2009 Project Abstract
For the Period Ending June 30, 2011

PROJECT TITLE: Projecting Environmental Trajectories for Energy-Water-Habitat Planning
PROJECT MANAGER: Peter Reich
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2009, Chp. 143, Sec. 2, Subd. 7b

APPROPRIATION AMOUNT: $ 180,000

Overall Project Outcome and Results

Just as weather flows across the surface of the earth, so does climate—only much more slowly. Understanding the flow of climate is of particular importance in Minnesota because Minnesota encloses the junction of the three great ecosystems of North America—western prairie, northern needle-leaf forests, and eastern broad-leaf forests. Conditions here are particularly sensitive to local changes, and therefore can also be indicators for the nation as a whole.

We applied new methods for understanding this flow of climate, in terms of direction and speed, to actual historical Minnesota weather data. Utilizing established data on both average temperature and total precipitation, we found the lines along which precipitation and temperature do not change and where those lines intersect across Minnesota's landscape. Tracking the advancement of an intersection over time, artifacts of historic importance on climate are identifiable, such as the beginning and end of the dust bowl era. For the present and future, the data show climate in recent years moving northward at a few miles per year.

Results have two major implications, first, as a new confirmation of rate of climate shifts from projections based on global circulation models, and second, as a fine-scale mapping of climate migration in Minnesota. In addition to the average migration, we found differences between longitudinal and lateral migration and differences within Minnesota's ecoregions.

This report outlines the significance of climate migration on habitat for trees, tree pests and diseases, and insects in Minnesota. The project has spawned future research to apply the implications of climate flow, such as how it relates to degree days and other agricultural parameters for the bioenergy industry.

A public product of this project is the Climate Tracker, found on the project website, http://www.cbs.umn.edu/climatetracker. Climate Tracker allows citizens to follow the flow of climate at any point in Minnesota over the past century—where it has been and where it is going.

Project Results Use and Dissemination

This was a two-year project. Its first year involved data assembly, algorithm validation, analysis, and preparation of preliminary maps and tables. In its second year, results were correlated with ecological, hydrological, physical, and social aspects. Included in the second year are a final report, public presentations, and web dissemination, which can be found at http://www.cbs.umn.edu/climatetracker. This website is designed to be user-friendly, useful, and interesting to both scientists and the general public. The interactive Climate Tracker application was developed as a novel way to dynamically view a century of data at a glance, while the brief video introduction presents information in a broader context and allows visitors to the website to meet some of the project researchers.

Future publications in scientific journals are expected to result from this project. Impacts of shifting climate on crops important to Minnesota's economy are being explored through collaborations with the Department of Agronomy and Plant Genetics at the University of Minnesota. A collaboration with the University of Minnesota's Department of Forest Resources is considering the interaction of climate and tree growth, tree ranges, and tree pests. A methods paper is underway documenting the methodology used in this project and comparing the resulting climate velocities with those found using Global Circulation Models.

Environment and Natural Resources Trust Fund 2009 Work Program
Final Report

Date of Report: October 31, 2011
Final Report
Date of Work Program Approval: June 16, 2009
Project Completion Date: June 30, 2011

I. PROJECT TITLE: Projecting Environmental Trajectories for Energy-Water-Habitat Planning

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Location: Saint Paul

Total Trust Fund Project Budget:	**Trust Fund Appropriation**	**$**	**180,000**
Minus Amount Spent:		**$**	**174,039**
Equal Balance:		**$**	**5,961***

* See budget notes at end of section IV.

Legal Citation: M.L. 2009, Chp. 143, Sec. 2, Subd. 7b

Appropriation Language:
$180,000 is from the trust fund to the Board of Regents of the University of Minnesota to combine detailed climatic records of Minnesota with present and past ecosystem boundaries to forecast future fine-scale flow of climate across the state impacting human activities and natural resources.

Amendment Approved [5/2/2011]:
II. and III. FINAL PROJECT SUMMARY:

Just as weather flows across the surface of the earth, so does climate—only much more slowly. Understanding the flow of climate is of particular importance in Minnesota because Minnesota encloses the junction of the three great ecosystems of North America—western prairie, northern needle-leaf forests, and eastern broad-leaf forests. Conditions here are particularly sensitive to local changes, and therefore can also be indicators for the nation as a whole.

We applied new methods for understanding this flow of climate, in terms of direction and speed, to actual historical Minnesota weather data. Utilizing established data on both average temperature and total precipitation, we found the lines along which precipitation and temperature do not change and where those lines intersect across Minnesota's landscape. Tracking the advancement of an intersection over time, artifacts of historic importance on climate are identifiable, such as the beginning and end of the dust bowl era. For the present and future, the data show climate in recent years moving northward at a few miles per year.

Results have two major implications, first, as a new confirmation of rate of climate shifts from projections based on global circulation models, and second, as a fine-scale mapping of climate migration in Minnesota. In addition to the average migration, we found differences between longitudinal versus lateral migration and within Minnesota's ecoregions.

This report discusses the significance of climate migration on habitats for species of trees, tree pests and diseases, and insects in Minnesota. The project has spawned future research to look at the implications of climate flow on the burgeoning bioenergy industry, as it relates to growing degree days and other agricultural parameters. Results obtained as part of this project are outlined here and are being developed in detail for peer-reviewed publication.

A public product of this project is an engaging Climate Tracker tool, found on the project website, http://www.cbs.umn.edu/climatetracker. Climate Tracker allows citizens to follow the flow of climate at any point in Minnesota over the past century.

IV. OUTLINE OF PROJECT RESULTS*:*

Result 1: Data and software assembly, computer runs.

Description:

We used the millions of observations that are combined in established databases of century-long climatological records, available across Minnesota and the bordering regions. From this vast collection we constructed mathematical representations that abstracted the prevailing conditions, interpolating to any point on the ground and at any time within the range of the data. We then used the mathematical representations to determine how regional conditions across Minnesota changed on a fine grid during the 20th century, and then made best estimates of how they are expected to change in the foreseeable future. We paid special attention to areas that could be sensitive to change, such as the historical prairie-forest border.

Amendment Approved 5/2/2011:

Summary Budget Information for Result 1: **Trust Fund Budget: $ 86,054**
Amount Spent: $ 86,054
Balance: $ 0

Deliverable	**Completion Date**	**Budget**
1. ***Data assembly, unification, database construction***	***11/30/2009***	$43,000
2. ***Software adaptation and automation of pilot programs***	***1/30/2010***	$27,000
3. ***Computer runs and production of working maps and tables***	***6/30/2010***	$16,054

Result Completion Date: 06/30/2010

Final Report Summary:

Assembly of daily data

The U.S. Historical Climatology Network (USHCN) is a group of 1219 stations, 33 in Minnesota, spread across the 48 contiguous states drawn from the U.S. Cooperative Observer Network. The USHCN was developed as a collaboration between NOAA's National Climatic Data Center (NCDC) and the Department of Energy's Carbon Dioxide Information Analysis Center (CDIAC). The stations produce an accurate and modern data set of daily values for maximum and minimum temperatures, precipitation, snowfall, and snow depth. Monthly values are available for maximum, minimum, and average temperature and total monthly precipitation.

The project was designed at the outset using USHCN daily data, and arrays were created and formatted to organize the voluminous data for rapid retrieval. Careful data auditing showed, however, a tradeoff between minimum number of data-days and number of months that met minimum requirements (Figure 1). In addition, the daily data contained no adjustments for biases resulting from historical changes in instrumentation and observing practices. Ongoing work at NCDC is now developing adjustments for daily maximum and minimum temperatures (Menne et al., 2011), and we look forward to a daily derived product in the future.

The USHCN Version 2 serial monthly data release used in this study is the most recent update to the USHCN datasets. Version 2 data were produced using a new set of quality control and homogeneity assessment algorithms. Two papers (Menne and Williams, 2009 and Menne et al., 2009) provide an overall description of the adjustment methods as well as an assessment of the Version 2 maximum and minimum temperature trends. The USHCN V2 website provides a brief summary of the processing steps at http://cdiac.ornl.gov/epubs/ndp/ushcn/monthly_doc.html.

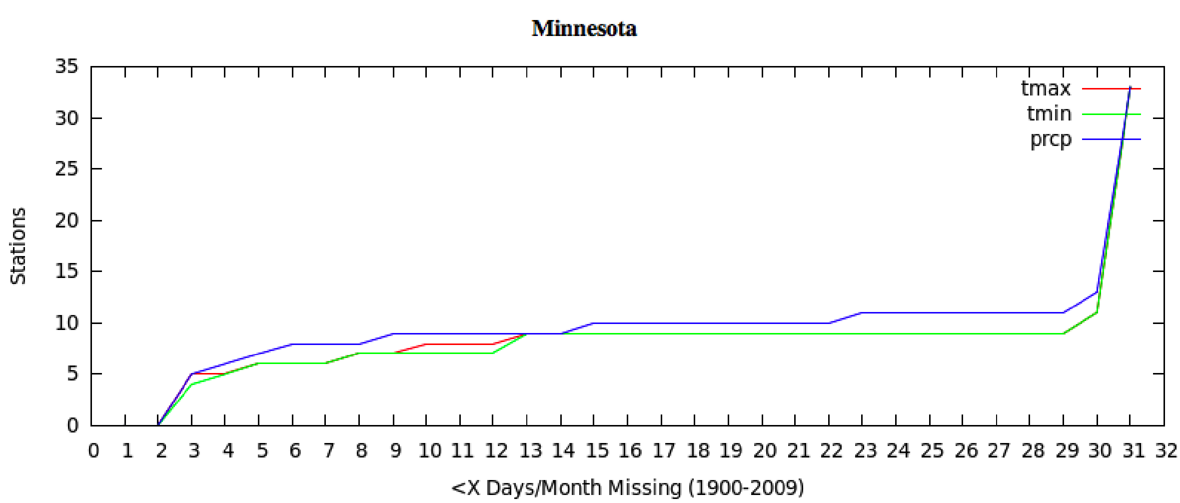


Figure 1. Daily data presented a tradeoff between minimum number of data days required for analysis and number of months that meet that requirement.

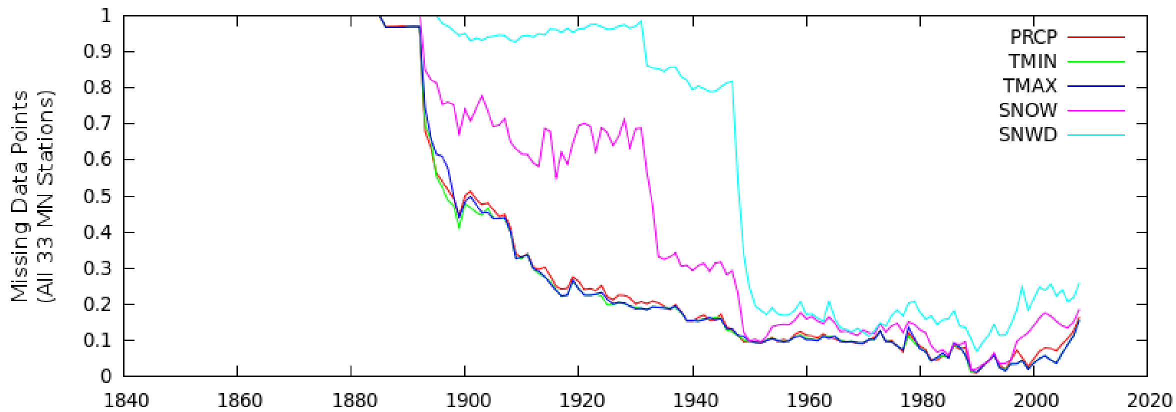


Figure 2. The amount of missing data as a function of time. Excessive missing data early in the record made fitting the daily data difficult. Monthly data did not have this problem.

Assembly and automation of monthly data

After acquiring data on total precipitation, maximum, minimum, and average temperature for all of Minnesota's USHCN weather stations, they were audited and formatted for processing. The numerical surface-fitting algorithms of the pilot programs were automated to run without manual assistance. In addition, the data preparation algorithms were coded in a standard format that can be publicly distributed and they were adapted to the expanded conditions of the present project.

Production of working maps and tables

Trial computer runs and prototype maps were constructed for testing the data and the programs. Software memory allocation and other technical methods used in the pilot program were streamlined to forms that are universally accessible. This is to facilitate distribution of the program and allow others to adapt the programs to new situations. Scaling of latitude and longitude and the generation of geographic Lambert Conical Orthographic projections were incorporated into the climate tracking component of the software.

Feedback to climate agencies

An incidental benefit of this project was feedback we were able to provide to the climate agencies and other groups who collect and maintain the climate data. Such feedback will reduce problems for other researchers and may considered part of the project's documentation and legacy. Feedback is detailed below.

An inconsistency between the USHCNv2 Monthly Data's documentation and file names was identified. The inconsistency prevented reliable matching between USHCN climate stations and their data; the USHCN welcomed this feedback and corrected this problem.

The USHCNv2 Monthly Data's documentation concerning the calculation of annual means was found to be ambiguous; it was unclear whether annual means were calculated as a separate product or as the mean of a given year's monthly means. The USHCN has resolved this ambiguity in their documentation.

A less important problem was the location information for the USHCN stations. The USHCN releases GPS coordinates for the stations in decimal degrees to three digits of accuracy and does not document the geodesic reference of the coordinates. Minnesota's climate station near the town of Ada, for instance, is located at 47.299N, 96.516W. At this level of accuracy, it is possible to locate the station to within 250-350 feet. Our results are robust against such small inaccuracies in siting, but this lack of precision could confound algorithms designed to automatically unbias station data. We provided this information to the USHCN for their consideration.

Canada's Climate Services' National Climate Data and Information Archive provides Canadian Daily Climate Data (CDCD) in a compressed binary format along with a DOS program to extract the data. This program is not well-suited to mass analysis of climate data, requiring the individual extraction of each station's data. Upon request, Climate Services provided the format of the binary files. The file they provided had been written in 1993 and contained multiple errors and omissions which had gone uncorrected. The CDCD data is divided into climate regions, though no map of these is available in any public archive. Upon request, Climate Services provided a low-quality map and later a high-quality map to address this. An updated set of documentation including this map and resolving the errors and omissions in the original documentation has been produced. This was provided to Climate Services and they will add it to their formal documentation. The information will also be made publicly available on this project's website.

Environment Canada, provides a set of monthly climate data for approximately 200 temperature stations and 400 precipitation stations. The documentation for that dataset, the Adjusted and Homogenized Canadian Climate Data (AHCCD), does not specify the units for the data, which is broken up into many different files. In the case of precipitation data, this prevents automated processing of the data. In the case of temperature data, there is ambiguity that introduces uncertainty in processing. A request for clarification was made in late July 2011, and changes are expected to the AHCCD documentation as a result.

The OpenLayers project, which we use in this project to display results interactively, is developing a JavaScript framework for dynamic display of GIS data on websites. Version 2.11, Release Candidate 1 (2.11RC1) was used extensively in developing the analysis tools for the later stages of this project, along with the project's website. To reduce visual clutter, the climate stations are grouped by proximity when they are displayed on the map; however, it is sometimes necessary to break these groups apart. OpenLayers did not provide a way of doing this, so a module was developed as part of this project. It is being evaluated by the OpenLayers group for inclusion in Version 2.12 of their product.

Result 2: Analysis, documentation, and publication.

Description:
Beginning concomitantly with Result 1, but emphasized after and following from the previous result, we used the working maps and tables to provide information relevant to, and as feasible evaluated, (1) delineation of areas having future potential for renewable bioenergy production, (2) ranges of locally threatened or endangered species, (3) the movement and velocity of climate near particularly vulnerable ecoregions, such as the prairie-forest border in Minnesota, (4) areas of increased dangers of fire and climate-related movement of pests and diseases of trees, both native and exotic, (5) artifacts of major historical shifts in climate in Minnesota.

Amendment Approved: 5/2/2011:

Summary Budget Information for Result 2:		
	Trust Fund Budget	**$ 93,946**
	Amount Spent:	**$ 87,985**
	Balance	**$ 5,961***

* See budget notes at end of section IV.

Deliverable	**Completion Date**	**Budget**
1. ***Correlation with ecological, physical, and local conditions***	***11/30/2010***	$42,000
2. ***Web-based time-lapse video files of results across Minnesota***	***1/30/2011***	$11,000
3. ***Analysis and reporting***	***6/30/2011***	$40,946

Result Completion Date: 06/30/2011

Final Report Summary:

Stages of analysis

(1) Daily data were collected by the United States Historical Climate Network (USHCN) and processed into smoothed monthly data. This step was performed by the USHCN. However, when we were pursuing the use of daily data, we were required to perform such a step, so it is relevant here.

(2) The monthly data was extracted from the USHCN files in which it was packaged.

(3) A subset of stations, regions, and/or months was selected and 30-year averages, stabilities, growth rates, and other relevant properties were calculated.

(4) Mathematical climatic surfaces were fit to these results.

(5) A set of geographic relevant points on the intersection of the climate surfaces were chosen, mapped to the surfaces, then tracked over time.

(6) Properties of the movement of the points (velocity of a point's entire track, velocity of a portion of its track, indicators of goodness-of-fit) were calculated.

(7) The surfaces and/or tracked points were overlaid on maps of the geopolitical terrain they traversed.

Each of the above steps was distinct in its requirements and different tools were therefore developed for each, using a programming language suitable for each step. Details on the programs, languages, and alternatives for each step are documented below, as a record and as an aid for those who would adapt these methods to other regions of the world.

(1) Generation of monthly data. USHCN daily data, initially hoped to provide valuable insights into discrete, extreme weather events proved untenable to work with for reasons stated earlier in this report. Programs and code for this step were developed by other parties in conjunction with the USHCN. Information on the USHCN generation of monthly data is available on the USHCNv2 Monthly Data website.

(2) Unpacking of monthly data. Throughout the project, the code for this process was written in the programming language C or C++. C compiles to computer code which, appropriately written, is extremely fast and efficient. It also allows excellent management of computer memory. Both of these properties were important, given that the USHCN daily data consumes 1.6GB and that intermediate processing steps require an additional 2-3GB of main memory (RAM). While we ultimately did not employ the daily data, we do not rule out its use in future projects we or others conduct. C is a widely-used and well-understood language. Therefore, when we began work with the monthly data, code was again developed in C. Code to unpack Canada's daily climate data was also developed. This code base is accessible from other programs via function calls and represents a unified module for accessing the climate data of the majority of North America's land mass. The source code is available on this project’s website.

(3) Calculation of averages. The code developed for this step was small, specific to the processing needs of this project, and therefore has a lower probability of reuse. Nonetheless, it is also available on the website.

(4), (5) Fitting of Surfaces/Tracking of Points. Commonalities in these two steps allowed the same language for both and many functions could be shared. The prototype code was developing using William Waite's Stage2 general purpose macro processor to produce Mathematica analysis scripts, the results of which were again passed through Stage2 to develop output suitable for mapping. This required some manual intervention and human judgment. The actual code for surface fitting and intersections was prototyped in Matlab and programmed in Python for speed and generality. The Stage2 pre- and post-processing steps were folded in Step 3 (calculation of averages) and the manual steps were automated to remove the need for human intervention.

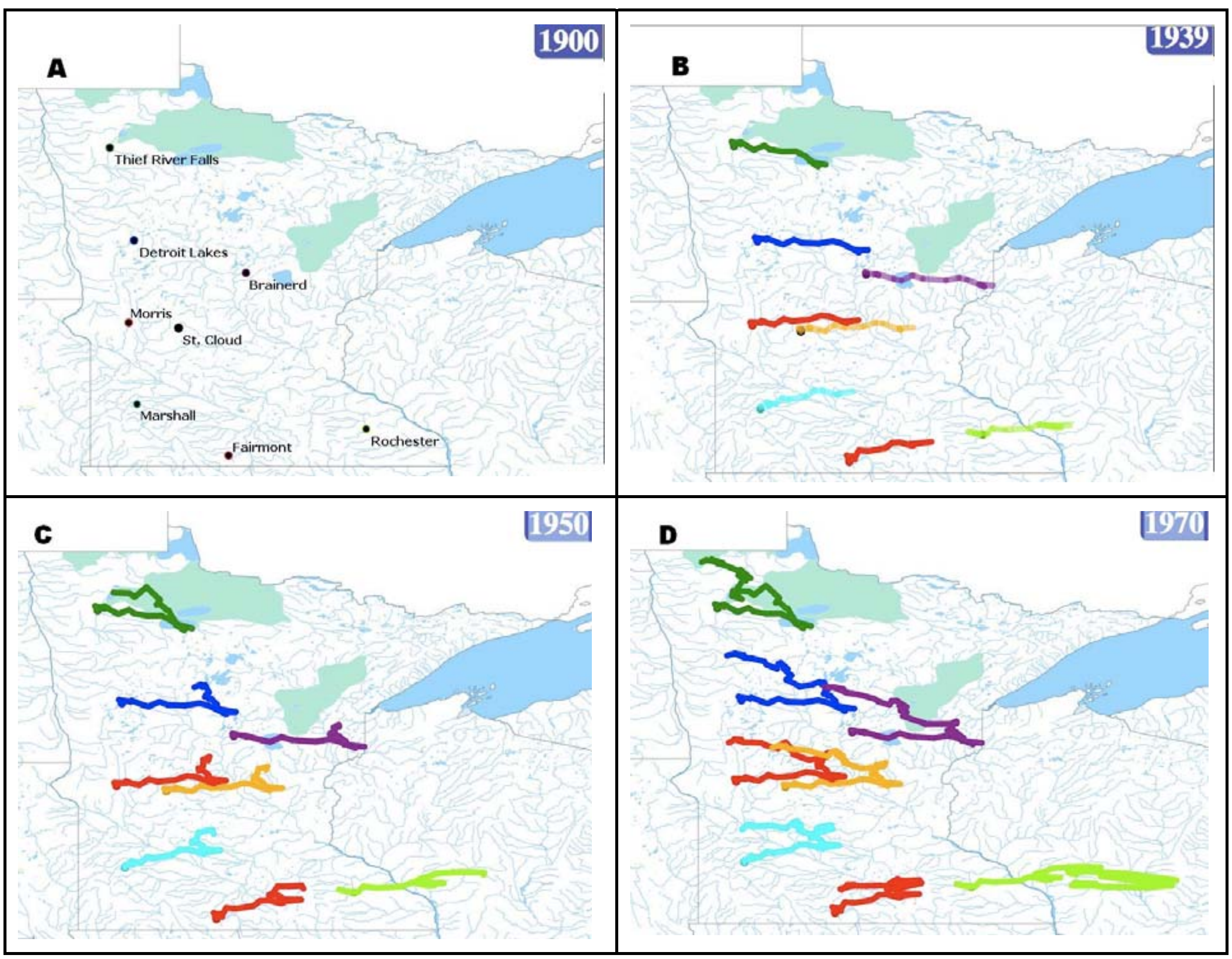
(6) Calculation of track properties. The track was represented by a series of GPS locations, one per year. Great circle distances between each sequential pair of points in the track were calculated in Javascript (see below) to reduce communication times. From these, the overall velocity and directional components of velocities of any subset of the track were calculated.

(7) Map overlay. Finally, we instituted procedures to make the map overlay step as intuitive, useful, accessible, and powerful as feasible, and available by web access. For those wishing to adapt our work to other applications, the technical details are as follows: A client-side

AJAX/Javascript/OpenLayers web application was developed to run with a Unix/Apache/PHP/SQL server stack. On the client-side, the web interface uses the open-source OpenLayers framework to display geopolitical maps of the areas of interest. We supplied the USHCN station information and the locations of all the stations. Specific instances of these were selected and climate surfaces fit (see above) to the selected stations using BASH scripts to run steps 2-4. The researcher may then select any point on the map, thereby initiating another AJAX request to launch a BASH script which runs step 5.The server returns the GPS points of the track. Step 6 is then performed on the client side using Javascript and the OpenLayers framework. Finally, the tracks were displayed using the Openlayers framework and made interactive through Javascript controls on the page. The resulting graphical interface allowed researchers full access to the analysis products of this project while being simple enough for anyone to use.

Artifacts of a moving climate

Parameters were expanded to explore other relevant aspects of a moving climate within participants' areas of expertise, such as forestry, forest pests, agriculture, wildlife, and biomass energy production, especially along ecosystem intersections. Participants targeted perceptible artifacts of climate change trends in related fields, such as the historical velocity of climate movement.



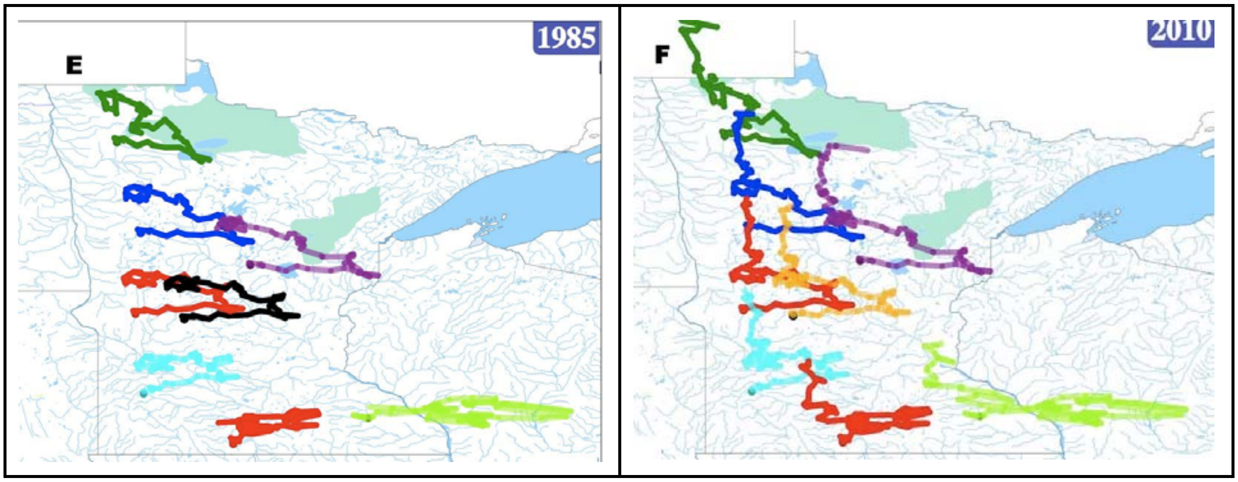


Figure 3A-F. Climate tracks for eight Minnesota cities.

A) Continuous, reliable weather station data, including monthly precipitation and temperature averages, began in Minnesota shortly after 1900 and is now curated by the USHCN. In this figure 30-year climate averages are tracked, originating from eight Minnesota cities representing some of the diverse environments throughout the state. A lateral movement is a change in precipitation (i.e. an eastern movement indicates dry, prairie rainfall patterns moving into a forest environment), and a north or southward movement indicates climatic temperature changes, where northward movement is warming and southward is cooling.

B) For four decades, from 1900 to 1939, the climate in all eight cities marched to the east at an average rate of 4-5 miles per year. The five southern cities had a small northward component. For example, Fairmont was moving northward at 1.30 miles per year during this period. The three northern cities had a southward component to their trajectories or tracks, averaging between 0.5 and 1.21 miles per year. Interestingly, the eastern extent of all eight climate tracks was reached in synchrony in 1939. In 1940, the tracks double back on themselves, indicating higher precipitation. The Dust Bowl in Minnesota lasted from 1933 through 1940 (Albertson and Weaver, 1944), then ended abruptly when precipitation resumed. These eight climate tracks clearly mirror the progress and sudden end to the climatic dust bowl conditions.

C.) The next decade, from 1940-1950, the climate of southern Minnesota tended to “hover” close to the eastern extent of its track, but in northern Minnesota the climate had already begun its retreat westward. In fact, by 1950 the Thief River Falls climate track had already achieved the entire western movement that it would regain immediately following dust bowl conditions. This suggests that northern Minnesota experienced climatic relief from the Dust Bowl earlier and more steadily than southern Minnesota.

D.) Two decades later, by 1970, the westward-retreating climate in southern Minnesota had caught up with the western movement of northern Minnesota. In terms of precipitation, most climate tracks ended near their original pre-1930s location. However, the temperature component had shifted somewhat northward. From 1900-1970, the northward velocity for all cities was between 0.5 and 1 miles per year.

E) A second period of climatic “hovering” with relative stability was 1970 to 1985. This is visible on the eight cities’ tracks by the tight “knots” where the climate had little net movement in any direction. An isolated, short-term burst from northwest to northeastward around 1988 corresponds to a damaging drought suffered in Minnesota and across the Midwest that year.

F.) In 2010, the climate tracks were heading almost due north. The east and west components were negligible, except for the tracks originating in Thief River Falls moving 1.3 miles per year eastward, and Brainerd, which abruptly added a 3.18 miles per year eastward component in 2009. The reason for this is not yet clear.

Notes: 1.) These tracks can be recreated on the website by loading all 33 Minnesota stations along with stations near MN borders, for a total of approximately 66 stations. See www.cbs.umn.edu/climatetracker for detailed instructions. 2.) The track originating in Rochester (light green) is included to illustrate results of choosing an area near the edge of the selected stations. To create a good fit, choose stations that are evenly distributed around the area of interest, including stations in neighboring states and Canada.

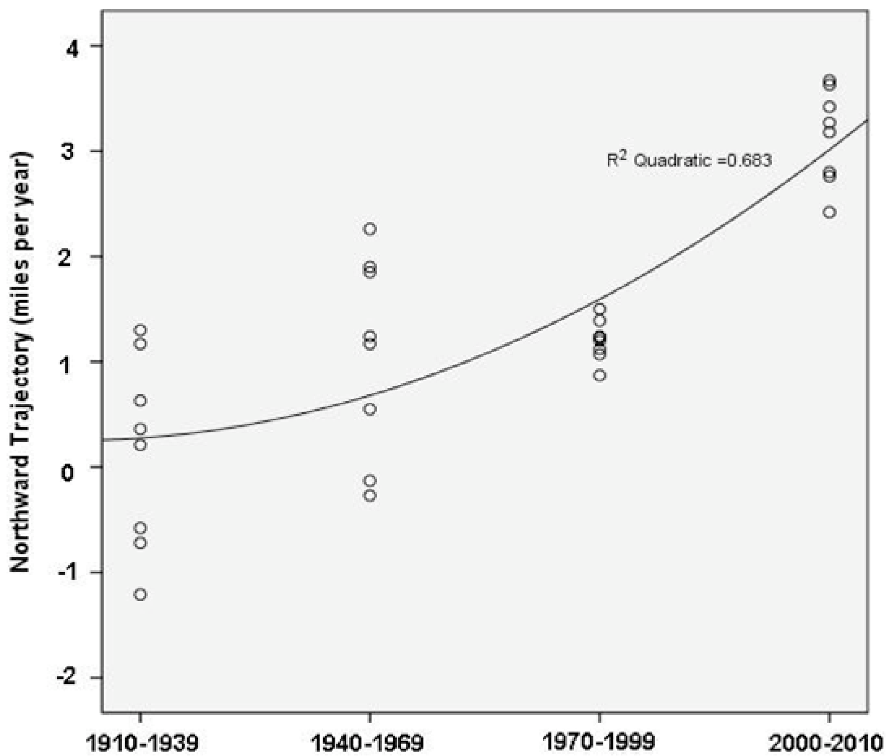


Figure 4a. Northward components of climate trajectory for eight MN cities are plotted for the time ranges indicated. The cities, mapped in Figure 3A, decrease in range of trajectories, and increase in overall speed over time.

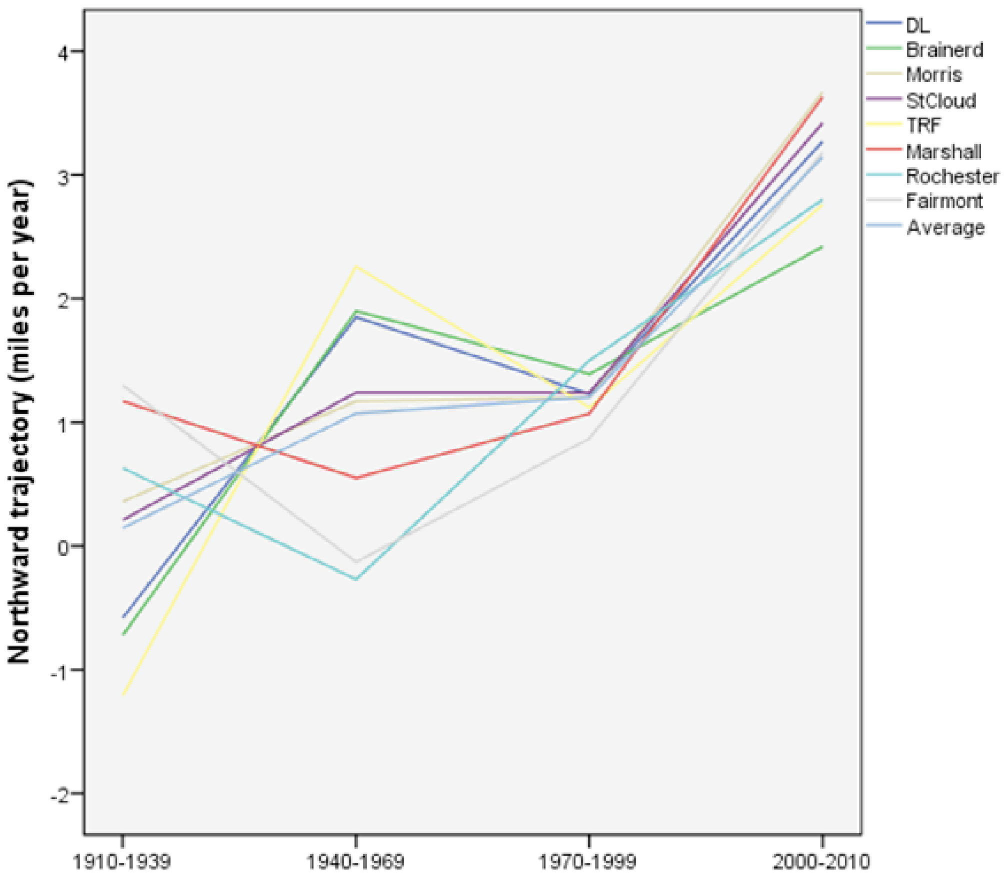


Figure 4b. Northward components of climate trajectory for eight MN cities are plotted for the time ranges indicated. Tracks that were initially moving southward (Thief River Falls, Brainerd, and Detroit Lakes) were decidedly moving northward by the 2000-2010 period.

Loarie et al. (2009) calculated climate velocity---the rate at which a given climate would move across the landscape annually during the present century---under a business-as-usual greenhouse gas emission scenario (IPCC A1B). Although the global mean velocity was projected to be 0.26 miles per year (0.42 km/yr), faster velocities of 0.6-4.0 miles per year were projected in flat areas of continental interiors such as Minnesota. Galatowitsch et al. (2009) estimated climate migration rates of 3.0-3.9 miles per year from SSW to NNE for each of eight ecoregions of Minnesota between 1970-1999 (midpoint, 1985) and 2060-2069 (midpoint, 2065). These indirect estimates for velocity of climate migration through the middle to late 21st century are in accord with the observed rates of northward climate migration in recent years from this project, of approximately 3 miles per year. Thus, this project provides independent confirmation of conclusions based on more abstract global circulation models.

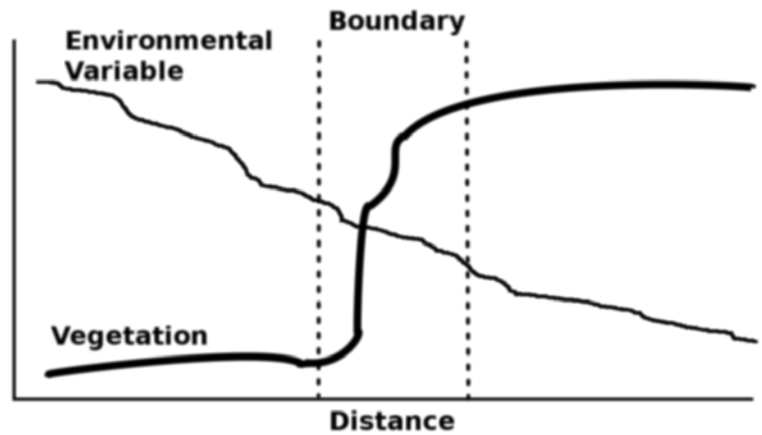


Figure 5: The general form of observations of biome boundaries. Environmental variables, such as precipitation and temperature, vary smoothly over distance, but vegetation, such as percent tree cover, shows a much sharper transition

Other authors (e.g. Danz, 2011; Fagan et al., 2003) have observed sharp changes in vegetation across smooth transitions in climate variables. An example of such observations is depicted in Figure 5. If we combine this observable fact about the world with the mathematics of the Climate Tracker, an interesting result emerges. The slope of a climate surface along a climate track is given in units such as “degrees per meter per year” or “inches of rainfall per meter per year.” Since climate track segments are each a year long, each segment is associated with a value in “degrees per meter” or “inches of rainfall per meter.” Multiplying the reciprocal of this figure (“meters per degree”, “meters per inches of rainfall”) by the derivative of the vegetation function (“% vegetation per meter”) gives an output in “% vegetation per degree” or “% vegetation per inch of rainfall.”

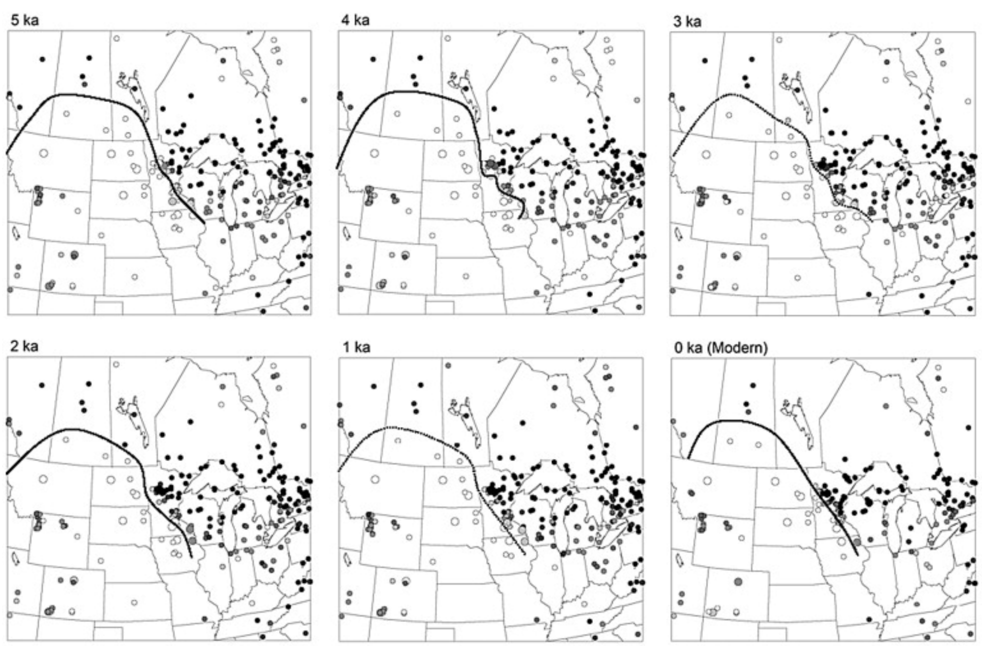


Figure 6. Williams et al. (2009) used fossilized pollen to determine the position of the prairie forest border for the last 11,000 years. This excerpt of their figure shows the boundary’s mobility over time.

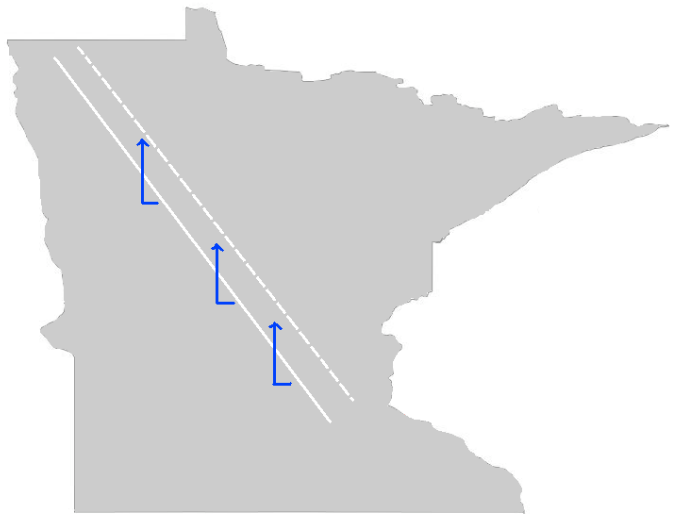


Figure 7. A schematic illustrating how a slight westward climate movement followed by northern movement can actually move the initial prairie forest border (solid line) eastward (dotted line).

Qualitatively, vegetation changes across space are steepest at boundaries, so the effects of fluctuations in climate will manifest themselves strongest and foremost there. In the past, boundaries occurred predominantly at the edges of ecosystems, but, since the effects are general, strong climate forcing should occur at any boundary. As Minnesota's landscape has become fragmented in the past century, this forcing applies to much of the state. On a large scale, the present trend in Minnesota is to push the prairie-forest boundary slightly to the west as the state's climate tracks move west, and to push its southern boundary strongly to the north in accordance with the trends in the climate tracks. However, because the prairie-forest border slants northwest to southeast, the net effect is that the border is moving to the east (Fig. 7).

Implications for state and national parks and other protected places

Minnesota's climate is moving northward at approximately several miles per year. Many individual species, especially plants, migrate much more slowly. However, invasive pests move faster. A worst case scenario for a species is that climate will shift its habitat faster than it can keep up while simultaneously introducing large numbers of predators. Sandel et al. (2011) state that "low-velocity areas are essential refuges for Earth's many small-ranged species." We consider possible outcomes for selected species below, but, for now, take a more general view.

Changing climatic parameters alone are rarely responsible for a species's extinction; rather, it is the impact of these changes on a species's environment.

Figure 8. Climate tracks overlaid on federal lands in Minnesota and surrounding states

Overlaying climate tracks on federal lands in Minnesota and its surrounding states shows that residence times for a particular climate point within any given parcel of protected land are brief. None of the presently protected lands in effected areas of Minnesota would have been sufficiently large to contain the precipitation variation of the Dust Bowl. Fortunately, this fluctuation was not long lived. No single parcel of protected land has proven large enough to contain recent variations.

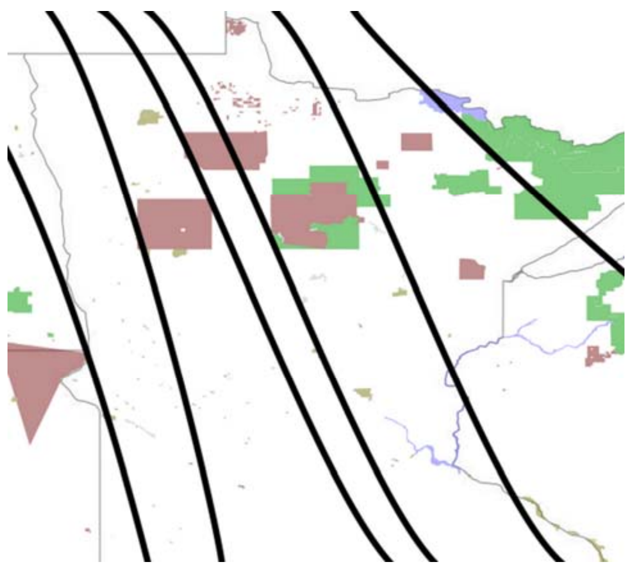


Figure 9. Generalized past and future climate paths in Minnesota

However, the serendipitous alignment of some protected lands, such as Paul Bunyan State Forest, Itasca State Park, the Red Lake region, and protected areas in Canada by the Northwest Angle form a “conservation parkway” along which climate pressures may push ecosystems. The Superior National Forest, Boundary Waters Canoe area, and Quetico Provincial Park form another such parkway. Other protected lands, such as the Dakota Tallgrass Prairie do not lie in such parkways and do not have other safe refuges to relocate to.

While individual species with low tolerance for climate change may conceivable be identified and transported to or replanted in new locations, this introduces them to new and subtly different environments with unknown ramifications. Ensuring clear paths for ecosystem movement helps maintain existing interspecial relations and may provide the most cost-effective method for preserving large numbers of species in the face of change.

Existing protected lands under state and federal schemes have served as a foundation for previous conservation efforts, yet they were not designed to conserve against all possible pressures. While our protected areas are fixed in space, the climates which give rise to the forests, grasslands, and species being protected are mobile.

Idle agricultural lands, patch forests, and marginal wetlands can all play roles as intermediate locations for ecosystems transitioning from one protected area to another. In other locations, they may be the only locations to which an ecosystem can move.

Species disperse at different rates and some may require special attention, others are of special interest. These are discussed below.

Implications for species movement

Climate velocities of several miles per year are considerably faster than rates of tree migration during the deglaciation of North America, which ranged from 0.06-0.25 miles per year for a variety of tree species (Davis 1981). Although some species that are capable of more rapid migration, such as aspen, were not mapped by Davis (1981), many species common to Minnesota today, such as jack, red and white pine, spruce, fir, oak, hickory and maple were analyzed by Davis (1981) and fall within the range above, and are unlikely to be able to migrate fast enough on their own to keep up with their optimum climate.

On the other hand, pests and diseases of trees, both native and exotic, can spread at least as fast as the climate. Dutch elm disease, chestnut blight, butternut canker, emerald ash borer, balsam woolly adelgid and hemlock woolly adelgid, for example, have moved much longer distances, having covered 300-1000 miles or more in one to several decades. Rates of spread of 12-20 miles per year occur for exotic fungal diseases such as Dutch elm disease and chestnut blight (Evans and Finkral 2010). Athough rates of spread for insect pests of trees are somewhat slower (5-8 miles per year for adelgids and emerald ash borer), many insects actually move substantially faster than that due to long-distance jumps caused by human movement of infested wood or nursery stock (Evans and Gregoire 2007, Liebhold and Tobin 2008).

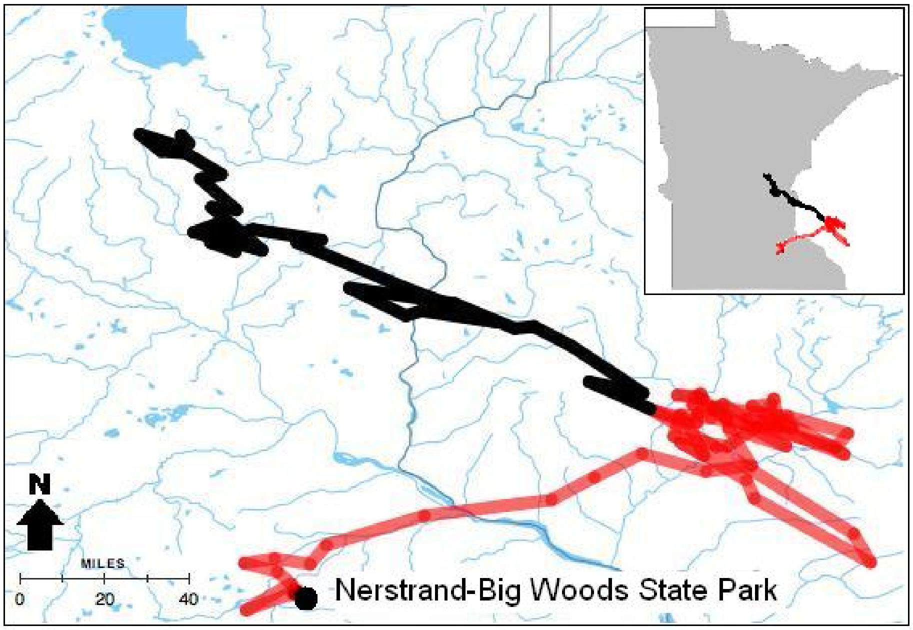


Figure 10. The climate track for Nerstrand-Big Woods State Park is shown from 1900-2010, with the years 1980-2010 indicated in black. This state park contains some of the only remaining native wildflower, Minnesota dwarf trout lily.

Dwarf trout lily

The Minnesota dwarf trout Lily (*Erythronium propullans*) is a federally endangered wildflower found nowhere else on earth other than maple-basswood forests in three counties in southeastern Minnesota (Rice, Goodhue, and Steele Counties; Sather 1990). The Minnesota dwarf trout lily may face the same problem as other rare native species with small isolated populations: namely that in a rapidly changing climate, it could be impossible for the species to migrate across a fragmented landscape at a rate necessary to keep up with its preferred climate. Climate Tracker shows that the climate of Nerstrand Bigwoods State Park, one of the locations where Minnesota dwarf trout lily grows, is moving north at an average of 2.70 miles per year between 1980 and 2010 (Fig. 10). This is faster than most native wildflowers can migrate (Cain et al., 1998), making the Minnesota dwarf trout lily a potential flagship species for how climate change will impact a large number of other rare native plants growing in fragmented habitats.

Canada Lynx

The Canada lynx is a large cat that is dependent on northern forests, including conifer forests, and young mixed birch, aspen and conifer forests and shrublands. In addition, deep snow cover for several months each year is necessary to support its principal prey species, snowshoe hare (McCann and Moen 2011). Northeastern Minnesota contains one of five critical habitat units in the 48 states for Canada lynx, which is federally listed as threatened in the contiguous U.S. (http://www.fws.gov/mountain-prairie/species/mammals/lynx/). The historic range of the Minnesota lynx includes the northern tier of counties, therefore the species could move out of the state within several decades if the climate continues migrating north for the last 30 years, as Climate Tracker has demonstrated.

Western Prairie fringed orchid

Western prairie fringed orchid (*Platanthera praeclara*) is a federally threatened plant that grows in medium to wet prairies and meadows (http://www.fws.gov/midwest/ endangered/plants/prairief.html). The species is threatened because of conversion of most prairies to farmland throughout its range. This is one species that may benefit from an eastward movement of the prairie-forest border in Minnesota, as Climate Tracker shows occurred during the mid 1900s, and may occur in the future. This is because large areas of public wildland that are unlikely to be converted to agriculture, and which may convert from forest to grassland with a changing climate, exist just to the east of its current range in northwestern Minnesota.

Mesophication of oak forests (SE, E and central MN)

A phenomenon known to foresters as 'Mesophication' has occurred from the 1950s through the 1990s in Minnesota and elsewhere across the lake states and northeastern U.S., during which the maples have steadily invaded oak forests. Oaks (e.g. northern red oak and white oak in Minnesota) grow best on well drained sandy soils, but may invade silty (i.e. mesic) soils during periods of dry climate, whereas maples (e.g. sugar maple and red maple) grow best on silty soils but may invade oak forests on sandier soils during periods of wet climate. Although consumption of oak seedlings by deer have helped maple, as has a lack of fire, a wetter summer climate likely underlies this maple expansion (McEwan et al., 2011), and this is shown by the westward expansion of climate in Minnesota in Climate Tracker during the mid 1900s (Fig. 3D).

Forest to grassland transitions

The northward and eastward track of climate in Minnesota in recent years, if it continues as expected, will present standing forests with environments typical of prairies. Forests can survive in such environments, but events such as wildfire or insect invasions can induce damage from which forests will have difficulty regenerating. Therefore, some places in Minnesota that are presently wooded can be expected to give way to more open grasslands.

A transition from forest to grassland ecology has multiple implications for the people of Minnesota, and for tourists visiting Minnesota, both positive and negative. For example, forest-based economies can adapt economically by harvesting grasslands rather than woodlands for bioenergy. Ongoing research sponsored by the Environment and Natural Resources Trust Fund and other sources has indicated harvesting to be an alternative that can encourage wildlife diversity and a sustainable ecosystem (Jungers et al., 2010). This research, on established prairie in the north-west, west-central and south-west regions of Minnesota, is also examining the economic, nutrient, and yield potentials for perennial grass biofuels, and the present project thus has relevance to that.

Prairie-forest border

In Minnesota, the prairie-forest border extends from the northwest along a curved path toward the southeast. Along the way is the triple point, where conditions conducive to northern needle-leaf trees give way to broad-leaf trees. This border has been characteristic of

Minnesota for thousands of years. But what is happening to it now, and what may happen in the foreseeable future?

The climate track over recent decades has a northward component and a slight lateral component. The westward component represents the wetter climate of eastern Minnesota moving slowly west, and the northward component represents warmer climate of southern Minnesota moving slowly north.

The slight lateral component is more pronounced in southern Minnesota and barely perceptible in the north (see Fig. 3). This means that the climatic conditions of the prairie-forest border are moving north and at the same time rotating to the east. In other words, the prairie-forest border is shifting to become more north-south than it has been. If these trends continue, northern parts of Minnesota will be more susceptible to changes than the south. This is notable since the north is favored for weekend retreats by Minnesota residents and out of state tourists alike. Fortunately, the northeast triangle, with its canoe-country lakes and forest, will be the latest to be affected, affording the most time for amelioration of global conditions that might be influencing environmental trajectories.

Overall location of the boundary between the original grasslands and forests in Minnesota was determined by climate, especially the balance between rainfall and evaporation and use of water by the vegetation—when this balance is positive (more rain than evaporation), forest is favored, and when it is negative, grassland is favored. Other factors such as sandiness of the soil, nearness to water bodies and topography fine tune the location of the prairie-forest border, creating the small twists and turns that occur at the township level (Danz et al., 2011). Climate Tracker shows that the climate favoring prairies moved east during the early 1900s, but then receded west during the mid 1900s (Fig. 3).

Implications for agriculture

The Climate Tracker suggests possible trends, so there is much future potential for collaborations with agriculture. Long term agricultural records of crops and yields by the USDA in many case are far more complete and accurate than records of non-commercial natural ecosystems. Therefore, agricultural archives form a good basis for comparisons with Climate Tracker models.

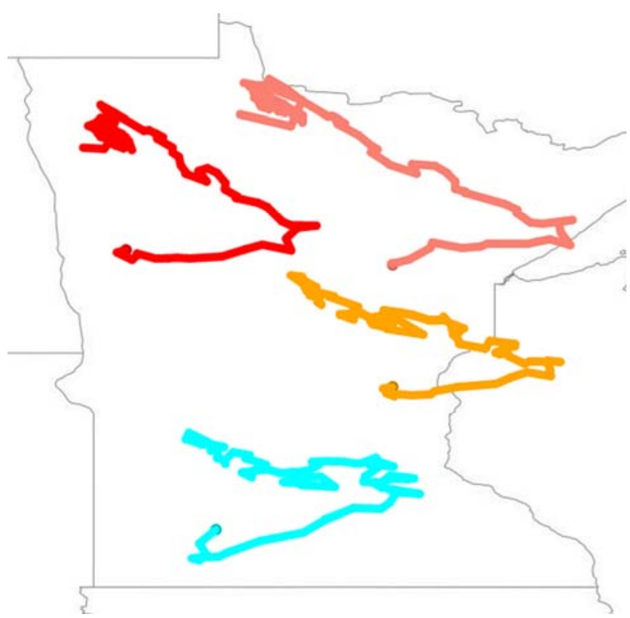


Figure 11. Growing-degree day tracks in Minnesota, with precipitation as the second climate variable

Growing-degree days are a widely used metric of an area’s potential agricultural productivity. Days with an average temperature below 50°F are said to have no growing-degrees. At 51°F, one growing-degree is accumulated; at 52°F, two growing-degrees are accumulated. At 86°F this trend stops and no more growing-degrees are gained for higher temperatures. Put another way, there is a temperature below which a given plant will not grow appreciably, and a temperature above which it will not grow any faster.

Substituting growing-degree days for temperature in the Climate Tracker yields an interesting result. Though temperatures in the state continue to rise, and climate tracks continue to move northward, growing-degree tracks in the north part of the state stalled in 1966 and have hovered since then. The south part of the state has seen continued movement, but larger as a result of changes in precipitation. Though the northern part of the state continues to warm, and to do so more quickly than the south of the state, the effects of fluctuating climate will be felt most strongly in the state’s southwest.

Implications for bioenergy

Figure 12. Grassland bioenergy potential now (left) and if growing conditions shift 60 miles northward (right). The broad bioenergy hotspot presently south of Fergus Falls remains within Minnesota, but the one presently near Thief River Falls moves largely out of the state. An area in the south-central that is not ideal for grassland bioenergy expands and moves north. The hotspot appearing in the Arrowhead Region is partly an artifact of the processing, to be refined as the paper describing these results is completed. Results are obtained, for each point of the landscape, from USDA databases, by (1) calculating the number of acres of former cropland in the neighborhood of each point that could be applied to grassland bioenergy, (2) multiplying by the yield per acre of production grasslands nearby (left) and 60 miles to the south (right, representing climate velocity of 3 miles per year for 20 years), (3) summing available energy production within a 50-mile radius of each point.

Implications for infrastructure

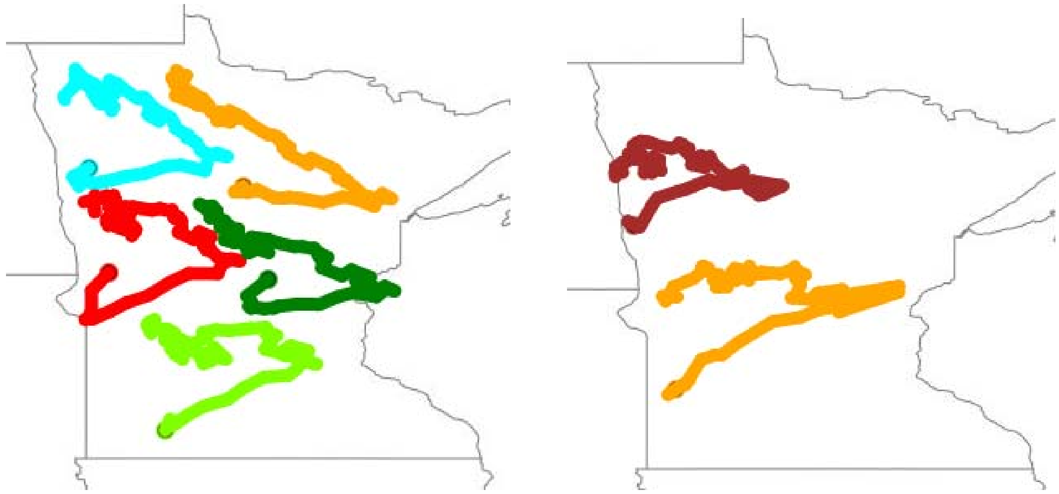


Figure 13. Climate tracks for cooling-degree days are depicted on the left while climate tracks for heating-degree days are depicted on the right.

While a full analysis of the impacts of climate on infrastructure was not part of the scope of this project, we include a partial analysis here. If only yearly average temperatures are considered, the Dust Bowl cannot be said to have had a large effect on the state's temperatures. Cooling- and heating-degree days tells another story.

Cooling-degree days are the difference between the average daily temperature and 65°F, neglecting those days cooler than 65°F. They accumulate over a year. Similarly, heating-degree days are the difference between 65°F and the average daily temperature, neglecting those days warmer than 65°F. Put another way, cooling-degree days can be thought of often and how strongly one's air-conditioning must be turned on, whereas heating-degree days represent how often and how strongly one's home heating must be turned on.

During the Dust Bowl, the need of both heating and cooling increased, which indicates years having both more days which are warm and more days which are cooler, or, overall, more days which are farther from being 65°F. As the Dust Bowl's eastward excursion ended in 1940, heating-degree days leveled off throughout most of the state. Heating infrastructure needs, then, have remained largely constant for the past seventy years.

Cooling-degree days are different, where cooling needs have remained essentially unchanged in southern Minnesota for the past seventy years, while northern Minnesota, and especially northeastern Minnesota, has an increased need for cooling.

Despite these trends, the *impact* of heating- and cooling-degree day fluctuations over time is not as easily assessed. Changing building codes, better forms of insulation, the introduction of central air, and double-paned windows have all played a part in determining the social and economic impacts of these changes. While projecting future infrastructure needs is outside the scope of this project, it is an example of how Climate Tracker may be useful outside of the biosciences.

Reporting to the public and scientific community

A project website presents the final products of the project to the public (see Appendix A). All data sources are listed and explained. All of the code and tools developed for the project are being made available for public download and analysis. Project contributors and biographies are listed. Funding sources are credited for their contributions. As publications resulting from the project become available, they will be added to the site and explained in accessible terms. The project's methodology is explained pictorially on the website, with examples drawn from actual Minnesota data. Appendix B contains this information, intended as an easy-to-understand explanation of the methods used in this project.

The site also includes access to the application developed during the project to facilitate extraction of climate data. Website visitors are able to select regions they find relevant and ask, for any point, where its climate conditions have been and are going. It provides citizen access to the data, devices, and developments of this project, making the information available to all.

In addition to the website, the project has been described in presentations by investigators and participating students, including:

- Clarence Lehman, University of Minnesota Open House. Environmental issues booth, 25,000 people in attendance. October 4, 2009.
- Clarence Lehman, Fertile, MN. October 22, 2009.
- Clarence Lehman, Glacier Lake State Park, MN. October 29, 2009.
- Clarence Lehman, Talcot Lake Wildlife Management Area, MN. November 19, 2009.
- Esther Widiasih, The Comparison of Different Projections for Environmental Trajectories Global Circulation Models vs. Surface Fitting Models. Mathematics of Climate Change Seminar. May 5, 2010.
- Clarence Lehman, keynote presentation at Tallgrass Prairie for Biofuel Conference, Guelph University, Ridgetown, Canada. May 25, 2010.
- Clarence Lehman, CIG Wildlife and Biofuels Demo. October 19, 2010.
- Richard Barnes, University of Minnesota Student Sustainability Symposium. October 28, 2011.

Anticipated publications

This project has uncovered new principles that deserve publication in the general literature of environmental science. Future papers are anticipated to cover (1) the methods developed to obtain the results described in this report, for those who want to extend these results to other areas of the globe. (2) Comparison of rates and directions of change between the new methods applied here and the projections from existing, more complex global circulation models. (3) Comparison of trajectories and speeds among climate, Minnesota's flora, and disruptive elements such as insect pests, pathogens, and fire. (4) Similarities and contrasts with conclusions from the USDA Forest Service Climate Change Tree Atlas. (5) Projections of agricultural concerns, including prospects for locations of 90 versus 100-day corn.

Budget notes

The project was completed under budget, since one anticipated item was not necessary and two were funded from other sources. In particular: (1) Special papers and inks for preparing maps and other results were not needed, since web development resources have advanced enough over three years that maps can be produced interactively for specific purposes, for $861.00 saved. (2) For in-state travel, dissemination to the public was able to be funded through a federal USDA Conservation Innovation Grant, as described above, and travel to understand the weather data was able to be accomplished by electronic communication, for $1600.00 saved. (3) Some funds that we expected to apply to a project video to make the results more accessible to citizens had to be done concurrently with the preparation of this report, hence after the project funding period. That video, available on the project website, was funded by the University of Minnesota, for $3500.00 saved. A total of $5961.00 is being returned to the state.

Concluding remarks

Projecting the climate tracks shows Minnesota's future as it *might be*, not as it *shall be*. Some changes are happening now and other short-term changes are probably unavoidable. But if the recent rate of the climate track continues at a few miles per year northward, it will take most of a century for all of Minnesota to have the climate of a prairie state, unconducive to northern forests. A century is only a single human lifetime, but it is a vast span in the course of modern civilization. There is still time to implement known methods of environmental improvement (e.g. Pacala and Socolow, 2004), enough of which will help restore equitable conditions of the past, and there is nearly a century of future innovations that could arise. We hope that studies such as ours will help clarify the environmental changes that may occur, and encourage new environmental efforts by showing that we may still have enough time to halt some of the possibly detrimental effects.

Project goal summary

In a multi-year, multi-faceted project like this, the basic goals and research questions can be lost in the discussion. To summarize the status of the project objectives, here are the proposed, completed, discontinued, and exceeded aspects, followed by future outgrowths of the project.

<u>1. What we proposed to do, per the deliverables:</u>

▪ Assemble data in suitable format; construct a database
▪ Adaptation and automation of pilot programs
▪ Develop computer runs and production of working maps and tables
▪ Correlation with ecological, physical, and local conditions
▪ Develop web-based time-lapse video files of results across MN
▪ Analysis and reporting, including:
  ▪ Delineation of areas having future potential for renewable bioenergy production,
  ▪ Ranges of locally threatened or endangered species,
  ▪ The movement and velocity of climate near particularly vulnerable ecoregions, such as the prairie-forest border in Minnesota,
  ▪ Areas of increased dangers of fire and climate-related movement of pests and diseases of trees, both native and exotic,
  ▪ Artifacts of major historical shifts in climate in Minnesota.

<u>2. What, of that, we did:</u>

▪ Assemble data in suitable format; construct a database
Completed as of final report; see "Assembly of daily data."

▪ Adaptation and automation of pilot programs

*Completed as of final report; see "*Production of working maps and tables.*"*

▪ Develop computer runs and production of working maps and tables
Please see number 3, below, as work went beyond what was proposed.

▪ Correlation with ecological, physical, and local conditions:
*Correlation with local conditions was enhanced once Climate Tracker matured to allow backwards tracking. Now, it's possible to easily see what area was experiencing a set of known climate conditions one to one hundred years ago. Correlation with ecological conditions is addressed in sections "*Implications for species movements," "Implications for bioenergy," *and* "Implications for agriculture*." Correlation with physical conditions is most obvious during the Dust Bowl years, and in less dramatic fashions, the droughts Minnesota suffered in 1977 and 1988.*

▪ Delineation of areas having future potential for renewable bioenergy production,
An example of delineation of bioenergy potential production areas is shown in Figure 12. This is based on analysis of USDA productivity and land availability. The methods used to create that figure are being expanded to other bioenergy and other agricultural aspects, such as corn and other commodity crops. Please see point 5, below for discussion of the future pursuits on this topic.

▪ Ranges of locally threatened or endangered species,
*The impact of climate velocity on Minnesota native and invasive species is discussed generally, along with several examples of specific species of interest in Minnesota; please see "*Implications for species movement.*"*

▪ The movement and velocity of climate near particularly vulnerable ecoregions, such as the prairie-forest border in Minnesota,
The final report addresses the vulnerability of the prairie-forest border. This addendum expands on this discussion by addressing the general mathematics of borders, which have implications for landscape fragmentation, and by discussing how climate tracks interact with protected lands; please see "Implications for state and national parks and other protected places"

▪ Artifacts of major historical shifts in climate in Minnesota.
The Dust Bowl years of 1933-1940 are the clearest artifacts of historical and historic climate identified by the Climate Tracker. Please see maps in Figure 3 - or use Climate Tracker to create new maps - which breaks down portions of the climate tracks for eight Minnesotan cities. In the discussion, shifts in climate are pointed out as they are encountered. Additionally, the Dust Bowl is depicted within the context of growing-degree days, an agriculturally-relevant metric of productivity.

▪ Develop web-based time-lapse video files of results across MN
Please see number 3, as work went beyond what was proposed.

<u>3. What we did beyond what we proposed</u>

▪ Develop computer runs and production of working maps and tables, and
▪ Develop web-based time-lapse video files of results across MN
The Climate Tracker application was initially intended to be a tool built for the sole use of the researchers on this project. However, the results were visually enlightening, so special effort was invested in making the Climate Tracker appropriate for public

evaluation and use. The result is an accessible website, which includes project background information, an approachable description of the methods employed, and instructions on how to use the application. Since climate change is a much-discussed topic, efforts were made to remain transparent and open about who conducted the project. To this end, a short video was sponsored, produced, and distributed at the College of Biological Sciences to introduce two of the U of M contributors. A short professional background of all contributors on the project can be found on the website as well.

Improving on the idea of pre-selecting and pre-recording time-lapse videos, Climate Tracker users can select locations and time frames of interest, then watch an animation of the moving climate. This has much greater interactive utility than a video.

An expanded feature of Climate Tracker is warming and cooling degree days. By changing an internal algorithm, Climate Tracker is able to track their movements, which have implications outside of the biosciences. With further future funding, this feature and others could be integrated with the current climate tracks.

4. What we did not do of what was proposed

As discussed under "Assembly of daily data," the proposed idea of using daily weather data was infeasible, due to unexpectedly missing data and related problems of continuity and completeness. We successfully bypassed the problems by substituting monthly data, but at the cost of resolution in the projections and at the cost of time for other aspects of the project in Result 2.

▪ Areas of increased dangers of fire and climate-related movement of pests and diseases of trees, both native and exotic

We did not address fire and pests, and will not be pursuing this further for the current report. Some analyses, such as emerald ash borer temperature tolerance, require data with more resolution, such as daily data. As previously discussed, we look forward to pursuing such topics using the methods we have developed, as daily data improves.

5. What we are doing in the future as outgrowth of this project

▪ Delineation of areas having future potential for renewable bioenergy production

Regular developments have been made to the Climate Tracker website to increase utility and approachability. Recently, a choice of background map was added so the user could correlate climate trajectories with roads, rivers and lakes, or federal lands. Seasonal climate tracks showing the different behaviors of summer and winter temperature and precipitation over time may be added in the future. Another contribution is a means of depicting tracks based on growing-degree days.

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V. Total Trust Fund Project Budget:

Personnel: $174,039 represents the sum total of salary and benefits to project investigators including: C Lehman who provided software expertise to carry out the computer computations, data processing, and geographic mapping, and worked with the technical and student assistants; E. Widiasih, S. Williams, R. Barnes, students involved in implementing the underlying mathematics for the climate projections, performing simulation, developing the website, map and report preparation; P Reich who managed the project, interacted with all participants in developing goals, interpreting data, and writing reports; L Frelich who contributed to the evaluation of plant community responses to climate velocity projections.

Contracts: $ none

Equipment/Tools/Supplies: $ none
No supplies, such as specialized inks and papers for mapping, were necessary. Mapped results are published online, which facilitates better animations, updates, and interactivity, along with broader availability to Minnesotans. To support development of the website, maps, and animations, an amendment on 5/2/2011 allowed Result 1 equipment allowances to be transferred into Result 2 personnel costs.

Acquisition, including easements: $ none

Travel: $ none
No visits to climatological stations were necessary for data retrieval or interpretation. Reviews with local climatologists, ecologists, and other experts were easily facilitated via phone and email, leaving anticipated travel funds unneeded. Several in-state presentations were given on this and complementary climate change projects, with travel expenses covered by other funding sources, including a USDA Conservation Innovation Grant that was targeted for public presentation of environmental issues.

Other: $ none

TOTAL TRUST FUND PROJECT BUDGET: $ 180,000

Explanation of Capital Expenditures Greater Than $3,500: No capital expenditure greater than $3,500 was necessary.

VI. PROJECT STRATEGY:

A. Project Partners:

Peter Reich was project manager. In addition: (1) ***Clarence Lehman*** (Ecology) provided software expertise to carry out the computer processing, and worked with graduate assistants. (2) ***Richard McGehee*** (Mathematics) provided mathematical expertise, and also worked with graduate assistants.(3) ***Lee Frelich*** (Forest Ecology) lent his expertise on the plant communities of Minnesota and how they are responding to present-day change in their conditions. (4) ***Mark Seeley*** (Climatology) applied his expertise with long-term climatic trends in the region. (5) ***Donald Wyse*** (Agronomy) contributed his expertise on agricultural systems. (6) We also employed undergraduate and graduate assistants.

B. Project Impact and Long-term Strategy:

This project had a broad scope, covering all four areas in the LCCMR 2009 Phase-2 Funding Priorities by providing tools and information important for planning the future of land, habitat, water, invasive species, and renewable bioenergy. In particular, the project provided tools and information on or relevant to the following issues, among others: (1) locations of lands suitable for future grassland, woodland, and potentially wetland bioenergy, (2) locations of lands suitable for food crops in the future, (3) conditions that affect invasive species, (4) future spatial boundaries of our state's ecosystems, (5) validation of other climate models, and (6) other various conditions involving human, animal, and ecosystem health.

The project addressed the above topics and assessed their scope, but focused in more detail on that subset of topics determined to be most relevant and feasible during the first phase of the effort. For all topics we assessed and described projected climatic features relevant to each specific issue, while evaluating qualitatively and wherever feasible quantitatively how projected climate features will influence the specific issues in focus. The project also aimed to increase awareness of the effects of global environmental change and thereby encourage actions that could ultimately help prevent or reverse some of its effects.

Our goal was to provide tools and information for planners to adapt to environmental changes before they actually occur, including adaptive management of the next-generation bioenergy industry. For example, long-term variability in temperature and rainfall might favor certain mixed species over single species, and potentially favor grassland biofuels over woodland ones. The techniques apply to the entire state of Minnesota, but they can also be able to be adapted by all other contiguous states of the union to later form a nation-wide assessment and expansion of the topics considered here locally.

C. Other Funds Proposed to be Spent during the Project Period:

No other funds allocated.

D. Spending History:

Please see Attachment A for spending history. An amendment to spending was granted May 5, 2011, allowing up to $8915 to be transferred from Result 1 to Result 2 salaries. This allowed additional focus to be placed on analysis, modeling, and reporting findings to a broader community.

VII. DISSEMINATION:

This was a two-year project. Its first year involved data assembly, algorithm validation, analysis, and preparation of preliminary maps and tables. In its second year, results were correlated with ecological, hydrological, physical, and social aspects. Included in the second year are a final report, public presentations, and web dissemination, which can be found at http://www.cbs.umn.edu/climatetracker. This website is designed to be user-friendly, useful, and interesting to both scientists and the general public. The interactive Climate Tracker application was developed as a novel way to dynamically view a century of data, while the brief video introduction presents information in a broader context and allows visitors to the website to meet some of the project researchers.

Future publications in scientific journals are expected to result from this project, as described in section IV.

VIII. REPORTING REQUIREMENTS: Periodic work program progress reports will be submitted not later than 12/15/2009, 2/15/2010, 7/30/2010, 12/15/2010, and 2/15/2011. A final work program report and associated products will be submitted between June 30 and August 1, 2011 as requested by the LCCMR.

IX. RESEARCH PROJECTS:

Attachment A: Final Budget Detail for 2009 Project

Project Title: *Projecting Environmental Trajectories for Energy-Water-Habitat Planning*

Project Manager Name: *Peter Reich*

Trust Fund Appropriation: $ 180,000

2009 Trust Fund Budget	Result 1 Budget:	Amount Spent (6/30/2011)	Balance (6/30/2011)	Result 2 Budget:	Amount Spent (6/30/2011)	Balance (6/30/2011)	TOTAL BUDGET	TOTAL BALANCE
	Data, software, computer runs			*Analysis, documentation, publication*				
BUDGET ITEM								
PERSONNEL: Academic wages and benefits (**R1:** Reich, 4% FTE; Lehman, 40% FTE; Frelich, 4% FTE; graduate research analyst, 80% FTE; technical specialists, 8.3% FTE; **R2**: Reich, 4% FTE; Lehman, 27% FTE; Frelich, 12% FTE; graduate research analyst, 80% FTE; technical specialists, 17% FTE;) ***Ammendment approved 5/2/2011: $3,946 transferred from Result 1 to Result 2*	86,054	86,054	0	91,485	87,985	3,500	177,539	3,500
Supplies *(specialized inks and papers for mapping)*	0	0	0	861	0	861	861	861
Travel expenses in Minnesota *(Reviews with local climatologists, agronomists, ecologists, plus any necessary visits to climatological stations, plus in-state presentations at public events and scientific symposia.)*	0	0	0	1,600	0	1,600	1,600	1,600
COLUMN TOTAL	**$86,054**	**$86,054**	**$0**	**$93,946**	**$87,985**	**$5,961**	**$180,000**	5,961

Appendix A – Introduction to the website

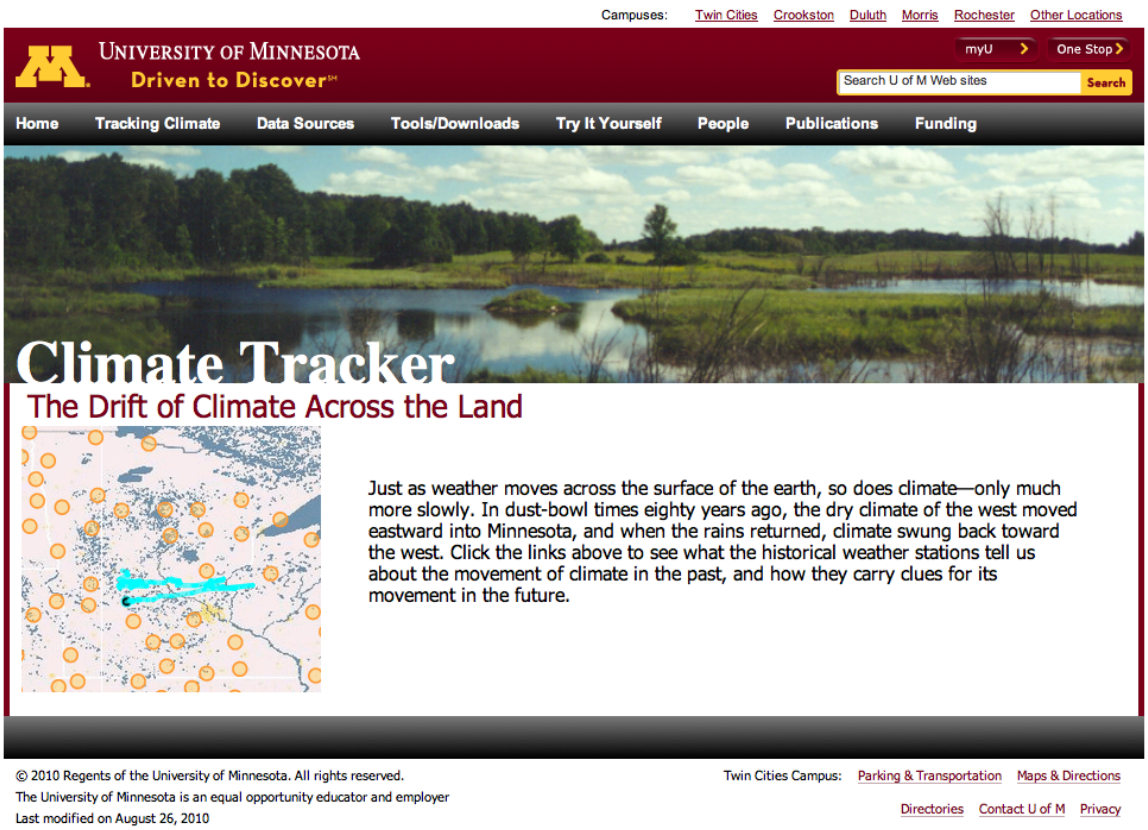


Figure A1. The Climate Tracker website is an account of the project background, methods, and results. A brief video introduction features researchers describing the project in a broader context.

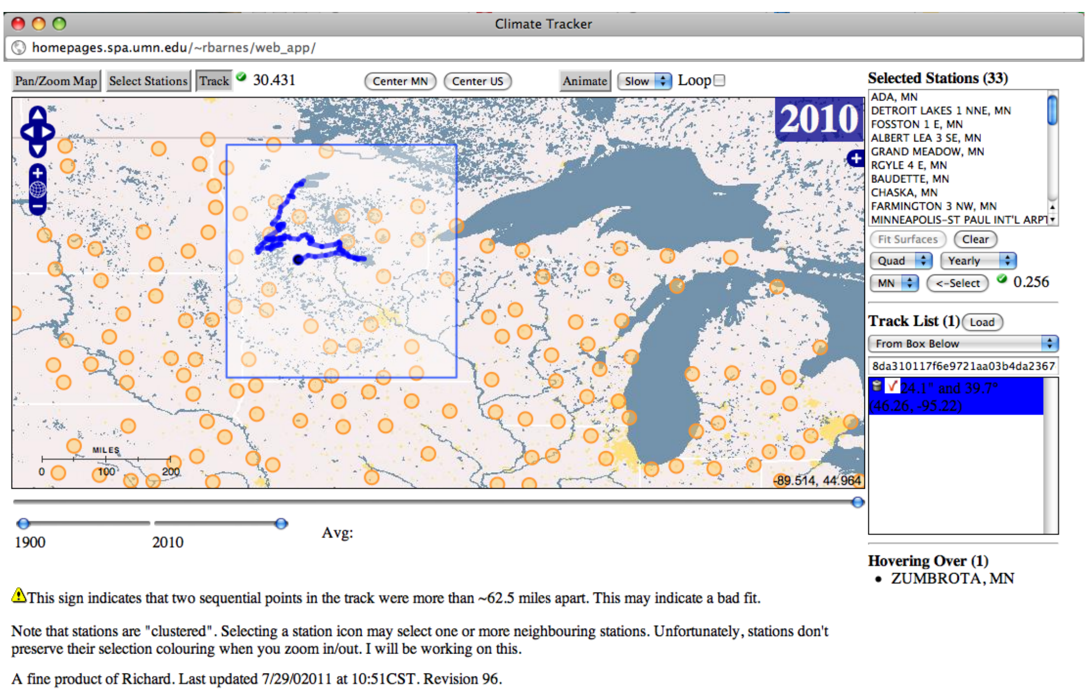


Figure A2. The interactive Climate Tracker lets visitors to the website select regions they find relevant and ask, for any point, where its climate has been and the direction it is going. It provides a way to see a century of climate data in motion at a glance.

Appendix B - Sketch of the principles employed

The full details of processing are esoteric, but the basic principals are not. Here is a distillation of the process we intend to be suitable for a broad audience.

A Meeting of Ecosystems

Part of the allure of Minnesota and the Upper Midwest—its appeal to visitors and residents alike—lies in its diversity—in all the different kinds of plants and animals that make the area their home.

Think for a moment of the whole of North America. The continent has many different ecosystems—tundra in the far north, ancient old-growth in the Pacific Northwest, real deserts in the Southwest—but there are three really large ecosystems: the northern forests of needle-leaved softwoods, the eastern forests of broadleaf hardwoods, and the central prairie grasslands—once amber waves of grain rolling westward to the Rockies.

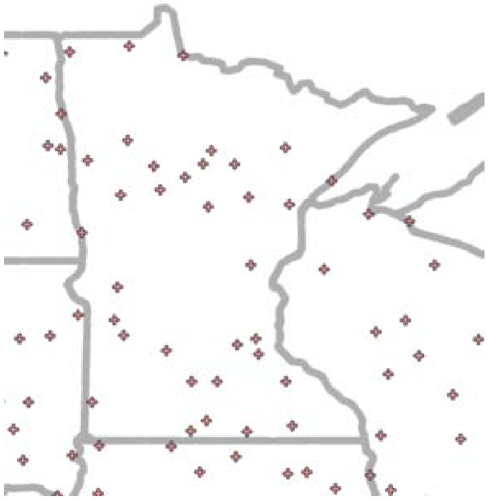
These three great ecosystems all join at a triple meeting point—what ecologists call a triple ecotone—in central Minnesota.

The interior of an ecosystem—for example at Red Lake, Ontario—will not soon see things changing beneath it. The places most sensitive to climate change are those at the boundaries of ecosystems. Minnesota is at the boundary of three, and that makes this area triply sensitive. So what is the fate of this triple meeting point? Where has it been and where will it go?

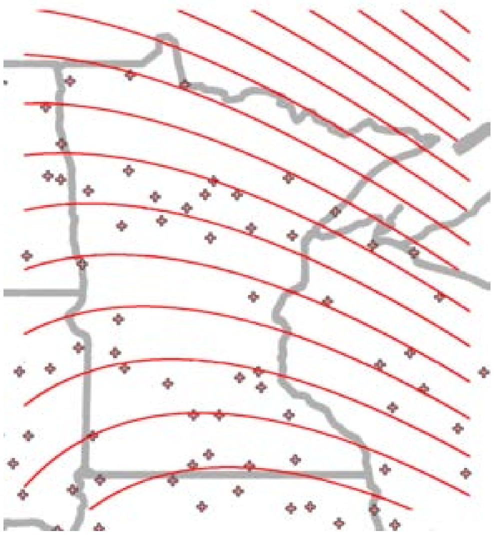
Pinpointing the Meeting Spot

The location of the triple ecotone is determined by several things, but a large part is climate. By identifying the climatic characteristics of a given place—its 30-year average precipitation and temperature—and by mathematically filling in smoothly between the member stations of the U.S. Historical Climate Network (USHCN), it is possible to track the climate over time by computer and see where a particular climatic spot is moving.

Pictorial Explanation



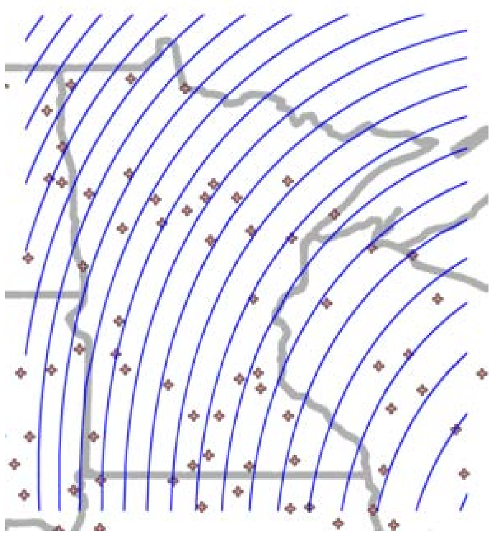
The process begins by looking at data from all the weather stations. There are about 1200 of these in the U.S. and 33 in Minnesota. Some stations' records date back as far as 1850, but the majority of the data are for 1900 onwards. Data are kept in the form of monthly averages and totals.



Each station keeps track of its average temperature every month. From these, we find yearly averages.

For a given year, we average the previous 30 years together; the result is the temperature of the station's climate for that year.

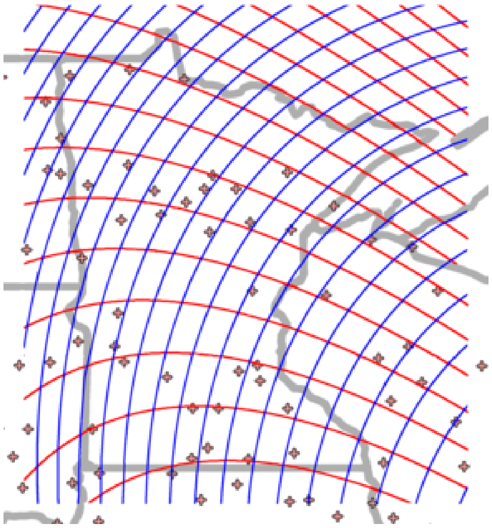
Using these known values, we can mathematically calculate the temperature of any other point on the map. If you were to draw curves between the points that have the same temperatures, it might look like this.



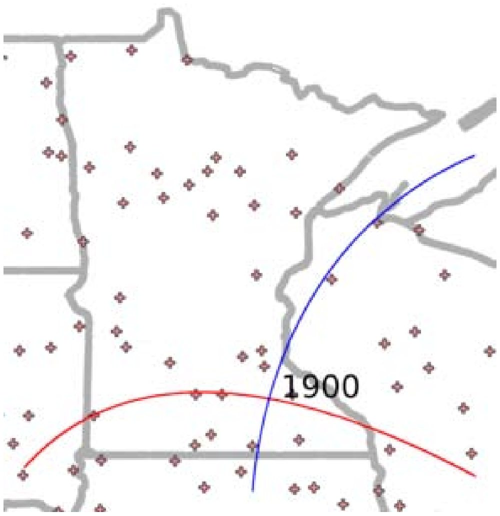
Each station also keeps track of its total precipitation for each month. From these, we find yearly totals.

For a given year, we average the previous 30 years together; the result is the precipitation of the station's climate for that year.

Using these known values, we can mathematically calculate the precipitation of any other point on the map. If you were to draw curves between the points that have the same precipitation, it might look like this.

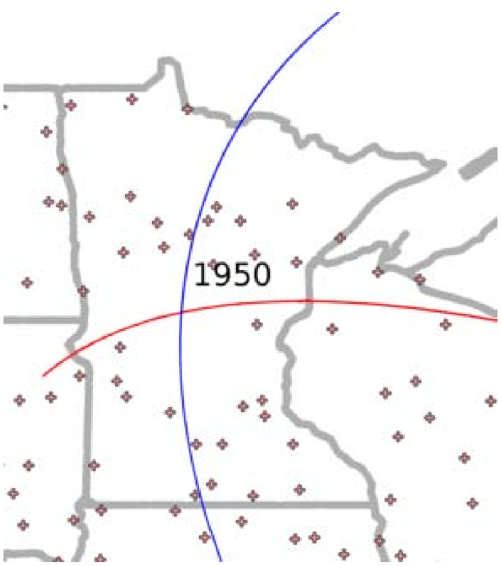


Now, we can overlay the precipitation and temperature curves on top of each other and find their intersections. Each intersection defines a climatic point—a specific combination of temperature and rainfall more or less hospitable to any given ecosystem.

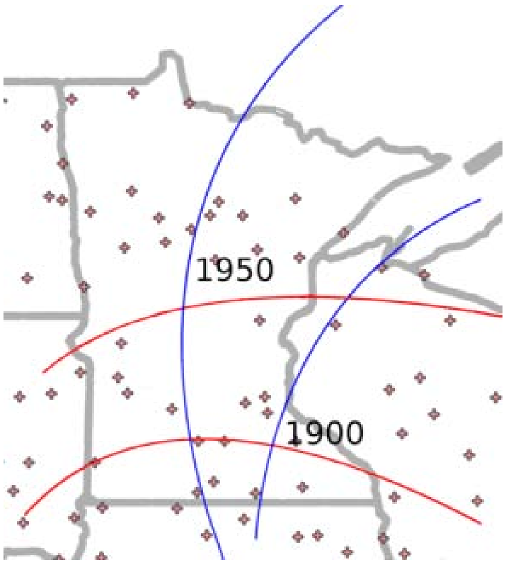


Now, let's make a few of the temperature and precipitation lines disappear.

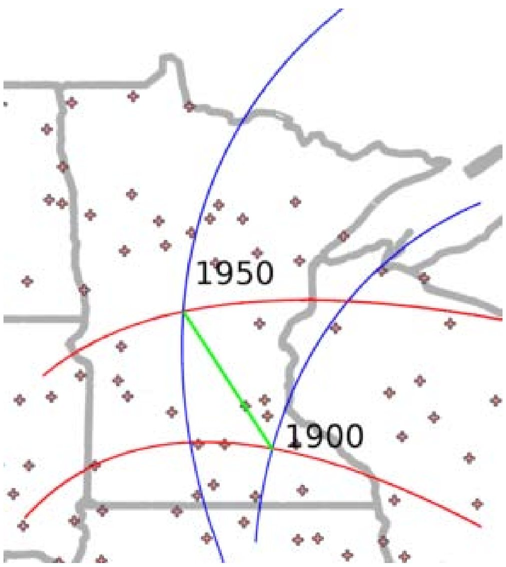
The intersection of the remaining lines is a climatic point. It shows where a particular combination of temperature and precipitation (let's say 52°F and 7" of rain) is in the year 1900.



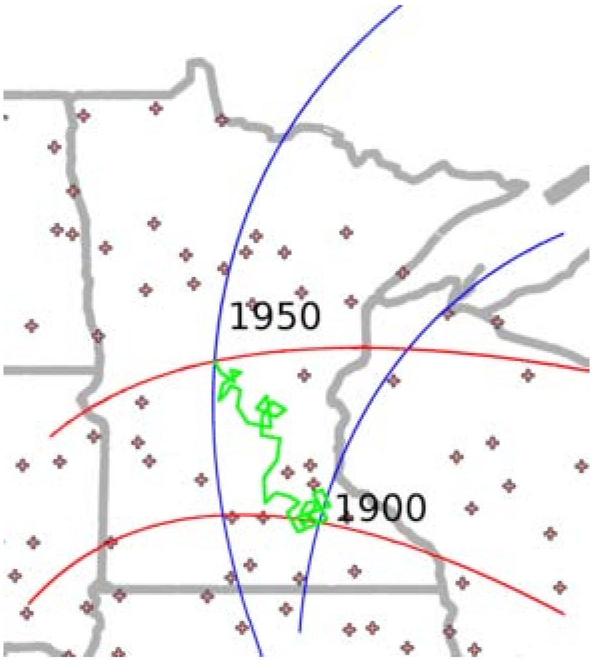
We can figure out where that same climatic point is in 1950.
(This isn't real data, it's just an example.)



Now, if we know where the climate was in both 1900 and 1950, we can begin to track its movement…



…by connecting the dots—in this case, climatic points.



Of course, connecting the dots between 1900 and 1950 doesn't say very much about where the climate has gone, so we connect each year's dot with the dot of the following year.

Remember, this isn't real data: it's an example.

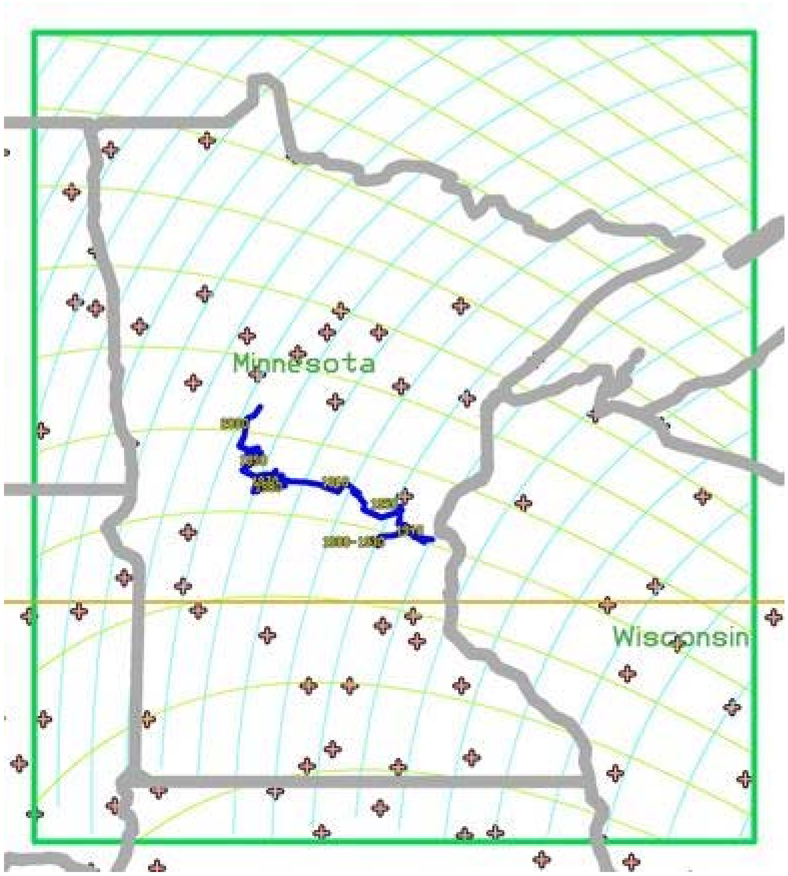
The new path connects every year and doesn't look as nice, but tells a more interesting story.

From 1900–1920, we see that the climate hovered in the same place. No two years' weather is the same, so the climate was always moving, but not very far: it was moving in circles.

From 1920–1930, the climate moved north and west. Some years it moved a lot, other years a little. During some years, it even reversed direction, but the general trend was north and west.

After a little more hovering and moving the climate arrived at its 1950 location.

This means that the climate of 1900 has moved to a new location by 1950, displacing whatever climate was there before.



Now, let's look at some real data; this is the story of one of Minnesota's climate points.

Our data for the point, located in south-east Minnesota, begins in 1900. Thirty years later, we have enough data to calculate the point's climate. At this time, in 1930, the Dust Bowl was just beginning and the point moved steadily eastward as a result of this change in climate. By the time the Dust Bowl ended, the point had touched the Wisconsin border, north of Taylors Falls. Had it stayed there, Minnesota would eventually have had only prairies, not forests.

But in just a single year it abruptly turned 180 degrees, retracing part of its path and beginning thirty-year northwestward journey toward the Dakota border, south of Fargo. Had it continued moving in this direction, Minnesota would eventually have had only forests and no prairies. But, instead, it stalled out and hovered in the middle of the state, southwest of Brainard.

In the last twenty years it has again abruptly changed direction, turning 90 degrees north and heading in the direction of the pine stands of Itasca.