, J.D.; Ollinger, S.V.; Driscoll, C.T. 1997. **Modeling nitrogen saturation in forest ecosystems in response to land use and atmospheric deposition.** Ecological Modelling. 101: 61-78.

Antenucci, J.C.; Brown, K.; Croswell, P.L. [et al.]. 1991. **Geographic information systems. A guide to the technology.** New York: Van Nostrand Reinhold. 291 p.

Bachelet, D.; Lenihan, J.M.; Daly, C. [et al.]. 2001. **MC1: a dynamic vegetation model for estimating the distribution of vegetation and associated ecosystem fluxes of carbon, nutrients, and water.** Gen. Tech. Rep. PNW-GTR-508. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 95 p.

Beckman, D.P.; James, R.L.; Randall, C.B. [et al.]. 1996. **Idaho forest insect and disease conditions and program summary 1995.** Report No. 96-1. Coeur d'Alene, ID: Idaho Department of Lands and U.S. Department of Agriculture, Forest Service Northern and Intermountain Regions. 45 p.

Bordeleau, C.; Guérin, D.; Innes, L. [et al.]. 1989. **Insectes et maladies des arbres, Québec–1988.** Forêt Conservation 56(1): 1-32.

Campbell, R.W. 1979. **Gypsy moth: Forest influence.** Agric. Info. Bull. 423. Washington, DC: U.S. Department of Agriculture, Forest Service. 45 p.

Cerezke, H.F.; Emond, F.J. 1989. **Forest insect and disease conditions in Alberta, Saskatchewan, Manitoba, and the Northwest Territories in 1987.** Info. Rep. NOR-X-300. Edmonton, AB: Forestry Canada, Northern Forestry Centre. 25 p.

Clarke, L.J.; Carew, G.C. 1987. **Forest insect and disease conditions in Newfoundland and Labrador in 1986.** Info. Rep. N-X-259. St. John's, NF: Canadian Forestry Service, Newfoundland Forestry Centre. 30 p.

Coulson, R.N. 1980. **Population dynamics.** In: Thatcher, R.C.; Searcy, J.L.; Coster, J.E.; Hertel, G.D., eds. The Southern Pine Beetle. Tech. Bull. 1631. Washington, DC: U.S. Department of Agriculture, Forest Service: 71-105.

Davidson, C.B.; Gottschalk, K.W.; Johnson, J.E. 1999. **Tree mortality following defoliation by the European gypsy moth (*Lymantria dispar* L.) in the United States: A review.** Forest Science 45: 74-84.

Davidson, C.B.; Gottschalk, K.W.; Johnson, J.E. 2001. **European gypsy moth (*Lymantria dispar* L.) outbreaks: A review of the literature.** Gen. Tech. Rep. NE-278. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 15 p.

Dolph, R.E. 1980. **Budworm activity in Oregon and Washington 1947-1979.** R6-FIDM-033-1980. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 54 p.

Eastman, J.R. 1999. **Idrisi32: Guide to GIS and image processing.** Worcester, MA: Clark University. 193 p.

Gutman, G.; Tarpley, D.; Ignatov, A.; Olson, S. 1997. **Global AVHRR-derived land climatology.** Boulder, CO: National Oceanic and Atmospheric Administration, National Geophysical Data Center. [CD-ROM].

Hardy, Y.; Mainville, M.; Schmitt, D.M. 1986. **An atlas of spruce budworm defoliation in eastern North America, 1938-80.** Misc. Pub. 1449. Washington, DC: U.S. Department of Agriculture, Forest Service. 52 p.

Howse, G.M.; Applejohn, M.J. 1988. **Forest insect and disease conditions in Ontario, Summer 1987.** Survey Bulletin. Sault Ste. Marie, ON: Canadian Forestry Service, Great Lakes Forestry Centre. 31 p.

Iverson, L.R.; Prasad, A.M. 1998. **Predicting potential future abundance of 80 tree species following climate change in the eastern United States.** Ecological Monographs. 68: 465-485.

Iverson, L.R.; Prasad, A.M.; Hale, B.J.; Sutherland, E.K. 1999. **Atlas of current and potential future distributions of common trees of the eastern United States.** Gen. Tech. Rep. NE-265. Radnor, PA: U.S. Department of Agriculture, Forest Service. 245 p.

Liebhold, A.M.; Barrett, H.R., eds. 1993. **Proceedings. Spatial analysis and forest pest management.** Gen. Tech. Rep. NE-175. Radnor, PA: U.S. Department of Agriculture, Forest Service. 186 p.

Liebhold, A.M.; Gottschalk, K.W.; Luzader, E.R.; Mason, D.A.; Bush, R.; Twardus, D.B. 1997. **Gypsy moth in the United States: An atlas.** Gen. Tech. Rep. NE-233. Radnor, PA: U.S. Department of Agriculture, Forest Service. 36 p.

MacLean, D.A. 1980. **Vulnerability of fir-spruce stands during uncontrolled spruce budworm outbreaks: A review and discussion.** Forestry Chronicle. 56: 213-221.

Magasi, L.P. 1989. **Forest pest conditions in the Maritimes in 1988.** Info. Rep. M-X0-174. Fredericton, NB: Forestry Canada, Maritimes. 25 p.

McConnell, T. 1996. **Montana forest insect and disease conditions and program highlights - 1995.** Report 96-2. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region, Forest Health Protection and Montana Department of Natural Resources. 29 p.

McConnell, T.J.; Johnson, E.W.; and Burns, B. 2000. **A guide to conducting aerial sketch mapping surveys.** FHTET 00-01. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team. 88 p.

Neilson, R.P. 1995. **A model for predicting continental-scale vegetation distribution and water balance.** Ecological Applications. 5: 362-385.

Pan, Y.; Hom, J.; Jenkins, J.; Birdsey, R. 2003. **Importance of foliar nitrogen concentration to predict forest productivity spatially across the mid-Atlantic region.** Forest Science. 49: In press.

Peltonen, M.; Liebhold, A.M.; Bjørnstad, O.N.; Williams, D.W. 2002. **Spatial synchrony in forest insect outbreaks: Roles of regional stochasticity and dispersal.** Ecology. 83: 3120-3129.

Price, T.S.; Doggett, C.; Pye, J.M.; Smith, B. 1998. **A history of southern pine beetle outbreaks in the southeastern United States.** Macon, Georgia: Georgia Forestry Commission. 62 p.

Sheehan, K.A. 1996. **Defoliation by western spruce budworm in Oregon and Washington from 1980 through 1994.** Tech. Pub. R6-NR-04-96. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 9 p.

Thonicke, K.; Venevsky, S.; Sitch, S.; Cramer, W. 2001. **The role of fire disturbance for global vegetation dynamics: coupling fire into a dynamic global vegetation model.** Global Ecology and Biogeography. 10: 661-677.

Trial, H., Jr. 1989. **Spruce budworm in Maine: The end of the outbreak: Biological conditions in 1986, 1987, and 1988, and a look at the future.** Tech. Rep. No. 28. Augusta, ME: Department of Conservation, Maine Forest Service, Entomology Division. 50 p.

U.S. Army Corps of Engineers. 1993. **GRASS 4.1 User's reference manual.** Champaign, IL: U.S. Army Corps of Engineers. 555 p.

Van Sickle, G.A. 1995. **Canadian aerial surveys for pest damage assessment.** In: McConnell, T. J., ed. Proceedings, Aerial pest detection and monitoring workshop. Report 95-4. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region, Forest Pest Management: 24-28.

Webb, F.E.; Blais, J.R.; Nash, R.W. 1961. **A cartographic history of spruce budworm outbreaks and aerial forest spraying in the Atlantic region of North America, 1949-1959.** Canadian Entomologist. 93:360-379.

Williams, D.W.; Liebhold, A.M. 1995. **Forest defoliators and climatic change: Potential changes in spatial distribution of outbreaks of western spruce budworm and gypsy moth.** Environmental Entomology. 24: 1-9.

Williams, D.W.; Liebhold, A.M. 1997. **Latitudinal shifts in spruce budworm (Lepidoptera: Tortricidae) outbreaks and spruce-fir forest distributions with climate change.** Acta Phytopathologica et Entomologica Hungarica. 32: 205-215.

Williams, D.W.; Long, R.P.; Wargo, P.M.; Liebhold, A.M. 2000. **Effects of climate change on forest insect and disease outbreaks.** In: Birdsey, R.; Hom, J.; Mickler, R., eds. Response of northern United States forests to environmental change. New York, NY: Springer-Verlag: 455-494.

Williams, D.W.; Liebhold, A.M. 2000a. **Spatial scale and the detection of density dependence in spruce budworm outbreaks in eastern North America.** Oecologia. 124: 544-552.

Williams, D.W.; Liebhold, A.M. 2000b. **Spatial synchrony of spruce budworm outbreaks in eastern North America.** Ecology. 81: 2753-2766.

Williams, D.W.; Liebhold, A.M. 2002. **Climate change and the outbreak ranges of two North American bark beetles.** Agricultural and Forest Entomology. 4: 87-99.

Zhu, Z.; Evans, D.L. 1994. **U.S. forest types and predicted percent forest cover from AVHRR data.** Photogrammetric Engineering and Remote Sensing. 60: 525-531.

Index to Figures

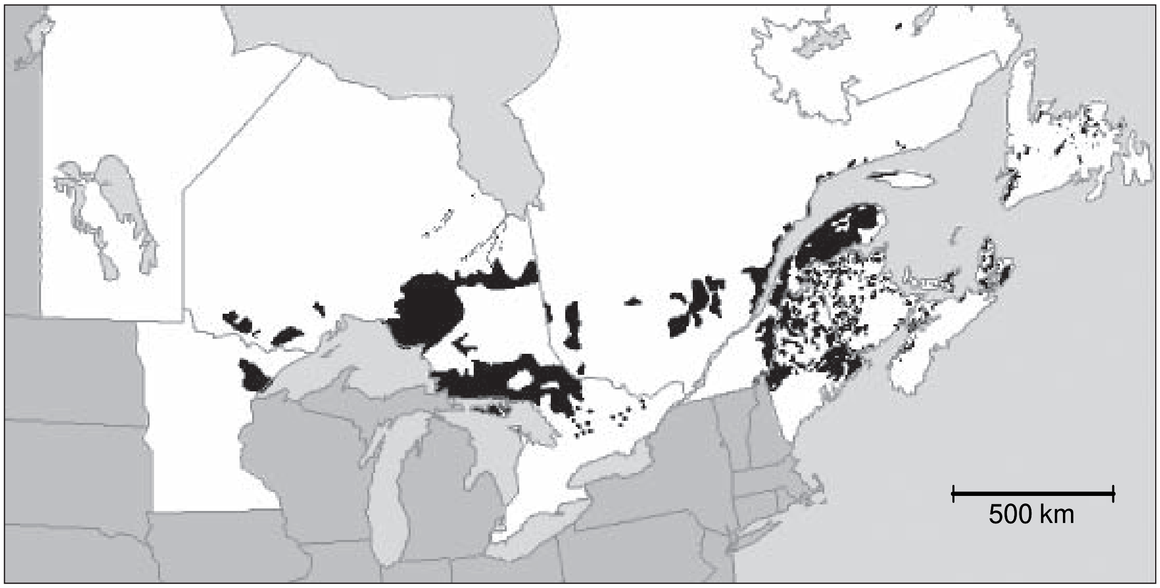


Figure 1a.—Area defoliated by eastern spruce budworm in 1981.

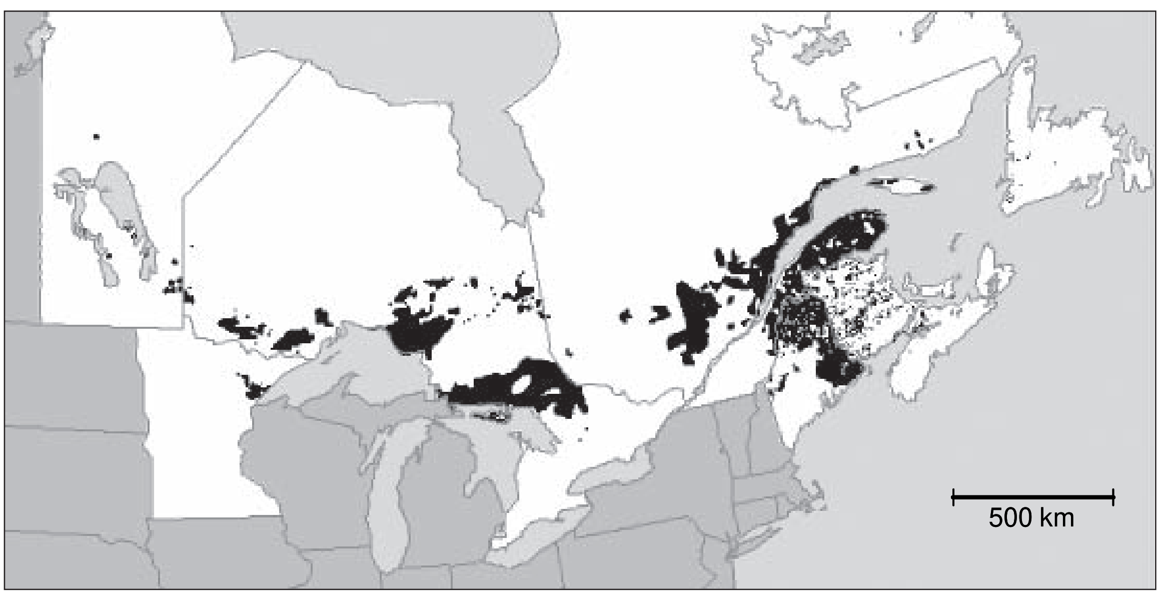


Figure 1b.—Area defoliated by eastern spruce budworm in 1982.

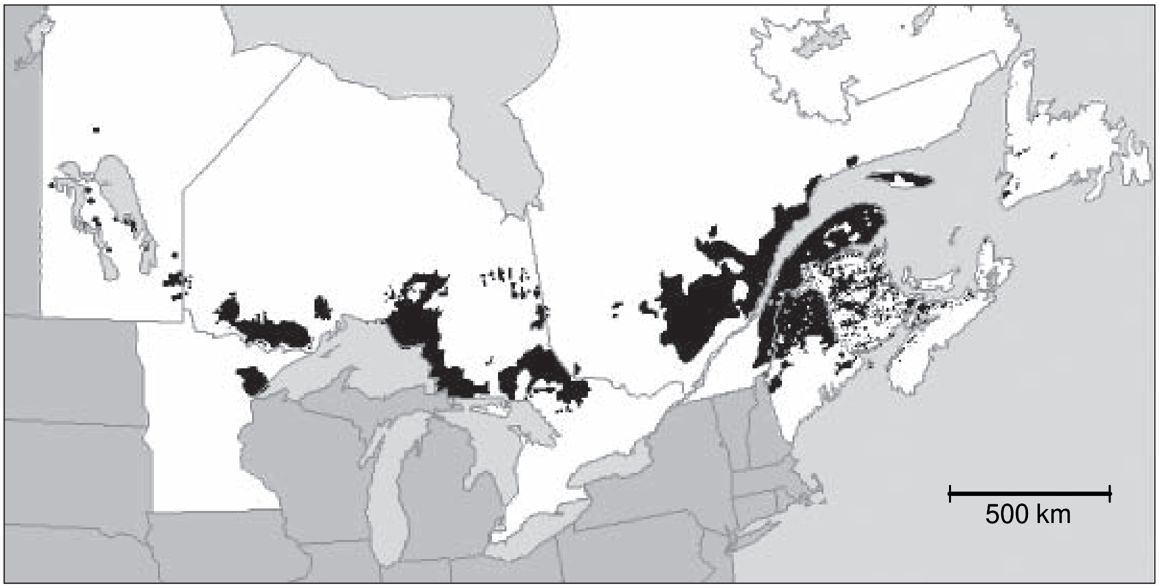


Figure 1c.—Area defoliated by eastern spruce budworm in 1983.

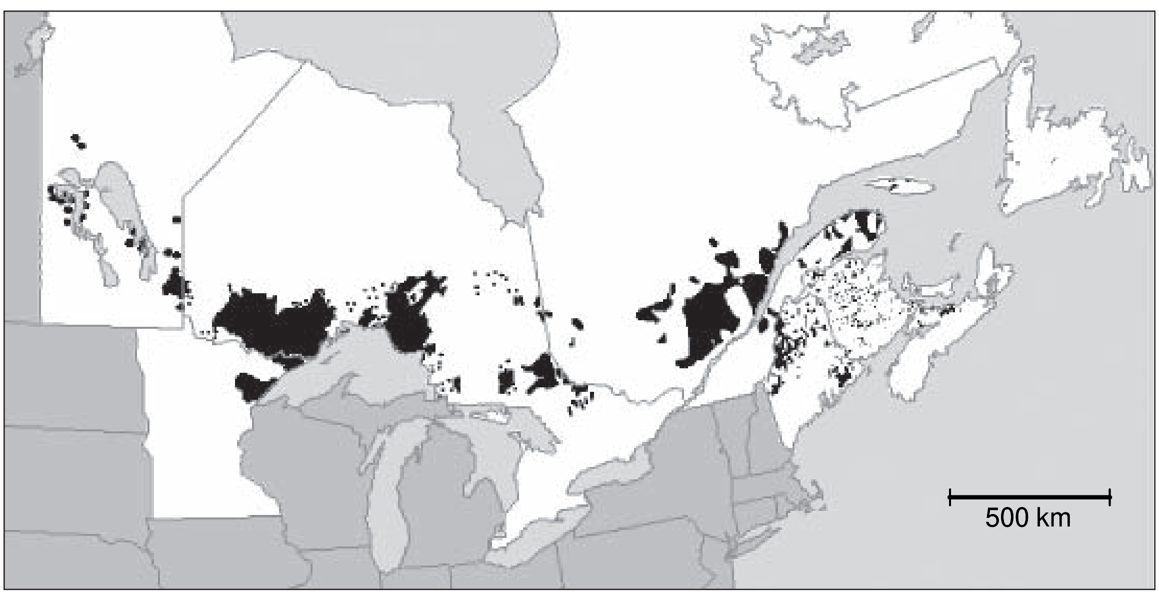


Figure 1d.—Area defoliated by eastern spruce budworm in 1984.

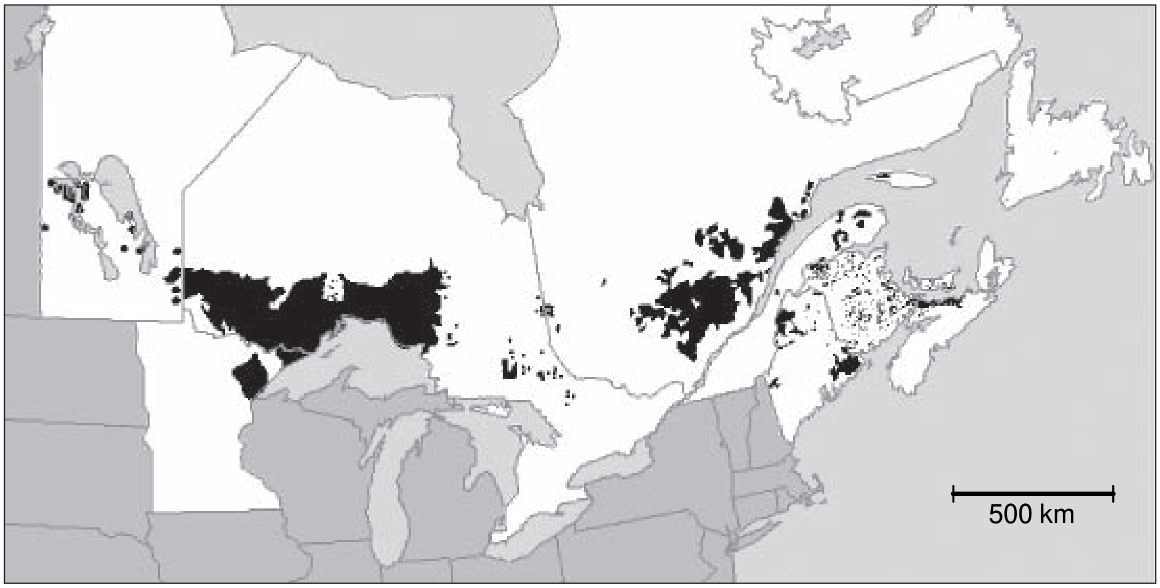


Figure 1e.—Area defoliated by eastern spruce budworm in 1985.

Figure 1f.—Area defoliated by eastern spruce budworm in 1986.

Figure 1g.—Area defoliated by eastern spruce budworm in 1987.

Figure 1h.—Area defoliated by eastern spruce budworm in 1988.

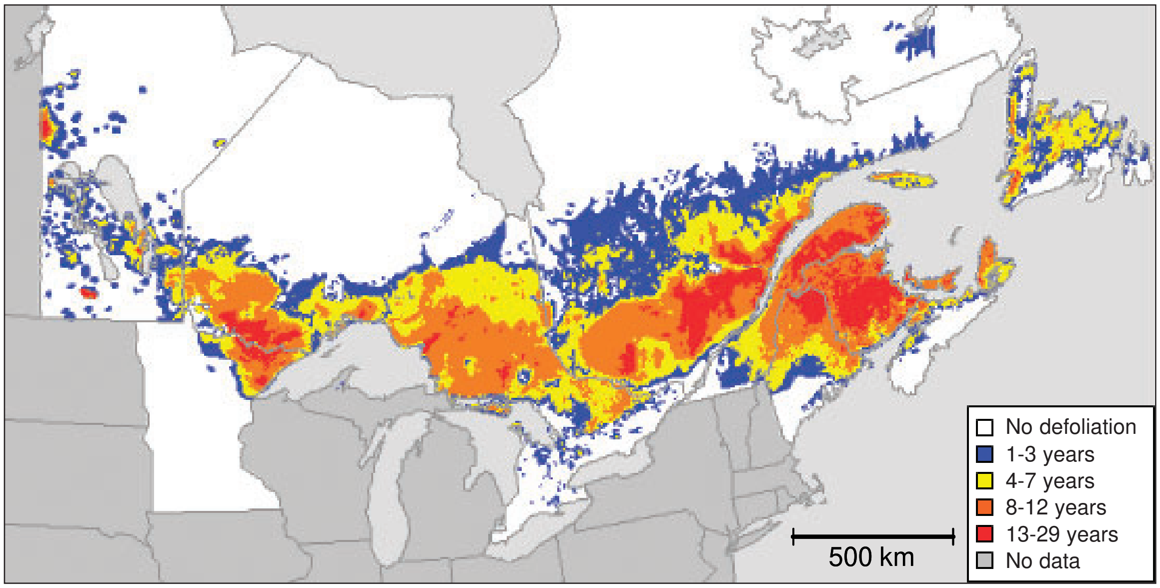


Figure 1i.—Frequency of defoliation by eastern spruce budworm from 1954 to 1988.

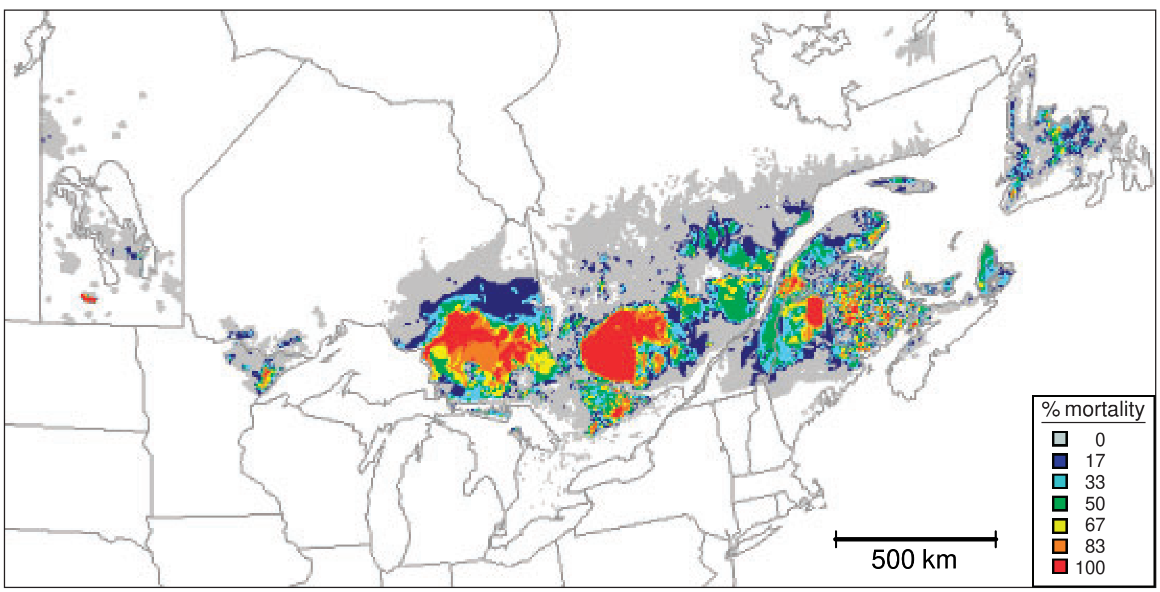


Figure 1j.—Expected mortality of susceptible forest resulting from eastern spruce budworm defoliation from 1966 to 1980.

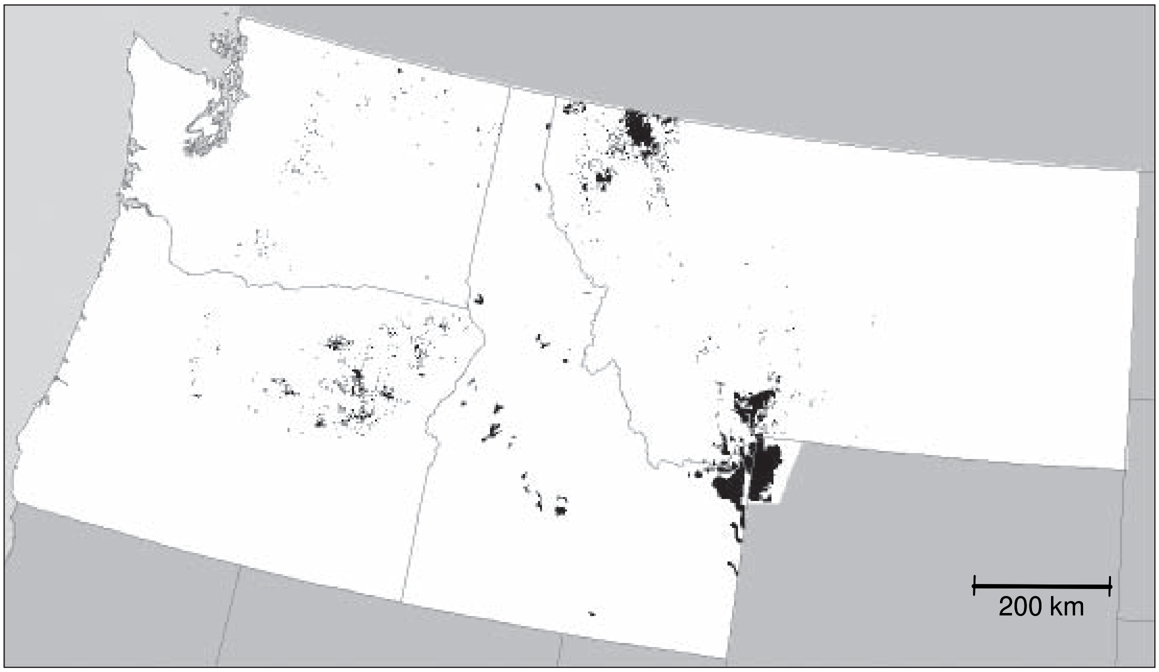


Figure 2a.—Area damaged by mountain pine beetle in 1980.

Figure 2b.—Area damaged by mountain pine beetle in 1981.

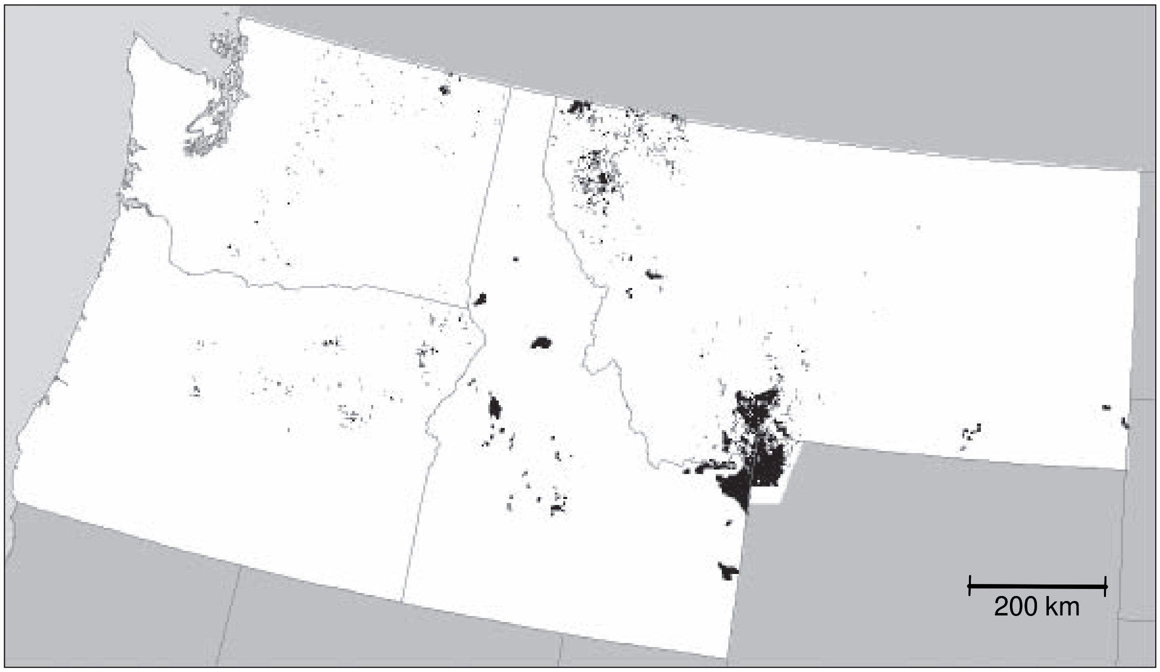


Figure 2c.—Area damaged by mountain pine beetle in 1982.

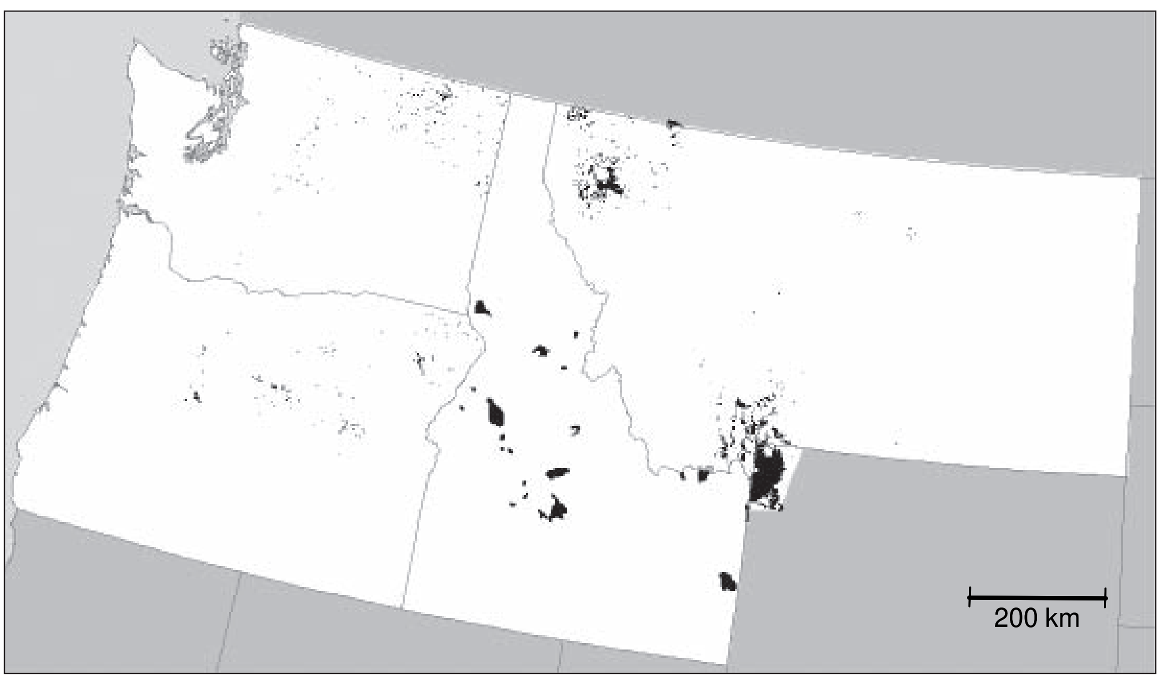


Figure 2d.—Area damaged by mountain pine beetle in 1983.

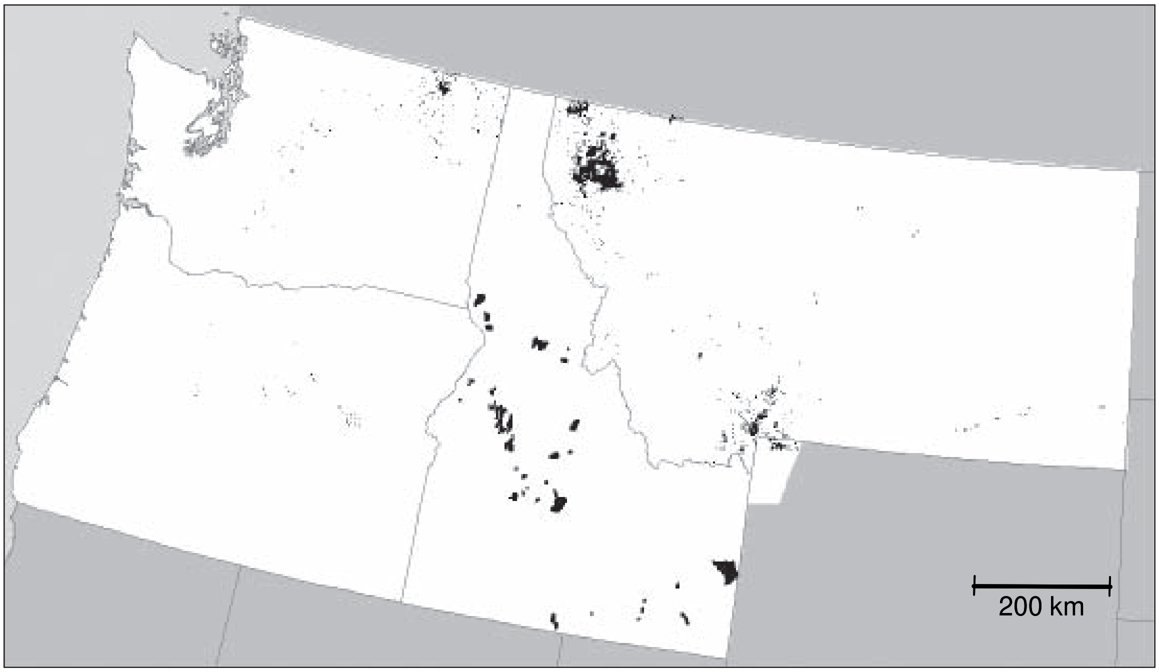


Figure 2e.—Area damaged by mountain pine beetle in 1984.

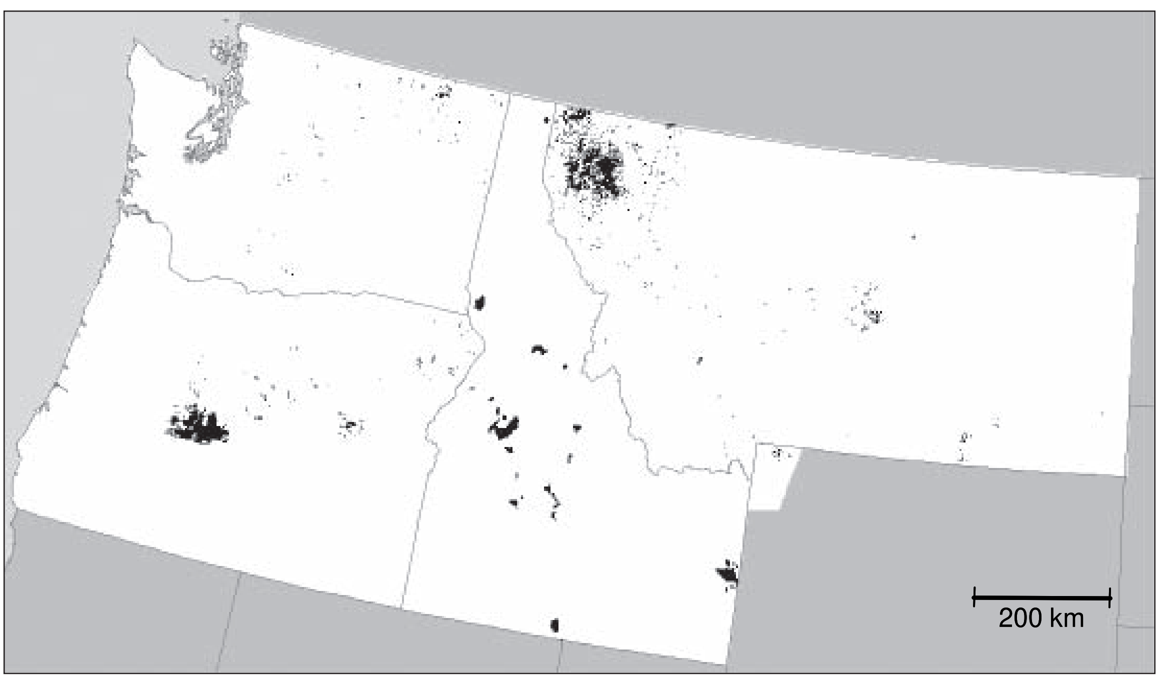


Figure 2f.—Area damaged by mountain pine beetle in 1985.

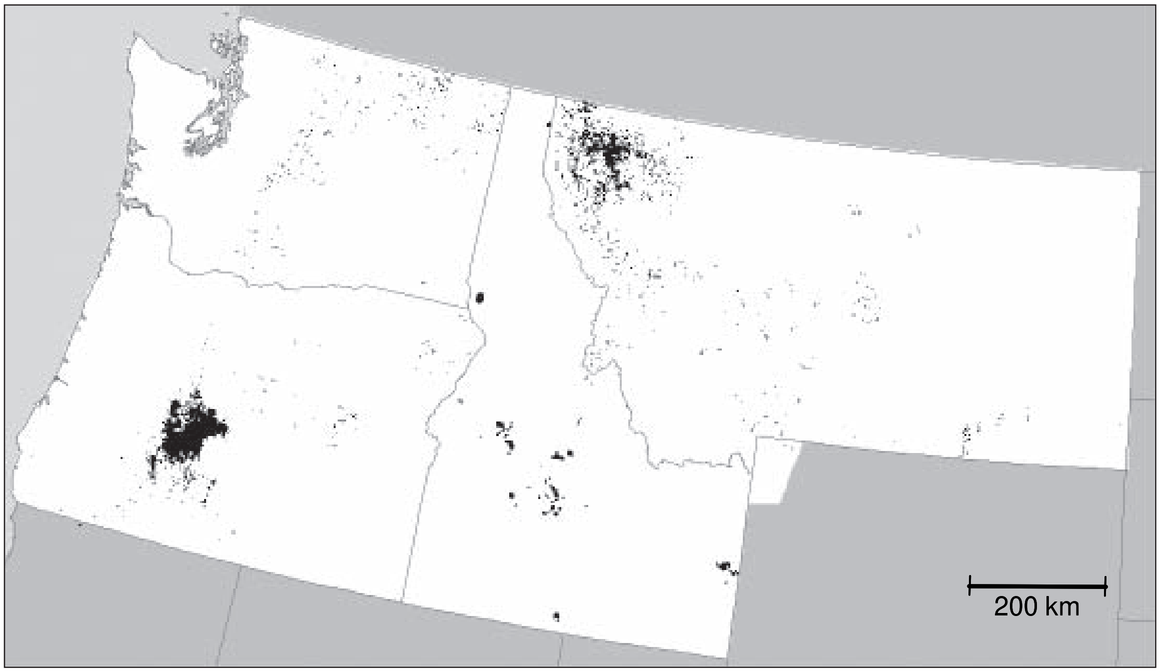


Figure 2g.—Area damaged by mountain pine beetle in 1986.

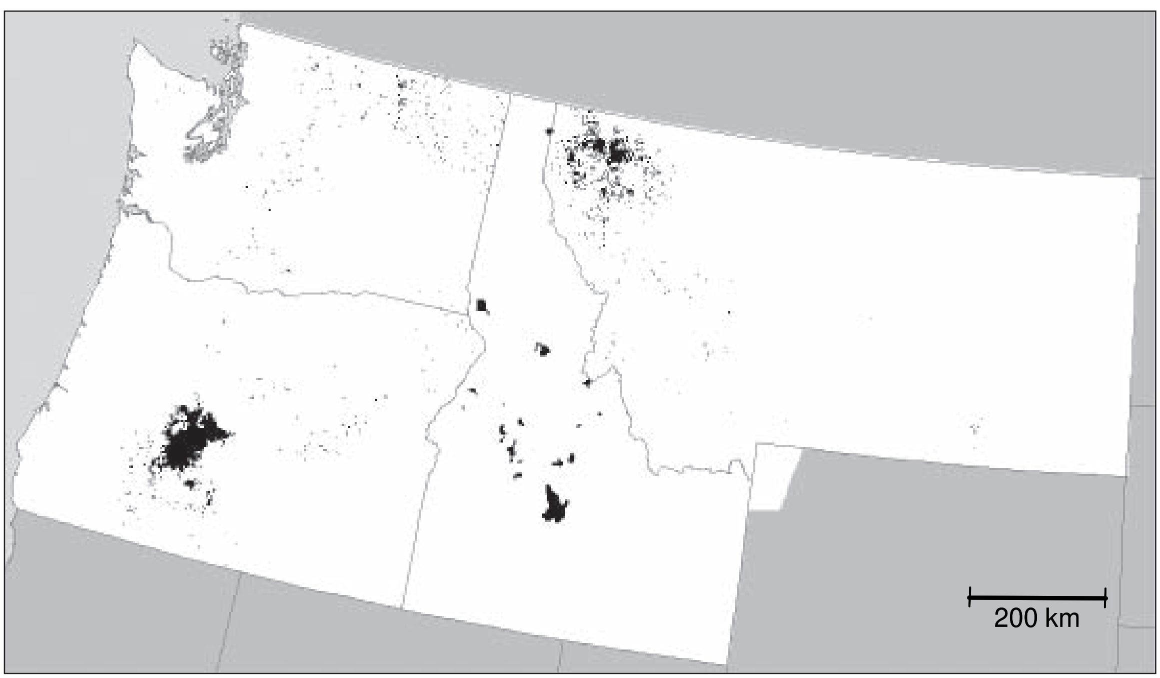


Figure 2h.—Area damaged by mountain pine beetle in 1987.

Figure 2i.—Area damaged by mountain pine beetle in 1988.

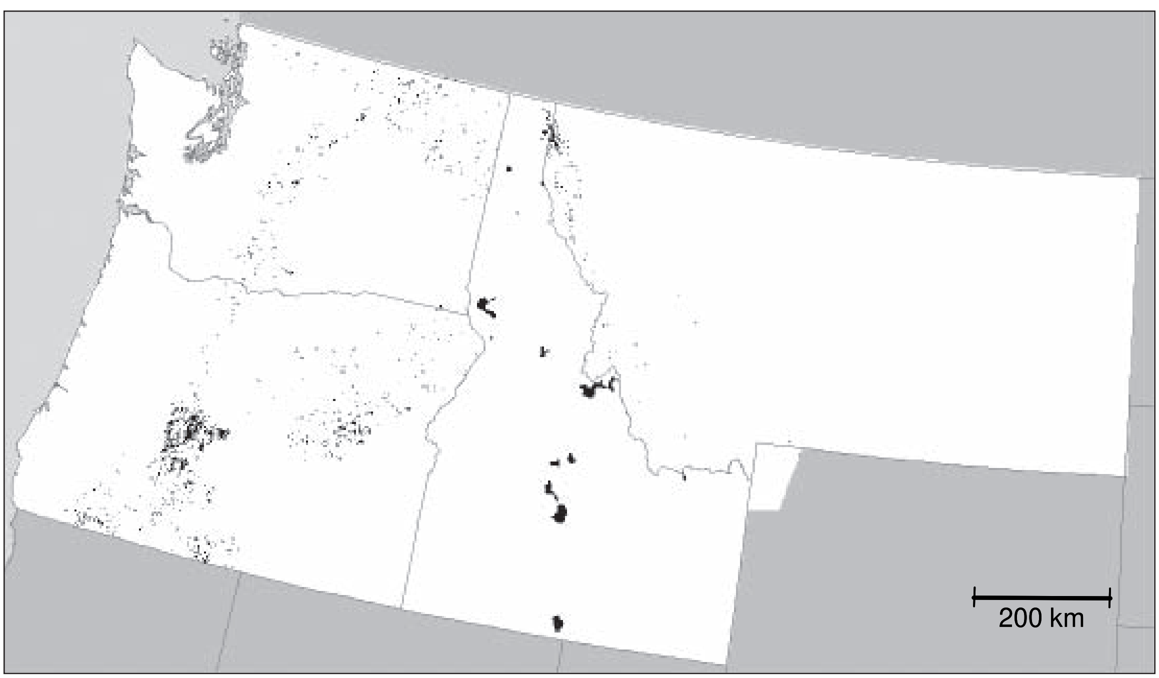


Figure 2j.—Area damaged by mountain pine beetle in 1989.

Figure 2k.—Area damaged by mountain pine beetle in 1990.

Figure 2l.—Area damaged by mountain pine beetle in 1991.

Figure 2m.—Area damaged by mountain pine beetle in 1992.

Figure 2n.—Area damaged by mountain pine beetle in 1993.

Figure 2o.—Area damaged by mountain pine beetle in 1994.

Figure 2p.—Area damaged by mountain pine beetle in 1995.

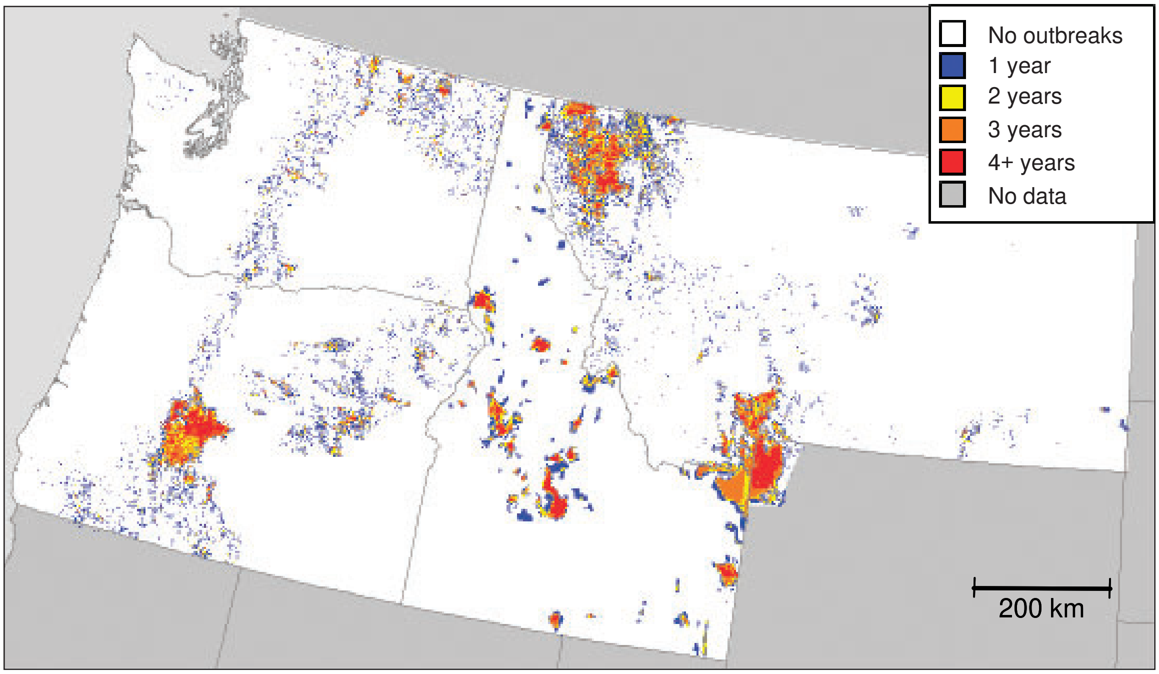


Figure 2q.—Frequency of outbreaks by mountain pine beetle from 1980 to 1995.

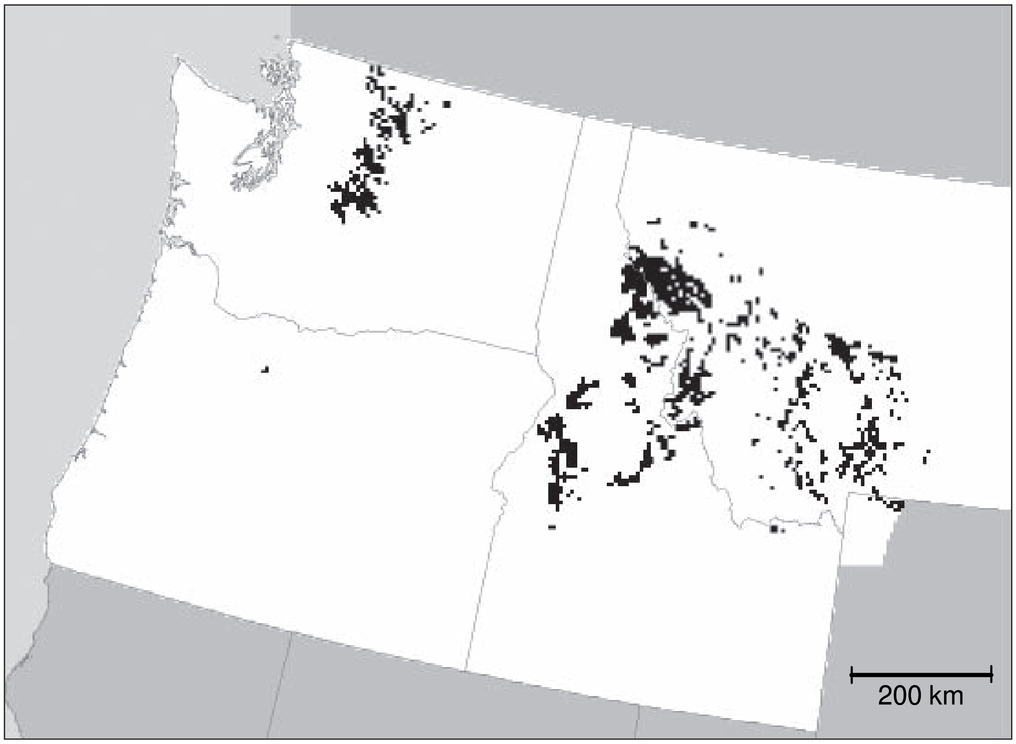


Figure 3a.—Area defoliated by western spruce budworm in 1977.

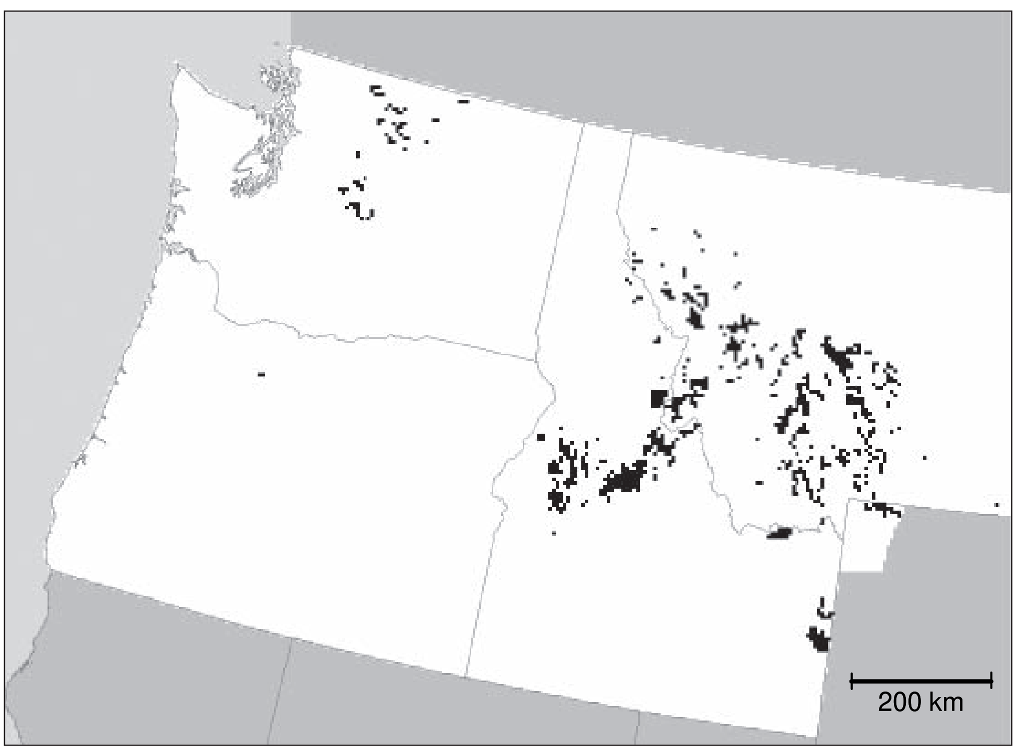


Figure 3b.—Area defoliated by western spruce budworm in 1978.

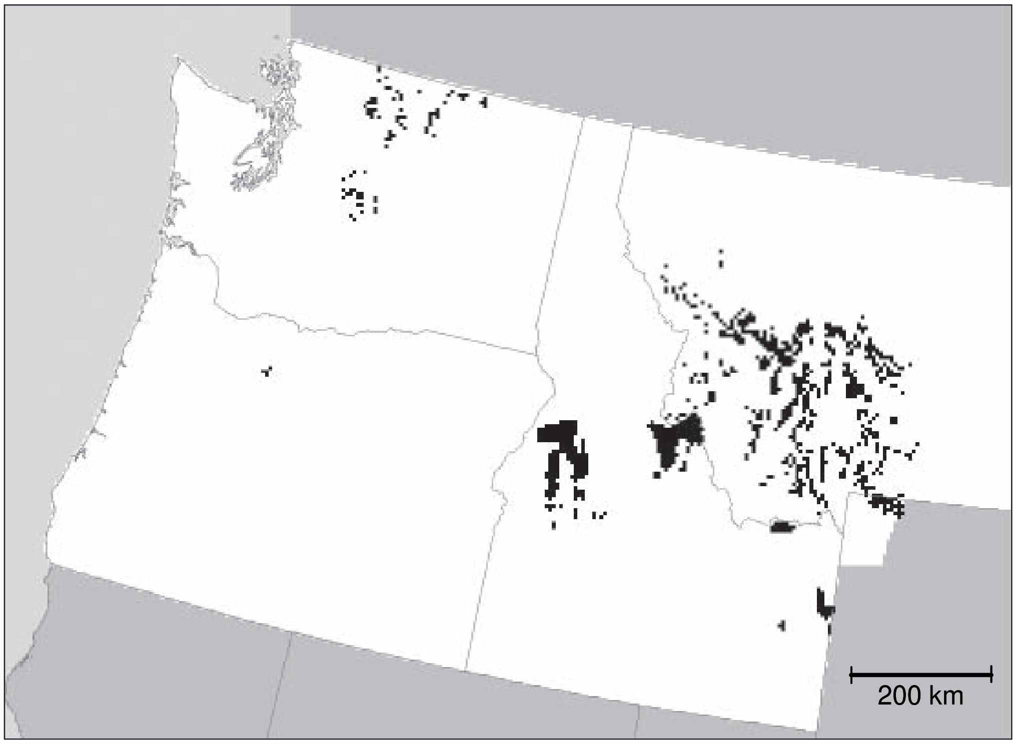


Figure 3c.—Area defoliated by western spruce budworm in 1979.

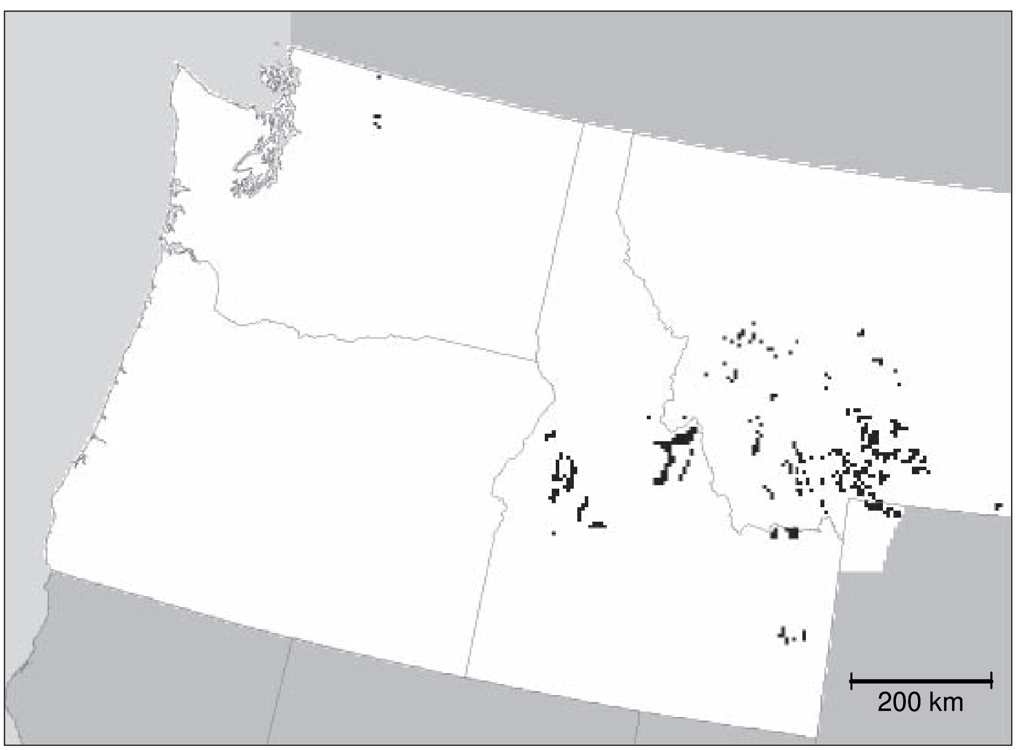


Figure 3d.—Area defoliated by western spruce budworm in 1980.

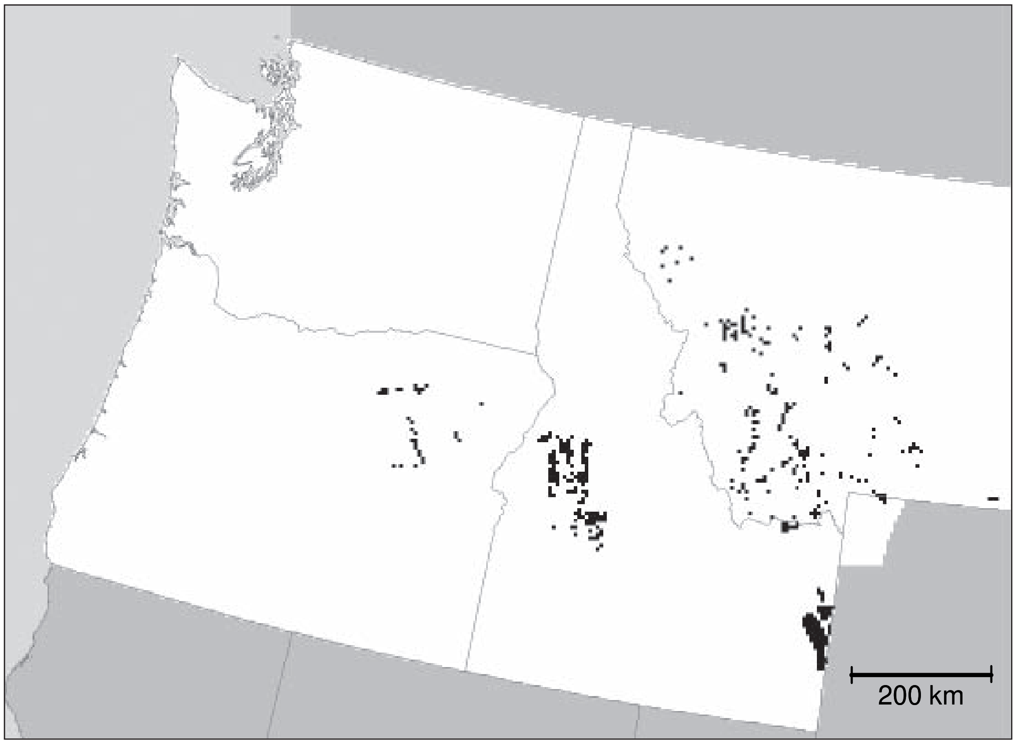


Figure 3e.—Area defoliated by western spruce budworm in 1981.

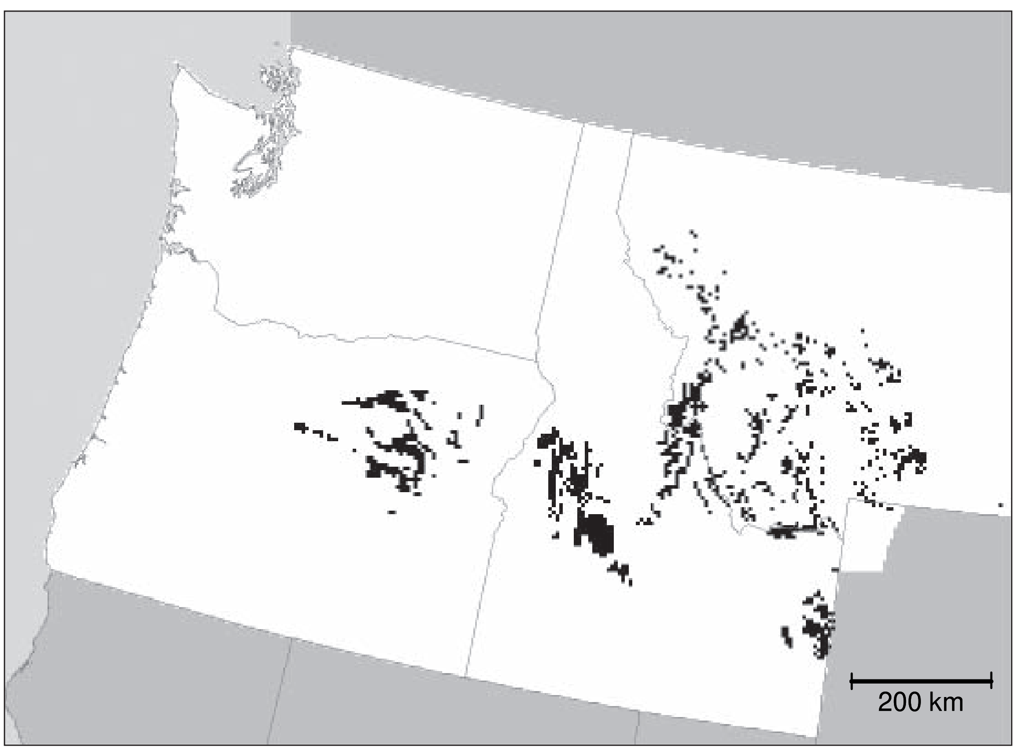


Figure 3f.—Area defoliated by western spruce budworm in 1982.

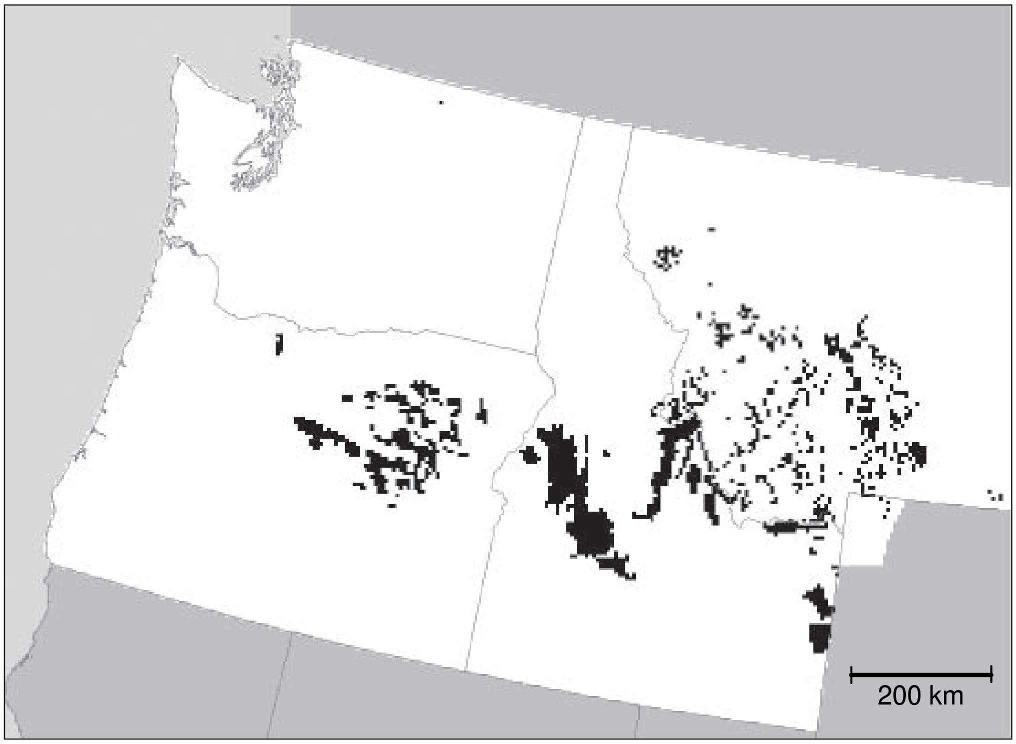


Figure 3g.—Area defoliated by western spruce budworm in 1983.

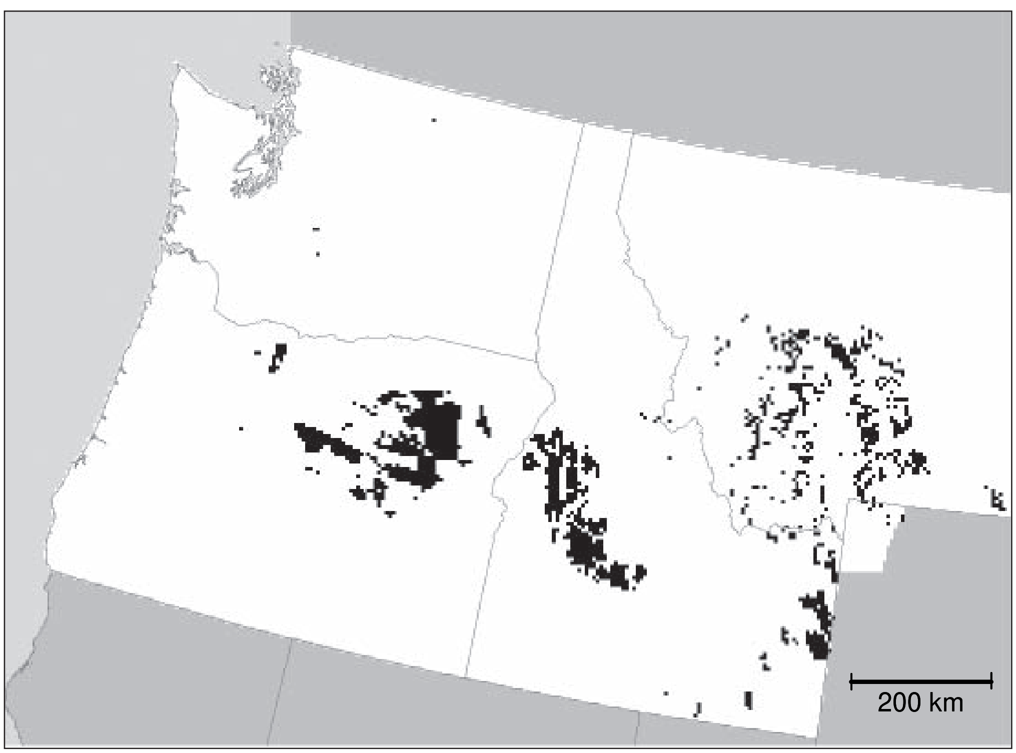


Figure 3h.—Area defoliated by western spruce budworm in 1984.

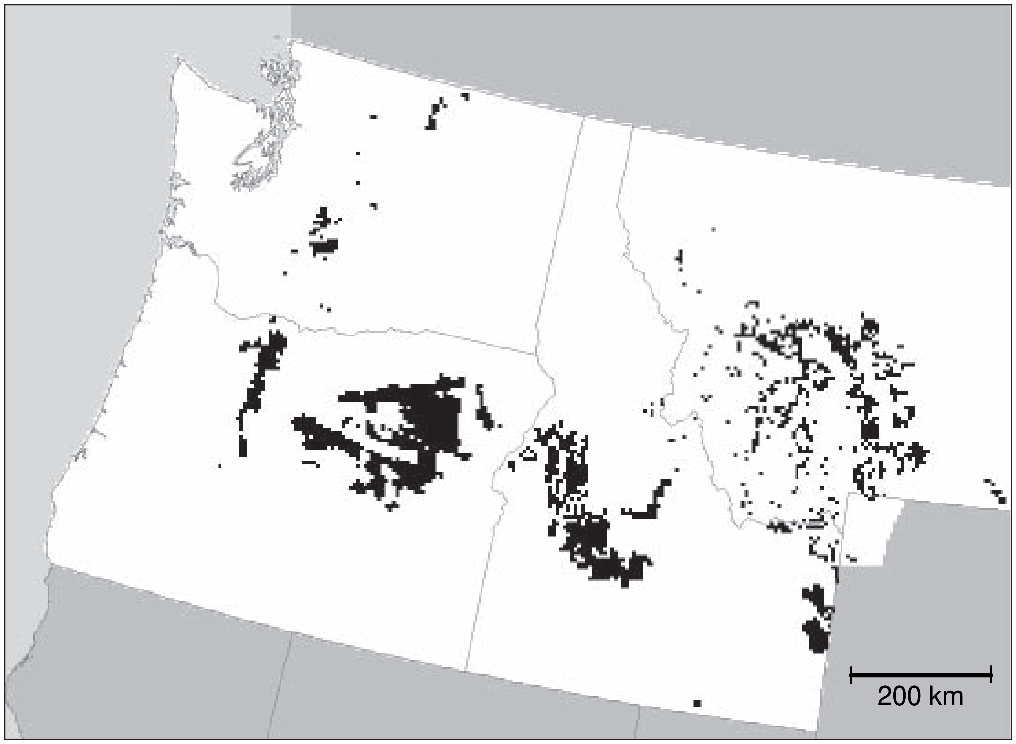


Figure 3i.—Area defoliated by western spruce budworm in 1985.

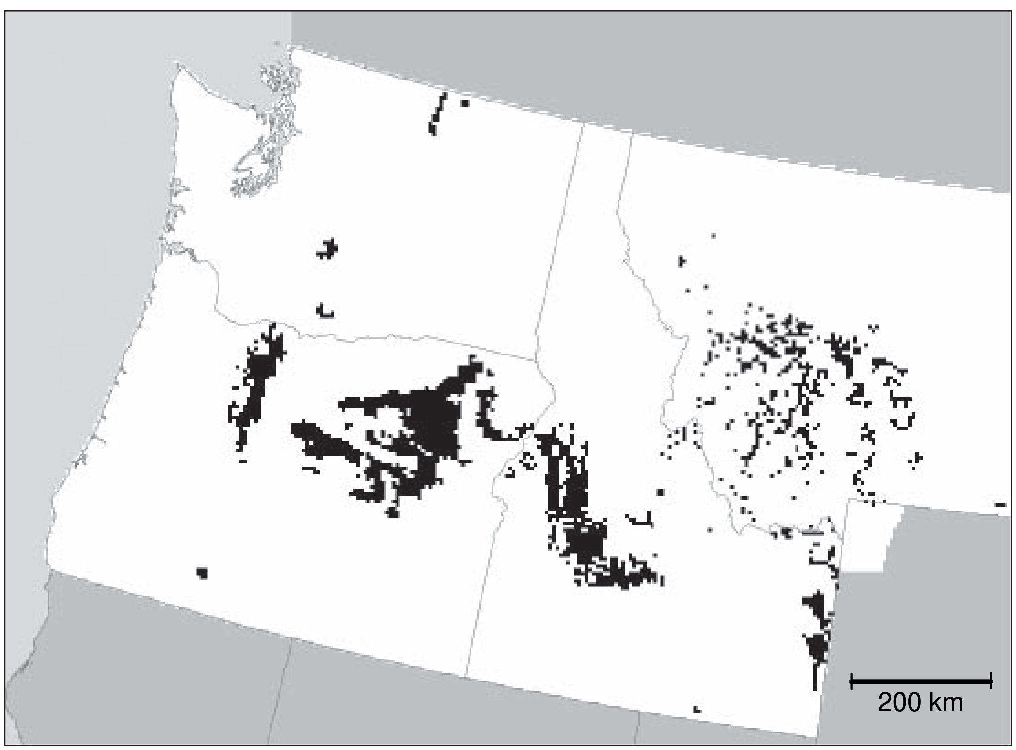


Figure 3j.—Area defoliated by western spruce budworm in 1986.

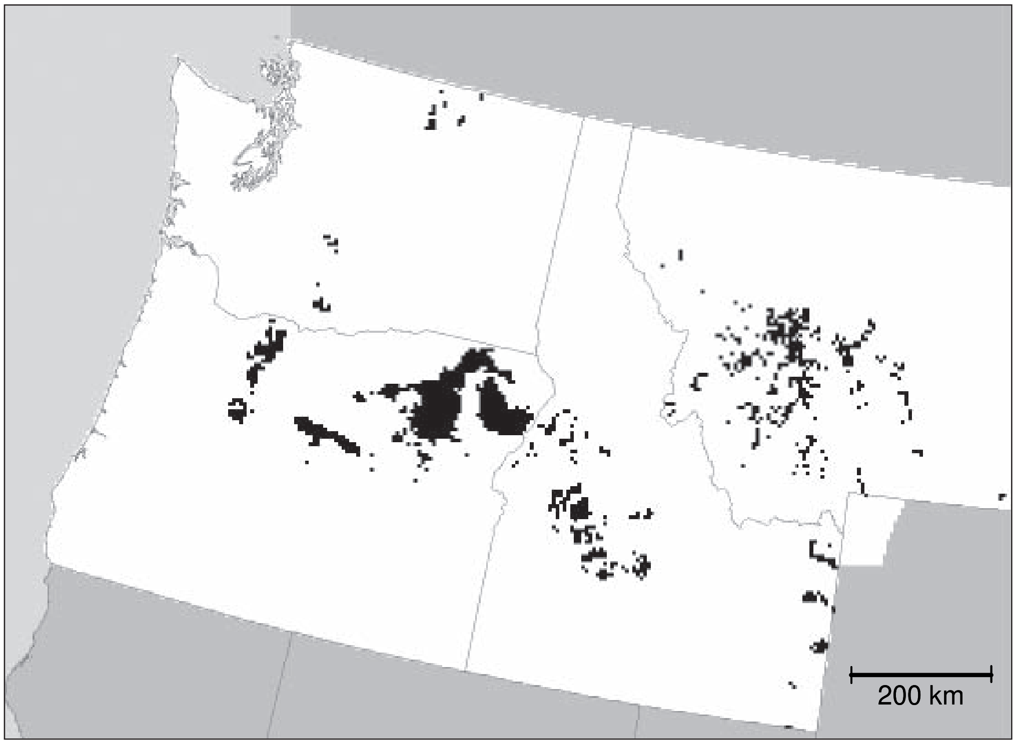


Figure 3k.—Area defoliated by western spruce budworm in 1987.

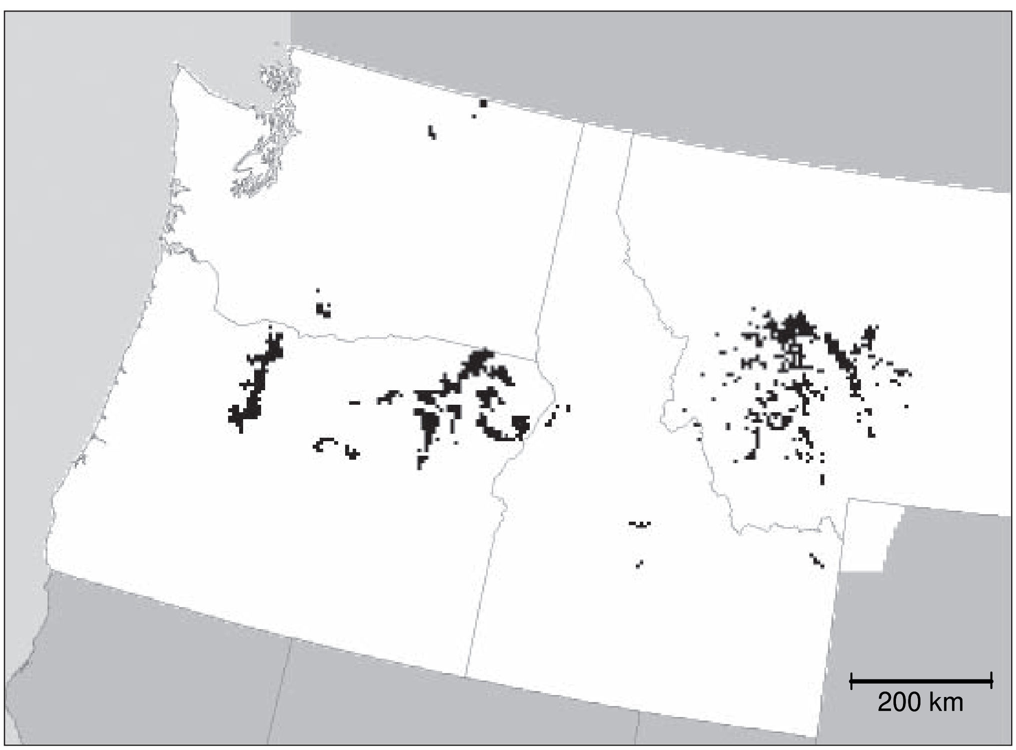


Figure 3l.—Area defoliated by western spruce budworm in 1988.

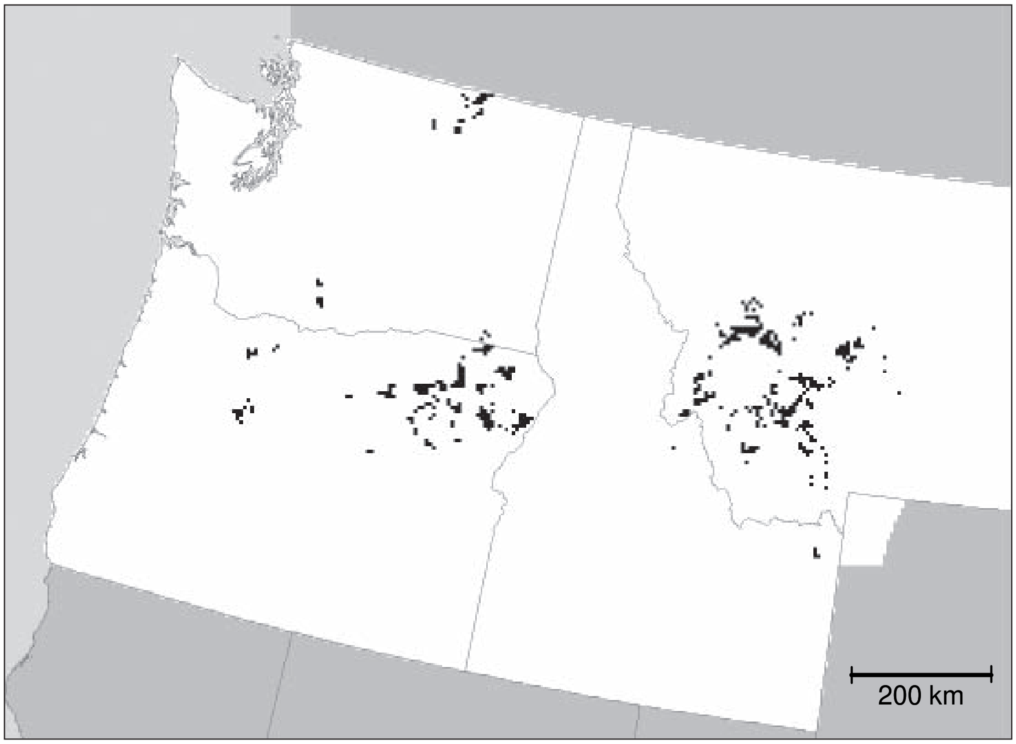


Figure 3m.—Area defoliated by western spruce budworm in 1989.

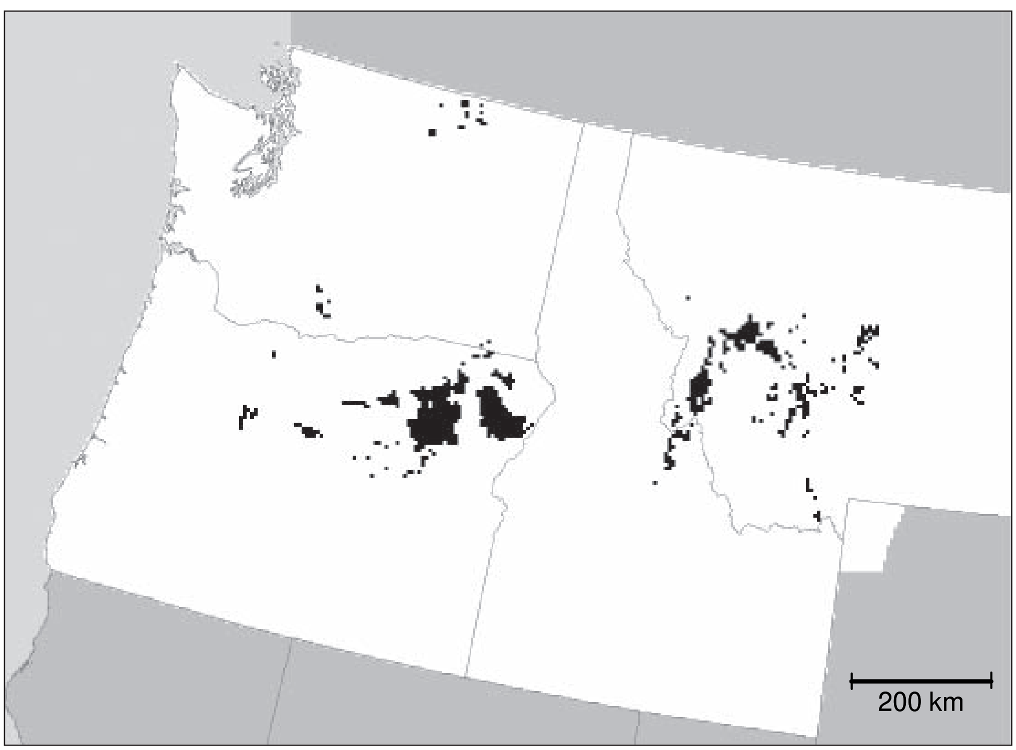


Figure 3n.—Area defoliated by western spruce budworm in 1990.

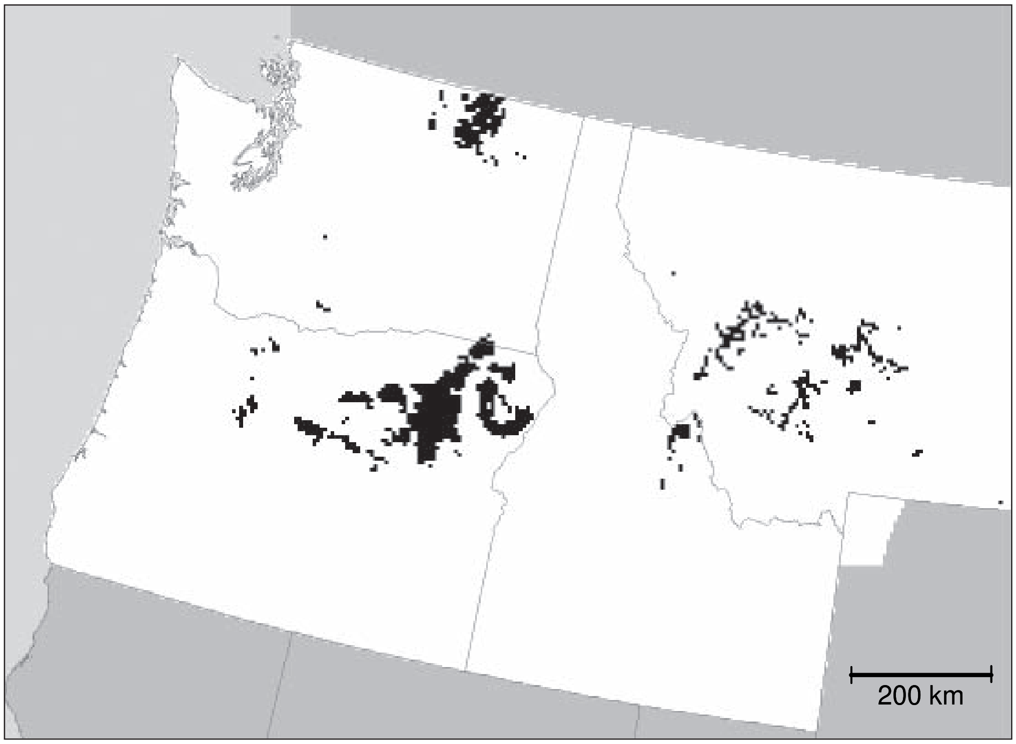


Figure 3o.—Area defoliated by western spruce budworm in 1991.

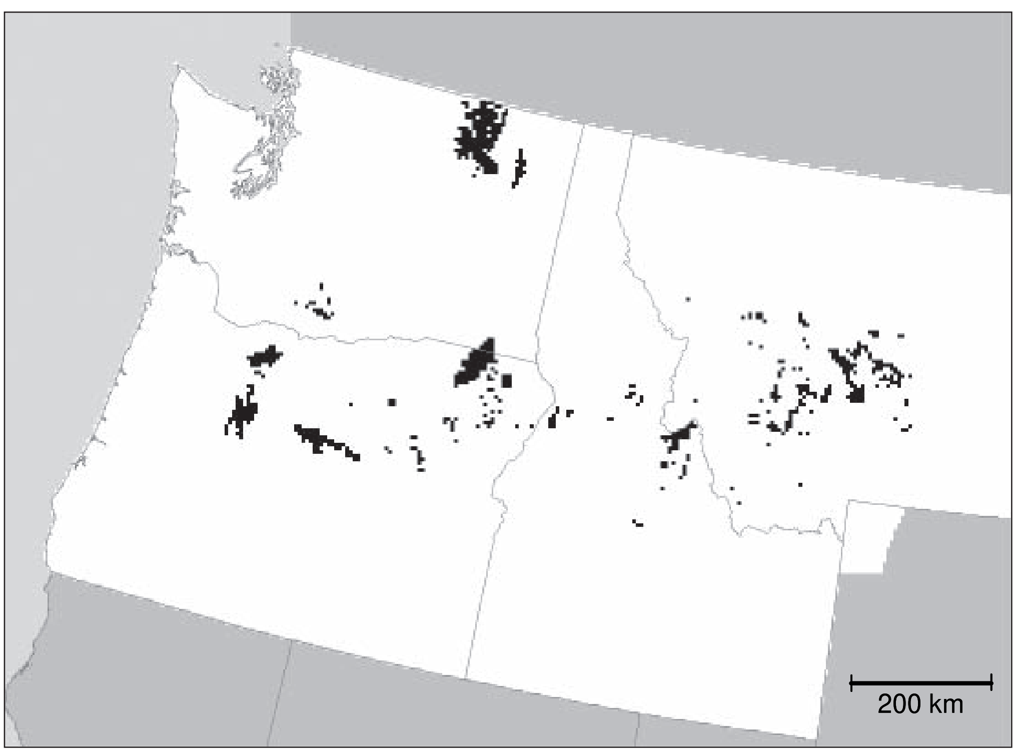


Figure 3p.—Area defoliated by western spruce budworm in 1992.

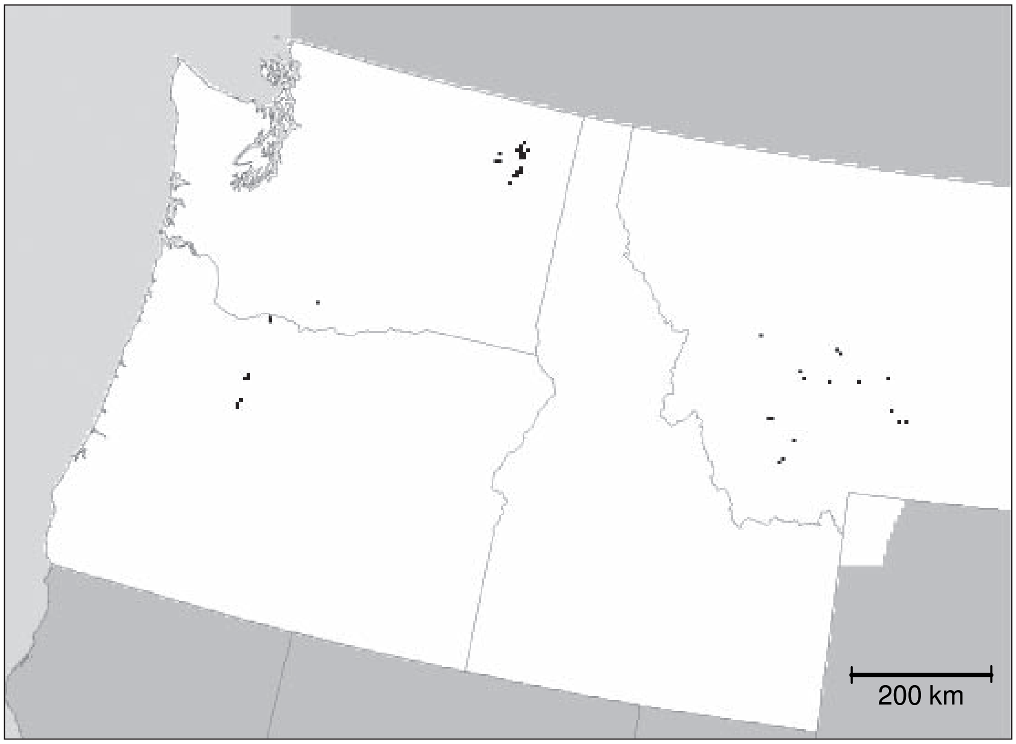


Figure 3q.—Area defoliated by western spruce budworm in 1993.

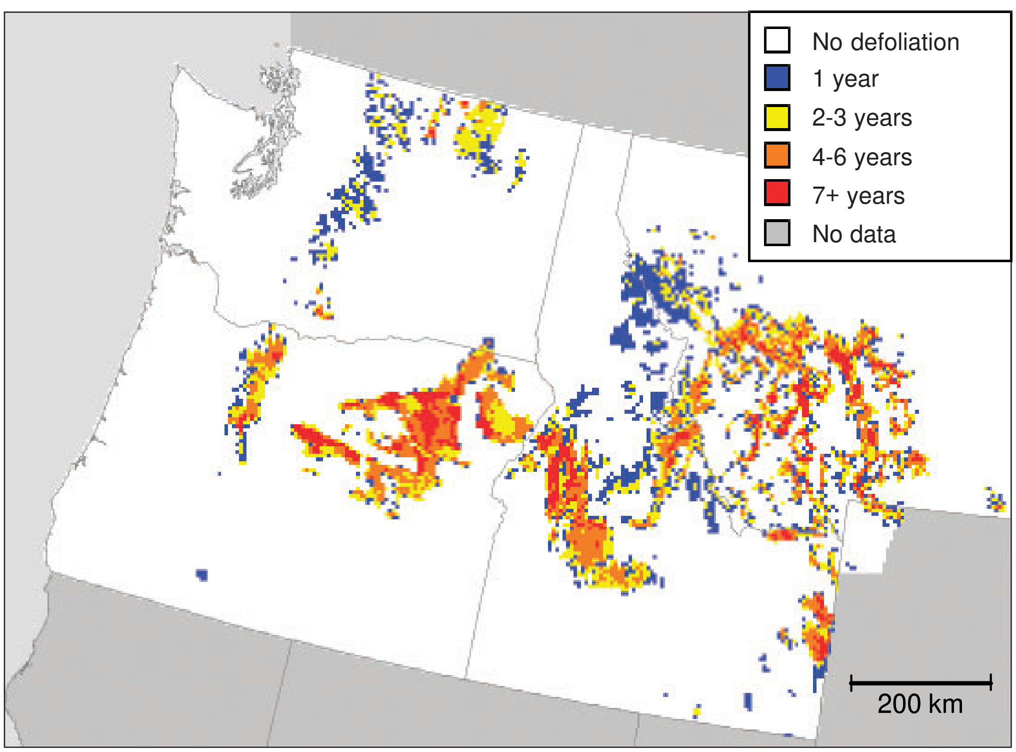


Figure 3r.—Frequency of defoliation by western spruce budworm from 1977 to 1993.

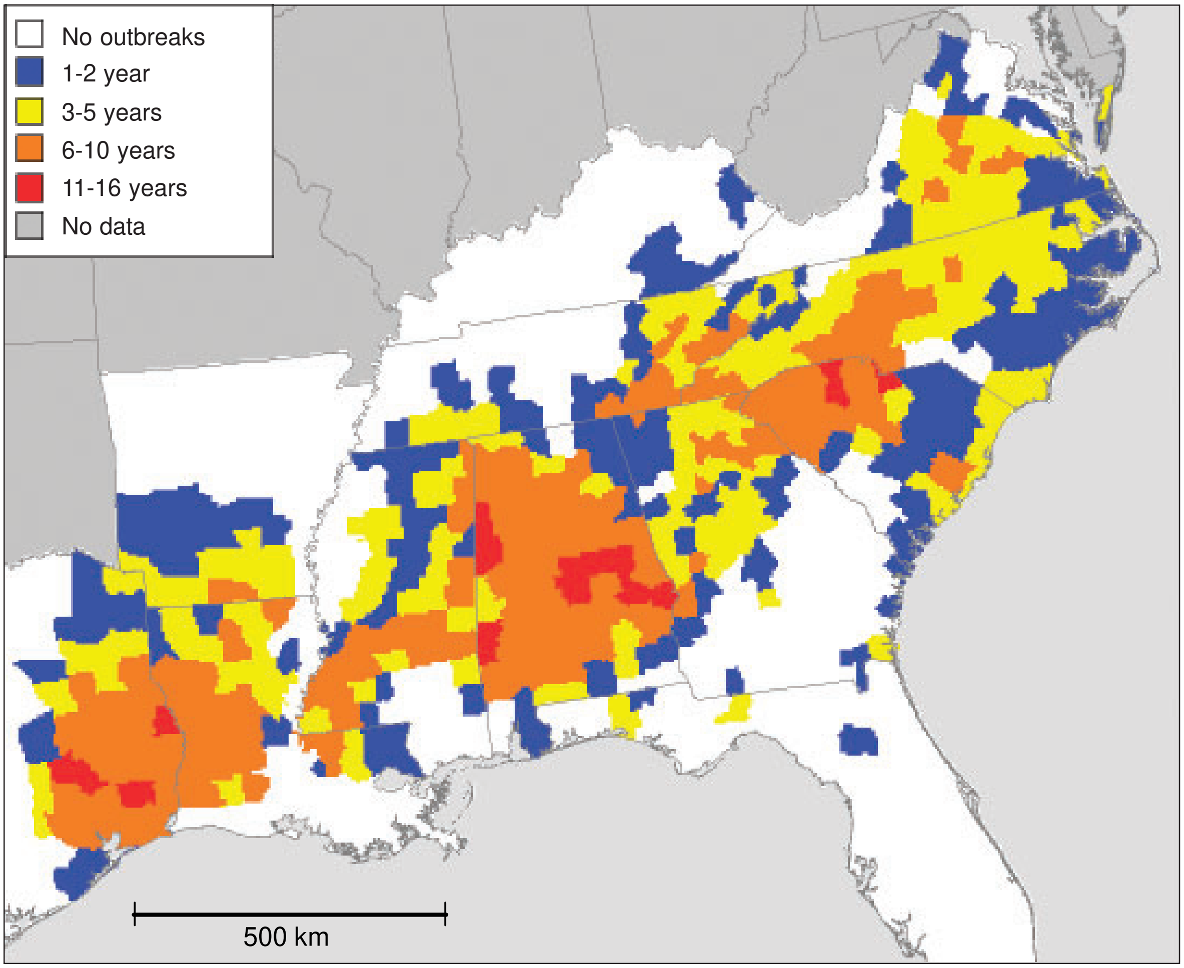


Figure 4.—Frequency of outbreaks by southern pine beetle from 1973 to 1994.

Williams, David W.; Birdsey, Richard A. 2003. **Historical patterns of spruce budworm defoliation and bark beetle outbreaks in North American conifer forests: an atlas and description of digital maps.** Gen. Tech. Rep. NE-308. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 33 p.

This atlas presents maps of historical defoliation by the eastern and western spruce budworms and historical outbreaks of the mountain and southern pine beetles during the past half century. The maps encompass various regions of the conterminous United States and eastern Canada. This publication also serves as documentation for an extended set of digital maps, which are available on our website. The digital maps are useful for investigating spatial dynamics of insect populations and for providing pest disturbance inputs to spatially explicit forest simulation models.

Keywords: *Choristoneura fumiferana*, *Choristoneura occidentalis*, *Dendroctonus frontalis*, *Dendroctonus ponderosae,* Lepidoptera, Tortricidae, Coleoptera, Scolytidae, maps, spatial dynamics, disturbance, vegetation models, Canada

Headquarters of the Northeastern Research Station is in Newtown Square, Pennsylvania. Field laboratories are maintained at:

Amherst, Massachusetts, in cooperation with the University of Massachusetts

Burlington, Vermont, in cooperation with the University of Vermont

Delaware, Ohio

Durham, New Hampshire, in cooperation with the University of New Hampshire

Hamden, Connecticut, in cooperation with Yale University

Morgantown, West Virginia, in cooperation with West Virginia University

Parsons, West Virginia

Princeton, West Virginia

Syracuse, New York, in cooperation with the State University of New York, College of Environmental Sciences and Forestry at Syracuse University

Warren, Pennsylvania

"Caring for the Land and Serving People Through Research"