ENVIRONMENTAL AND ECONOMIC RESEARCH AND DEVELOPMENT PROGRAM

Climatic Analogs, Climate Velocity, and Potential Shifts in Vegetation Stucture & Biomass for Wisconsin Under 21st-century Climate-change Scenarios

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Executive Summary

Climate is a fundamental constraint on the distribution, diversity, and abundance of species, and projected climate changes over this century are expected to have a major effect on US species, ecosystems, and the services that they provide. Recent temperature rises appear to be already affecting the most climatically sensitive and fast-responding components of Wisconsin landscapes, with observed decreases in the length of lake ice cover, earlier timing of spring flowering, and the earlier spring arrival of migrating birds. In the US and in the Northern Hemisphere, many species ranges are shifting northwards and upwards, consistent with forcing by warmer temperatures. Species distribution models driven by climate scenarios for this century consistently predict that these range shifts will continue as temperatures rise.

In Wisconsin, average annual temperatures in Wisconsin increased by 0.6°C (1.1°F) between 1950 and 2006, while winter temperatures increased by 1.4°C (2.5°F) over the same period. Annual precipitation has increased by 10%, with much of that increase attributable to an increase in the frequency and intensity of heavy precipitation events. By the middle of this century, Wisconsin temperatures are projected to increase (on average, across the state) by 2.2 to 5°C (4 to 9°F), a rate about four times the rate observed between 1950 and 2006. The direction of annual and summer precipitation changes is less certain, but global climate models consistently predict increases in winter precipitation and the frequency of extreme precipitation events. Given the observed historic climate changes in Wisconsin and the likelihood of continued climate change driven by rising greenhouse gas emissions, there is a need to assess the potential effects of projected climate changes on Wisconsin's species and natural resources and use this information as the basis for adaptation strategies designed to improve the resistance, resilience, and response paths available to Wisconsin's ecosystems. A major milestone in this effort was the formation of the Wisconsin Initiative on Climate Change Impacts (WICCI) and its 2011 report: Wisconsin's Changing Climate: Impacts and Adaptation.

In this EERD-supported project, we build upon the 2011 WICCI report by applying its downscaled 21st-century climate projections for Wisconsin to three sets of analyses designed to assess and summarize the potential effects of climate change on Wisconsin's species and landscapes: 1) Climate-analog analyses, which identify contemporary analogs for the future climates projected for Wisconsin (Section 2), 2) Climate-velocity analyses, which measure the spatial rate of climate change (Section 3), and 3) dynamic global vegetation model simulations of Wisconsin vegetation and carbon sequestration (Section 4). In these analyses, we used climate change simulations for three standard socioeconomic scenarios: the B1 scenario, in which atmospheric CO_2 concentrations are stabilized at 550 parts per million (ppm) by the end of this century, the A1B scenario, which is a 'business-as-usual' scenario in which CO_2 reaches 720 ppm by 2100AD, and the A2 scenario, a high-end scenario in which CO_2 reaches 820 ppm by 2100 AD.

All analyses point to the potentially transformative effects of changing climates over this century upon Wisconsin vegetation and landscapes. For example, by the end of this century, under the A2 scenario, Madison's climates may resemble those in eastern Kansas, while Superior, WI's climates may resemble those found in Milwaukee. Under the A2 scenario, there is little or no overlap between Wisconsin's contemporary climates and those projected for the end of this century. Instead, the range of potential climatic analogs for late-century climates in Wisconsin stretches across a broad band stretching through Oklahoma, Kansas, Missouri, Iowa, Illinois, Michigan, Ohio, and West Virginia. Conversely, under the B1 CO_2-stabilization scenario, projected climates for northern Wisconsin most resemble those currently found in southern Wisconsin and Michigan, while the projected climates for southern Wisconsin most resemble current climates in Illinois, Iowa, and eastern Kansas.

The spatial velocity of climate change varies widely among climate variables: temperature-related variables such as mean annual temperature or mean winter temperature have the highest velocities, while

precipitation related variables tend to have the lowest velocities. The highest velocities are associated with winter temperature, reaching 5.6 km yr^{-1} (averaged across scenarios). For comparison, species ranges shifted during the climate warming accompanying the last deglaciation at rates estimated to range from 0.1 to 1 km yr^{-1}, and recent latitudinal range shifts are on the order of 1.7 km yr^{-1}. Hence, the possibility exists that some dispersal-limited species will not be able to migrate quickly enough to stay within their climatic zones without assistance. Moreover, because species are differentially sensitive to particular aspects of the climate system, the strong differences among climate variables in their projected climate velocities offers a potentially powerful mechanism for community reshuffling and the emergence of novel mixtures of species. Species that are temperature-sensitive and able to migrate quickly may experience the largest rates of northwards expansion, while species that are less temperature-sensitive or are dispersal-limited may experience either stable or contracting ranges.

Vegetation simulations by the Lund-Potsdam-Jena (LPJ) model consistently indicate that northern evergreen trees will decline in their abundance and extent in Wisconsin, while the ranges and abundances of temperate deciduous species will expand northwards. The simulated loss of evergreen tree cover ranges from 37% to 62% by 2050 and from 91% to 100% by 2100. Evergreen losses are highest for the warmer climate simulations and when the effects of climate are not ameliorated by the physiological effects of rising CO_2 on plant productivity and water use efficiency. All LPJ simulations indicate a northward expansion of deciduous trees, but differ over whether there will be a loss of deciduous trees in southern Wisconsin. In all scenarios, the amount of carbon stored in Wisconsin's natural ecosystems is predicted to decrease during the 21st century. By 2050, the loss ranges from 318 gC m^{-2} (1.7%, B1) to 1975 gC m^{-2} (10.4%, A2fixCO2). By the late 21st century, the projected loss ranges from 1037 gC m^{-2} (5.4%, B1) to 5,083 gC m^{-2} (26.7%, A2fixCO2). In the LPJ simulations, the physiological effect of CO_2 mitigates (by about two-thirds) but does not neutralize carbon losses caused by climate change alone. The importance of the CO_2 physiological effect remains uncertain and a major area of scientific research; these simulations are probably nearer to the upper-end of the strength of this effect. Projected carbon losses are highest for the climate simulations that predict the most warming and drying in Wisconsin. For the high-end A2fixCO2 scenario, Wisconsin natural vegetation is projected to lose 18.9 Tg CO_2 per year. By 2100AD, this amount increases to 29.7 TgCO_2 per year. The amount of carbon lost in the B1 scenario is about 40% of the A2 projections, suggesting a positive feedback in which efforts to mitigate global CO_2 emissions further reduces the emissions from Wisconsin terrestrial ecosystems.

In summary, all climate scenarios and all analyses based upon these scenarios project at least some amount of climate-driven vegetation change in Wisconsin over the next several decades to century. However, the difference in projected climate impacts between the B1 and A2 scenarios are large. These analyses indicate a utility to developing both climate-adaptation and climate-mitigation strategies: laying the policy and infrastructure groundwork for adapting to the climate changes that are inevitable or at least highly probable (approximated by the B1 scenario) while developing mitigation strategies that reduce greenhouse gas emissions and hence avoid the higher-end scenarios with the fastest rates of projected climate change. There is a critical need to develop adaptation strategies that will increase the resilience of Wisconsin ecosystems to projected climate change and, when necessary, ease the transition to the new communities and mixtures of species that may arise in this state over the coming century. The prospect of novel ecosystems, shaped by the intersection of climate change with new patterns of land use, new species introductions, and other drivers of ecological change, poses a new but solvable challenge to decision makers, resource managers, and other stewards of Wisconsin's natural resources. Priority actions include the testing and development of climate-adaptation management strategies, improved monitoring capacity in order to obtain early warning of gradual or abrupt change, and investment in ecological forecasting capacity.

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List of Acronyms

CCR	Center for Climatic Research, University of Wisconsin-Madison, Nelson Institute for Environmental Studies
CO_2	Carbon dioxide
EERD	Environmental and Economic Research Program
FACE	Free Air CO_2 Enrichment
GCM	General Circulation Model of the atmosphere
IPCC	Intergovernmental Panel on Climate Change
LPJ	Lund-Potsdam-Jena dynamic global vegetation model
NPP	Net Primary Productivity
PPM	Parts per million by volume
PFT	Plant Functional Type
SDM	Species Distribution Model
SED	Standardized Euclidean Distance
WICCI	Wisconsin Initiative on Climate Change Impacts

Section 1: Introduction

1.1 Climate Change and Adaptation Planning in Wisconsin

Climate sets fundamental constraints on the distribution, diversity, and abundance of species, both domesticated and wild. It affects the frequency and intensity of floods, the amount and quality of Wisconsin's water, and the length of our growing and snow seasons. Climate change has the potential to affect crop yields and to affect agricultural practice with respect to planting date, hybrid varieties, and crop rotation. There is strong evidence that historic temperature rises have already begun to affect Wisconsin landscapes, with decreases in the length of time of ice cover on Lake Mendota and other lakes and earlier timing of spring flowering and other temperature-cued events. Over this century, climate change is likely to transform the distribution and abundance of plant and animal species in Wisconsin. Some species may disappear from Wisconsin, while other immigrant species are expected to arrive, creating novel communities and landscapes, unlike those that we live in and manage today.

Given the observed historic climate changes in Wisconsin, the projections that these changes will continue and accelerate, and the known sensitivity of species to climate, there is a need to a) assess the potential effects of projected climate changes on Wisconsin's species and natural resources and b) use this information as the basis for adaptation strategies designed to improve the resistance, resilience, and response paths available to Wisconsin's ecosystems (Millar et al., 2007). In service of this goal, the Wisconsin Initiative on Climate Change Impacts (WICCI) formed a statewide partnership among scientists and stakeholders charged with 1) assessing and anticipating climate change impacts on Wisconsin's built environments, 2) evaluating the vulnerability of human and natural systems to projected climate change, and 3) recommending implementable adaptation strategies and solutions for Wisconsin's stakeholders (WICCI, 2011, p. 10). A major milestone in this effort was the publication of the 2011 report Wisconsin's Changing Climate: Impacts and Adaptation.

In this EERD-supported project, we have built upon the 2011 WICCI report by applying its downscaled 21st-century climate projections for Wisconsin to a series of analyses designed to assess and summarize the potential effects of climate change on Wisconsin's species and natural environments. Three distinct and complementary sets of analyses were performed: 1) Climate-analog analyses, which identify contemporary analogs for the future climates projected for Wisconsin (Section 2), 2) Climate-velocity analyses, which measure the spatial rate of change for multiple climate variables (Section 3), and 3) simulations of Wisconsin vegetation responses to 21st-century climate change using a dynamic global vegetation model (Section 4). The information in this report is primarily oriented towards conservation planning and management of biological resources, but the approaches shown here are general and flexible, and are applicable to other Wisconsin stakeholder needs.

1.2 Historic and Projected Climate Changes for Wisconsin

Recent research has documented that Wisconsin's climate is changing, and are projected to continue changing over at least the next several decades (WICCI, 2011). Between 1950 and 2006, average annual temperatures in Wisconsin increased by 0.6°C (1.1°F), while winter temperatures increased by 1.4°C (2.5°F) over the same period (Kucharik et al., 2010; WICCI, 2011). The length of the growing season has increased by 5 to 20 days (Kucharik et al., 2010). Annual precipitation has increased by 10% (Kucharik et al., 2010), with much of that increase attributable to an increase in the frequency and intensity of heavy precipitation events (Kunkel et al., 1999). The rising temperatures are linked to decreased lake ice duration (Ghanbari et al., 2009; Magnuson et al., 2000), earlier springtime bud-break and flowering (Bradley et al., 1999; Parmesan, 2007; Zhao and Schwartz, 2003), timing of bird migration (Bradley et al., 1999), and other shifts in seasonally temperature-cued events.

These changes are projected to continue over this century. By the middle of this century, Wisconsin temperatures are projected to increase by 2.2 to 5°C (4 to 9°F), a rate about four times the rate observed between 1950 and 2006 (WICCI, 2011). The direction of precipitation changes by mid-century is less certain: over 90% of general circulation models (GCMs) project increases in winter precipitation (Notaro et al., in press), but only half predict increases in summer precipitation (Christensen et al., 2007; Lorenz et al., 2009). Most models predict an increase in total annual precipitation, on the order of a 25% increase (WICCI, 2011). The frequency of extreme precipitation events is expected to continue to increase for the Midwestern US, particularly in the spring and fall (Cook et al., 2008; Holman and Vavrus, in press; Lorenz et al., 2009; US Climate Change Science Program, 2008).

The detailed climate trends and projections for Wisconsin that are reviewed above are the result of painstaking compilations of meteorological data (Kucharik et al., 2010; Serbin and Kucharik, 2009) and the synthesis of this data with climate-model projections by climatologists at the University of Wisconsin-Madison, working as part of the Wisconsin Initiative on Climate Change Impacts (WICCI, 2011).

A key effort by the WICCI Climate Working Group has been to statistically downscale the global climate projections for the 21st century reported in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) to an 0.1° by 0.1° (8km) grid for the State of Wisconsin. This statistical downscaling is accomplished in two stages (Notaro et al., 2010; Notaro et al., in press): first, the local weather station data is used to establish an empirical relationship between large-scale atmospheric conditions such as regional patterns of air pressure to local-scale phenomena such as daily precipitation at individual locations. Second, these relationships are applied to the 21st-century projections of the general circulation models. The particular statistical method used here is based on the bias-corrected spatial disaggregation technique (Maurer et al., 2007; Wood et al., 2004; Wood et al., 2002) but modified to predict probability density functions of daily precipitation and temperature rather than single values (Notaro et al., 2010; Notaro et al., in press). This approach better preserves information about climate variability and the probability of extreme events, while debiasing the GCM simulations to adjust for systematic offsets between the modeled and observed climates for Wisconsin (Notaro et al., 2010; Notaro et al., in press). All analyses in this report are based upon the WICCI downscaled estimates of Wisconsin's future climates. Maps of historic and projected climate changes for Wisconsin can be found at http://ccr.aos.wisc.edu/resources/data_scripts/wisconsin_climate/.

1.3 Assessing and Planning for The Effects of Projected Climate Change on Wisconsin Species and Landscapes

Plants and animals are highly sensitive to temperature and water availability, and the climate changes projected for the 21st century are expected to transform the distribution of species and hence the composition, distribution, and functioning of ecosystems. In the US and in the Northern Hemisphere, many species ranges have begun to shift northwards or upwards, in a manner consistent with global warming (Chen et al., 2011). Cold-adapted species such as black spruce, balsam fir, American marten, and snowshoe hare, may disappear from the state or at least have substantially reduced population abundances and geographic ranges by the end of this century (WICCI, 2011). Hardwood trees in southern and central Wisconsin, such as hickory, black oak, and black walnut, are expected to expand their range in Wisconsin, while species currently south of Wisconsin, whose northern limits are limited by winter cold, are expected to expand their range northward into the state. However, species responses to 21st-century climate change are unlikely to follow the simple temperature-based model of 'northern species out, southern species in' outlined above because a) species differ in both their sensitivity to particular dimensions of climate and their dispersal capacity; b) the projected temperature changes will interact with changes in other biologically important climate variables (e.g. changes in moisture availability during the growing season, the frequency of extreme climate events), with the spatial rate and direction of change varying widely among climate variables, and c) climate change in Wisconsin will interact with other phenomena such as changes in land use and housing growth (Radeloff et al., 2005; Radeloff et al., 2010) and the introduction and control of exotic species and pests such as garlic mustard, kudzu, emerald ash borer, and hemlock woolly adelgid. As a consequence, climate change is expected to alter both the species within Wisconsin and the reshuffling of these species into novel communities, unlike any seen at present (Hobbs et al., 2006; Hobbs et al., 2009; Saxon et al., 2005; Williams and Jackson, 2007).

The last deglaciation offers an important case study of the effects of climate change on physical and biological systems. Between roughly 18,000 and 6,000 years ago, the mile-high continental ice sheets covering half of North America melted away, sea level rose by over 300 feet, atmospheric CO_2 concentrations rose from 200 to 280 ppm, and species shifted their ranges by hundreds of kilometers (Williams et al., 2004). The global mean temperature rise accompanying these dramatic events was on the order of 5°C (Ruddiman, 2007) and possibly as low as 2-3°C (Schmittner et al., 2011), values within the range of temperature rises projected for this century. Over this time period, Wisconsin landscapes transformed from being mostly ice, tundra, and boreal parkland to the mixture of prairie, northern hardwoods, and mesic deciduous forests characteristic of natural landscapes today (Strong and Hills, 2005; Williams et al., 2001; Williams et al., 2000). Many of the plant communities during the last deglaciation were composed of extant species, but rearranged into mixtures not found at present (Gonzales and Grimm, 2009; Maher, 1982; Williams et al., 2001).

A standard tool in conservation planning for climate change is species distribution models (SDMs), which combine contemporary information about species-climate relationships with climate change scenarios to project future shifts in species ranges and areas of potential habitat (e.g. Elith and Leathwick, 2009; Iverson et al., 2008; Prasad et al., 2007-ongoing). SDMs are widely used to inform conservation making such as reserve selection and managed relocation of species (Hannah et al., 2007; Heller and Zavaleta, 2009; Hoegh-Guldberg et al., 2008). SDMs have a strong predictive ability when characterizing contemporary species distributions (Elith and Leathwick, 2009) and some recently observed range shifts (Kharouba, 2009) and remain a critical tool for characterizing the exposure of species to climate change (Dawson et al., 2011). However, the predictive accuracy of empirical SDMs for the 21st century is challenged by the strong individualistic behavior of species when responding to climate change (Davis, 1981); the difficulty of establishing the mechanistic underpinnings of this individualistic behavior for more than a few well-studied species (Buckley et al., 2010; Kearney and Porter, 2009); the likely emergence of 'no-analog' climates outside the range of variation recently experienced by species (Williams and Jackson, 2007; Williams et al., 2007); and the possibility that species-climate relationships will change over time due to altered genetic frequencies within populations and species (Davis et al., 2005), altered interactions among species (Gilman et al., 2010; Urban et al., 2012), and the effects of CO_2 on plant physiology (Ehleringer et al., 1997; Field et al., 1995). In summary, SDMs are a valuable but rough guide to assessing the vulnerability of species to climate change and assessing areas of conservation value (Williams et al., 2012), and we refer the interested reader to other resources employing SDMs to predict climate-driven shifts in species ranges (e.g. Morin et al., 2008; Prasad et al., 2007-ongoing).

Here we report on a series of complementary analyses designed to assess the potential effects of climate change for Wisconsin. We begin with relatively general and flexible tools – climate-analog (Section 2) and climate-velocity analyses (Section 3) then move to a mechanistic modeling of future vegetation and carbon dynamics in Wisconsin using a dynamic global vegetation model (Section 4). Climate-analog analyses (Hayhoe et al., 2010; Hayhoe et al., 2009; Veloz et al., 2012; Williams et al., 2001) provide a comparison between the future climates projected for Wisconsin and contemporary climates found elsewhere the US at present. They provide a locally-centered tool for assessing the magnitude of projected climate change, described as the spatial distance between a Wisconsin location and that of its best climatic analog. Climate-velocity analyses provide estimates of the local spatial rate of climate change, which is critical when assessing the capacity of species to migrate. Climate velocity information is one critical element for managers determining whether to employ relatively intensive climate-adaptation interventions such as managed relocation (Hoegh-Guldberg et al., 2008; McLachlan et al., 2007; Richardson et al., 2009). Dynamic global vegetation models offer a mechanistic approach to modeling the joint and separate effects of changing climate and rising atmospheric CO_2 on vegetation distributions and the sequestration of carbon in terrestrial ecosystems. We employ here the Lund-Potsdam-Jena (LPJ) model (Sitch et al., 2003) and use it to assess the possibility that Wisconsin terrestrial ecosystems will shift from their current status as a carbon sink to becoming a source of CO_2 to the atmosphere over this century.

SECTION 2: CONTEMPORARY ANALOGS FOR WISCONSIN'S FUTURE CLIMATES

2.1 INTRODUCTION

Climate-analog analysis is a place-based and comparative approach to understanding and assessing the magnitude and potential effects of climate change. In climate-analog analyses, the future climates projected for a target location are compared to all locations in a reference dataset (usually comprising the late 20th century or other reference time period), and the closest matches (i.e. the closest analogs in the reference dataset) are identified. For example, by the end of this century, analyses of the WICCI climate projections suggest that the climates in Madison, WI may most resemble those currently found in southeastern Kansas, while the climates in Superior, WI may most resemble those found in Milwaukee (Fig. 2.1, http://www.wicci.wisc.edu/climate-map.php).

Climate-analog analysis is a flexible tool with a number of useful features for adaptation planning and communication (Veloz et al., 2012). The closest matches in the reference dataset can be analyzed for information about species present, dominant crop types and farming practices, insurance costs associated with climate extremes and other natural hazards, and other climate-linked characteristics (Hallegatte et al., 2007; Hayhoe et al., 2010; Kopf et al., 2008; Parry and Carter, 1988). The climate-dissimilarity metrics embedded within climate-analog analyses are useful for summarizing multivariate changes in climate (e.g. monthly mean temperatures and precipitation) into a single composite index of climate change (Williams et al., 2007) and identifying climate-change hotspots (Diffenbaugh et al., 2008). Simply displaying the locations of the closest analogs provides a powerful visual impression of the potential magnitude of climate change, which can be measured as the spatial distance and bearing between the target and its closest analogs in the reference dataset (Ordonez and Williams, in review; Veloz et al., 2012). From the perspective of biological conservation, this information can be used to estimate e.g. the distance species might have to migrate over the next century to remain within climatic conditions similar to present (Ackerly et al., 2010; Ordonez and Williams, in review; Veloz et al., 2012). Climate-analog analyses can also be applied to identify future 'no-analog' climates, i.e. target locations where the future projected climates are dissimilar to all instances in the reference dataset (Saxon et al., 2005; Williams and Jackson, 2007; Williams et al., 2007). This analysis in reverse can be used to identify places at risk of 'disappearing' climates, i.e. climate conditions that exist today that may not exist in the future (Saxon et al., 2005; Williams et al., 2007).

In this section we describe climate-analog analyses applied to the WICCI downscaled climate projections for Wisconsin. These analyses are based on the projected climates for the middle and late 21st-century, and use observed North American climate data for the late 20th century for the reference dataset. We use three sets of climate variables: seasonal means for temperature and precipitation in combination, temperature variables only, and precipitation variables only. We analyze simulations from 15 GCMs and three emission scenarios, and compare results among scenarios and GCMs in order to estimate the uncertainty caused by choice of climate model and emissions scenario. All methods and results shown here are reported in Veloz et al. (2012), and an interactive version of the climate-analog maps can be found at http://www.wicci.wisc.edu/climate-map.php . Interested users can click on a Wisconsin target location to find other places in the US with climates similar to the future climates projected for the Wisconsin location. See also http://ccr.aos.wisc.edu/resources/data_scripts/wisconsin_climate/ for maps of projected changes for individual climate variables.

2.2 Data and Methods

The future climate projections for Wisconsin are based on the WICCI downscaled datasets (see Section 1), with climate data extracted for two time periods the middle 21st-century (2046-2065 AD) and late 21st century (2081-2100 AD). We analyzed climate simulations from the A2, A1B, and B1 emission scenarios and analyzed 11 to 14 GCMs per scenario (Table 2.1). (This variation is because some climate modeling teams either did not run all three of the emission scenarios in the 2007 IPCC Fourth Assessment Report or did not store the daily data needed for the WICCI downscaling; here we use all of the simulations downscaled by WICCI). These scenarios reflect a range of possible future economic growth, development conditions and greenhouse gas concentrations in the atmosphere, with the B1 a low-end greenhouse gas emissions scenario, the A1B a 'business-as-usual' scenario, and A2 a high-end scenario. In the B1 scenario, atmospheric CO_2 stabilizes at 550ppm by 2100 AD, while in the A2 scenario, atmospheric CO_2 reaches 820ppm and is still rising at 2100 AD (IPCC, 2000). The reference climate dataset consists of gridded observational data at 1/8° spatial resolution, with North America as the spatial domain, developed by Maurer and colleagues (2002) from meteorological station data.

For all datasets, temperature and precipitation were calculated for four seasons: winter (December, January, and February; DJF), spring (March, April, and May; MAM), summer (June, July, and August; JJA), and fall (September, October, and November; SON). For all seasons, we calculated mean daily precipitation (mm). For MAM and SON temperatures, we calculated mean monthly values, while for JJA we calculated the means of maximum daily temperatures and for DJF we calculated the means of minimum daily temperatures. These choices are intended to better capture the effects of seasonal highs and lows on species distributions.

From these simulations, we calculated seasonal values of temperatures (°C) and precipitation (mm/season). Mean seasonal values for temperature and precipitation were calculated using monthly data from 1950 to 1999. Results are reported for individual GCMs and for model ensembles, which were calculated by averaging the seasonal temperature and precipitation simulations across GCMs for each scenario and time period.

A key methodological decision in climate-analog analyses is the choice of distance metric and method for standardizing all climate variables to a common scale (Ackerly et al., 2010; Williams et al., 2007). Here we used standardized Euclidean distance (SED), calculated as

$$SED_{ij} = \sqrt{\sum_{k=1}^{n} \frac{\left(b_{ki} - a_{kj}\right)^2}{s_{kj}^2}}$$

where n is the number of climate variables, b_{kj} is the 21st-century value at target location i, a_{ki} is the 20th-century value of climate variable k at reference location j, and s_{kj} is the standard deviation of interannual variability of variable k. Standardization is necessary to put all variables on a common scale, while using interannual variability as the basis of standardization is useful because it upweights climate changes that are large relative to background variability. We used the 21st-century projections for the Wisconsin target to calculate interannual variability, so that the standardization would be the same for all SED values calculated for target i.

For each Wisconsin location, we recorded the minimum SED (i.e. the climatic distance between the target and its closest contemporary analog), the spatial distance and bearing between each Wisconsin location and its closest contemporary analog, and the percent cover of the dominant land cover type at the WI location and its closest analog. Land cover data is from the National Land Cover Database, resampled to a 250m by 250m resolution (Homer et al., 2004). We used the Tukey test (Steel et al., 1996) to determine whether results significantly differed among time periods, emission scenarios, and GCMs.

2.3 Results and Discussion

Two example locations in Wisconsin – the cities of Madison and Superior –illustrate the application of climate-analog analysis to Wisconsin's 21st-century climate change projections (Fig. 2.1). The first analysis (Fig. 2.1 a,b) compares the late 20th-century climates for these two cities to late 20th-century climates elsewhere in North America. Unsurprisingly, each city matches to itself as its own best climatic analog, and each city is roughly centered within a zone of similar climates. This zone tends to be relatively narrow with respect to latitude and broad with respect to precipitation, largely because temperature variables are upweighted in importance relative to precipitation. This upweighting occurs because precipitation tends to have a higher interannual variability relative its spatial variability, downweighting the contribution of precipitation to the standardized Euclidean distance metric.

By the mid-21st century, as temperatures in Madison and Superior rise, the locations of their most similar 20th-century climates are shifted southward (Fig. 2.1 c-f). The closest contemporary analog for Madison's mid-21st-century climates is found in western Illinois, while the closest analog for Superior is found in the Milwaukee area of southeastern Wisconsin (Fig. 2.1 c,d). By the late 21st century, the 6.7°C (12.06°F) mean annual warming projected for Madison (for the model ensemble) causes the location of Madison's closest analog to shift to the border between eastern Kansas and Oklahoma. Interestingly, a similar amount of warming is projected for Superior (6.1°C, or 11.0°F), but the closest contemporary analog remains in the Milwaukee area, presumably because Superior's position near Lake Superior tends to constrain its pool of potential climatic analogs to other locations also close to the Great Lakes.

The results shown for Superior and Madison are generally representative of the changes expected for northern and southern Wisconsin, except that Superior is more affected by its proximity to the Great Lakes than other northern Wisconsin locations. By the middle of this century, projected climates for northern Wisconsin most resemble those currently found in southern Wisconsin and Michigan, while the projected climates for southern Wisconsin most resemble current climates in Illinois, Iowa, and eastern Kansas (Fig. 2.2 a,c,e). The results for the three socioeconomic scenarios (B2, A1B, and A2) are generally similar, suggesting a relatively high confidence in mid-century climate projections. This is useful information for conservation planning, because it suggests that choice of emission scenario is a relatively small source of uncertainty for near-term planning efforts (Hawkins and Sutton, 2009).

However, by the end of this century, the climate-analog results differ strongly among scenarios. For the low-end B2 socioeconomic scenario, in which atmospheric CO_2 and climates stabilize by mid-century, the distribution of climate analogs is generally stable between the middle and late 21st century (Fig. 2.2 a,b). For the 'business-as-usual' A1B and A2 scenarios, in which greenhouse gases and global temperatures continue to rise through the 21st century, the belt of contemporary analogs to Wisconsin's late-21st-century climates continues to expand southward and westward (Fig. 2.2 d,f). Under these higher-end scenarios, the contemporary analogs for Wisconsin's future climates are almost all outside the state's border, in a belt stretching through Oklahoma, Kansas, Missouri, Iowa, Illinois, Michigan, Ohio, and West Virginia.

The spatial dispersal in the climatic analogs (Fig. 2.2) is caused by contemporary climatic differences among Wisconsin locations and by differences among GCMs in their future climate projections. Because the former is constant while the latter varies among the GCM climate simulations, this spatial dispersal serves as a useful index for the amount of uncertainty in climate change projections. In general, the amount of uncertainty increases from low-emission to high-emission socioeconomic scenarios (Fig. 2.2 a,b vs. c-f) and from the near future to the more distant future (Fig. 2.2 a,c,e vs. b,d,f). The relatively narrow latitudinal range of analogs compared to the very wide longitudinal range of analogs (Fig. 2.2) is because the range of variations among models in their temperature projections is small relative to their precipitation projections: higher uncertainty in precipitation translates to a broader sampling of analogs across the east-to-west moisture gradient (Fig. 2.2 h) in eastern North America. Thus, projected warming acts as the first-order control on the selection of analogs, while precipitation acts as an additional but more uncertain constraint.

These analog results can be aggregated to spatial units according to stakeholder and management needs. For example, analog analyses for the Central Sand Plains Ecological Landscape (Fig. 2.3) suggest that by the middle of the 21st century, its climates may resemble those found in eastern Iowa today, while by the end of this century, its climates may resemble those found in eastern Kansas. Similarly, the climate-analog analyses can be used to find climatic 'sister cities' for Wisconsin cities (Table 2.2), with late 20th-century climates that resemble the projected future climates for Wisconsin. For example, under the low-emission B1 scenario, Milwaukee's climates may resemble those of Akron, Ohio by the end of this century, or, under the high-emission A2 scenario, Milwaukee's climates may resemble those of St. Louis, MO (Table 2.2).

SECTION 3: CLIMATE VELOCITY

3.1 INTRODUCTION

Climate-velocity analysis, introduced by Loarie et al. (2009), complements SDMs and climate-analog analyses because it serves as a measure of climate risk that describes the local *rate* of climate change, in ecologically relevant terms. Species have four basic options when responding to climate change and climate variability: migrate to newly favorable regions, persist *in situ* with local changes in abundance, evolve, or go extinct (Blois and Hadly, 2009). During past glacial-interglacial cycles, migration has been a primary mechanism by which species have accommodated past climate changes (e.g. Davis, 1976; Webb, 1981). However, projected 21st-century rates of climate change are as fast or faster as those observed during past glacial-interglacial cycles (Overpeck et al., 2003) and species dispersal now is hindered by habitat fragmentation. Hence, there is a risk that the rates of climate change projected for this century may be too fast for species with limited dispersal capacity to keep up (Loarie et al., 2009; Pearson, 2006; Schloss et al., 2012), and climate-velocity analysis is a tool for assessing that risk (Ackerly et al., 2010).

Climate-velocity analysis essentially rescales 21st-century climate-change projections to estimates of the spatial rate of climate change. This is accomplished by dividing the projected temporal rates of change for a climate variable by the local spatial rates of change for that same variable. For example, the velocity (V) of mean annual temperature (T) is calculated as:

$$V_T = \frac{T_t}{T_s}$$

where the units for V_T is °C/km, T_t is the projected temporal rate of change between two reference time periods (°C/yr) and T_s is the local spatial rate of change at a location (°C/km). T_s is calculated by measuring the mean difference between the temperatures at a target grid cell with respect to the temperatures at its neighbor grid cells (Loarie et al., 2009), and so represents local-scale heterogeneity in T. High-velocity areas are inferred to correspond to higher risk for dispersal-limited species and may be priority regions for the managed relocation of species (Hoegh-Guldberg et al., 2008), particularly in areas of high biodiversity (Burrows et al., 2011). Recent analyses suggest that endemic species (i.e. species with small geographic ranges) are preferentially found in areas with historically low climate velocities, suggesting that these regions have been important climatic refugia for species with limited dispersal capacity (Sandel et al., 2011).

Because spatial heterogeneity is incorporated into climate velocity analysis, an interesting aspect of climate velocity analysis is that it is highly correlated with topographic heterogeneity; therefore it predicts low temperature velocities in mountainous areas, and high temperature velocities in low-relief areas (Ackerly et al., 2010). This is because temperature gradients are much steeper by elevation than by latitude, so e.g. a 1°C warming translates into a smaller spatial displacement and lower velocity. An implication of this approach is that mountainous areas and other heterogeneous areas may serve as important buffers for species tracking climate change by offering many nearby micro- and meso-scale climatic refugia for species (Ackerly et al., 2010; Sandel et al., 2011).

A key limitation of climate velocity analyses to date is that they have been univariate, focusing on mean annual temperature alone (Burrows et al., 2011) or at most bivariate, considering mean annual temperature and precipitation (Ackerly et al., 2010). Univariate analyses focusing on temperature are a reasonable first-pass indicator of climate risk, but overlook the effects of changes in precipitation, seasonal timing, extreme events, and other climatic factors on population abundances and species distributions. Additionally, focusing on mean annual temperature alone may underestimate maximum climate velocity, because in these analyses winter temperatures are projected to warm at a faster rate than mean annual temperature (Ordonez and Williams, in review; WICCI, 2011). Species tend to respond individualistically to climate change, because each species is uniquely sensitive to particular aspects of the climate system and because species differ in their dispersal method and capability. Hence, differences among climate variables in their 21st-century direction and rates of climate change act as a potentially powerful mechanism for reshuffling species into novel communities (Ordonez and Williams, in review). Last, climate-velocity analyses to date have not provided information about the direction of climate change but only the local rate.

In this section, we present multivariate climate velocity analyses for Wisconsin for 19 climate variables. Wisconsin offers a useful example of climate complexity in an area of relatively low topographic variability. Because Wisconsin is in the middle of the North American continent (meaning that its projected 21st-century temperature rises are relatively large, Christensen et al., 2007) and because topographic variability is generally low, we can expect that climate velocities for the state will be relatively high. However, the distribution of Wisconsin species and vegetation is strongly affected by its position at the intersection between two major climatic gradients: a north-south gradient in temperature and an east-west gradient in precipitation and moisture availability, each of which is modified by proximity to Lakes Superior and Michigan (Curtis, 1959). All analyses in this section are originally reported in Ordonez and Williams (in review).

3.2 Data and Methods

All climate-velocity analyses use the WICCI projected climate datasets described in Sections 1 and 2. Two reference time periods were used in this analysis: late-20th-century (1961 to 2000) observational datasets and downscaled late-21st-century climate projections (2081 to 2100). All analyses were based on the WICCI resolution of 5 arc-minutes or 8 km. We used the three emission scenarios (B1, A1B, A2) described above. All analyses used the climate-model ensembles, in which results were averaged across the simulations from individual climate models (Section 2).

The 19 climate variables represent a mixture of climatic and 'bioclimatic' variables that are widely used in species distributional modeling, phenological modeling, and other studies of climate-driven ecological dynamics (e.g. Burrows et al., 2011; Elith and Leathwick, 2009; Fitzpatrick et al., 2008; Fitzpatrick et al., 2011; Heikkinen et al., 2006). The variables used are annual mean temperature, mean diurnal range, isothermality, temperature seasonality, maximum summer temperature, minimum winter temperature, temperature annual range, mean temperature of the wettest quarter, mean temperature of the driest quarter, mean summer temperature, mean winter temperature, annual precipitation, precipitation of the wettest month, precipitation of the driest month, precipitation seasonality, precipitation of the wettest quarter, precipitation of the driest quarter, summer precipitation, and winter precipitation. All variable definitions follow those in the WorldClim dataset (Hijmans et al., 2005).

We first show the projected changes for individual climate variables, using histograms to show changes in the availability of particular climatic conditions within Wisconsin. Results are summarized for the state (Fig. 3.1) and for five ecoregions within the state (Appendix 1): the Driftless Area, North-Central Hardwood Forests, Northern Lakes and Forests, Southeastern Wisconsin Till Plains, and Western Corn Belt Plains. Ecoregions were defined using the EPA-Level III ecoregions of North America (Commission for Environmental Cooperation, 1997, 2009; Wiken et al., 2011, http://www.cec.org/Page.asp?PageID=924&ContentID=2336).

Temporal gradients in variables were calculated as the slope of a linear model fitted through all years from 2000 to 2100AD. Spatial gradients were calculated as the average difference in climatic variables between a target grid cell and its eight neighboring grid cells in a 3x3 window, using the average maximum technique (Burrough and McDonnell, 1998).

3.3 Results and Discussion

Projected changes for the 19 climate variables follow the patterns summarized in Section 1.2: temperatures rise and annual precipitation increases (Fig. 3.1). These patterns are similar across emission scenarios (Fig. 3.1) and ecoregions (Appendix 1). The overall shape of the distribution of climate variables in Wisconsin remains the same between the late 20th and late 21st-centuries (e.g. a pronounced bimodality in summer temperature) but the mean position of the distribution shifts. For temperature-related variables such as mean annual temperature or mean winter temperature, there is little or no overlap between their late 20th century and late 21st century distributions, under the upper end socioeconomic scenarios (Fig. 3.1). This pattern reinforces the finding that the best contemporary analogs for Wisconsin's projected late-21st-century climates are largely outside of the state (Fig. 2.2).

The spatial velocity of change varies by an order of magnitude among variables, with median velocities ranging from 0.1 to 4.3 km/yr (Fig. 3.2). Velocities for temperature-related variables are higher than velocities for precipitation-related variables, e.g. the velocity of mean annual temperature is an order of magnitude higher than for mean annual precipitation (Fig. 3.2). The mean velocity of mean annual temperature for Wisconsin (4.3 km yr^{-1}, averaged across scenarios) is higher than the global average (0.08 to 1.26 km yr-1, Loarie et al., 2009). Additionally, in Wisconsin, the velocity of winter temperature is higher than for annual temperature, reaching 5.6 km yr^{-1} (Fig. 3.2). Thus, these results indicate that the rate of climate change in Wisconsin will be as fast or faster than expectations based on global averages. Moreover, velocity analyses based on mean annual temperature alone can underestimate the maximum potential climate velocity.

Given that species vary in their climatic sensitivity and dispersal capacity, the large differences among climatic variables in their projected velocities creates a mechanism for differential rates and directions of species migration and the reshuffling of species into novel associations. For example, species with a high dispersal capability and a strong sensitivity to temperature may be expected to rapidly shift their ranges northwards, as is predicted by SDMs (e.g. Morin et al., 2008; Prasad et al., 2007-ongoing). However, species that are dispersal limited may show more gradual or static range dynamics. Evidence for the latter is provided by recent analyses of juvenile and adult tree species distributions in the Forest Inventory Analysis surveys, which suggest that many tree species are either experiencing stable or contracting ranges at their northern limits (but see Woodall et al., 2009;

Zhu et al., 2011). Species that are primarily tracking changes in moisture availability, rather than temperature, may also experience relatively small range shifts. However, for moisture-limited species, the velocity and direction of change is more uncertain due to the uncertainty in GCM projections in precipitation (Fig. 2.2).

Section 4: Vegetation and Land Carbon Projections for Wisconsin

4.1 Introduction

How will the projected climate changes affect forest structure and carbon sequestration in Wisconsin? In recent decades, both global and US forests have been a net carbon sink, most likely because these ecosystems are regrowing following 19th- and 20th-century land clearance, with other factors including climate change, rising atmospheric CO_2, and nitrogen deposition (Hurtt et al., 2002; Pacala et al., 2001; Pan et al., 2011). Wisconsin forests also appear to be a net sink at present; forest inventories suggest that Wisconsin forests sequestered 1.92 to 2.1 7.7 Tg C yr^{-1} (7.9 to 8.5 million tons of CO_2) between 1992 and 2001 (Brown et al., 2008). This sink was mainly due to carbon sequestration within standing forests, with a smaller contribution attributed to an estimated net increase in forest extent on the order of 0.98 million acres (Brown et al., 2008). At smaller spatial scales, the net carbon balance of Wisconsin ecosystems is heterogeneous, with some areas close to a net balance or net releasing CO_2 to the atmosphere, due to local variations in vegetation type, forest harvest, and disturbance history (Desai et al., 2007; Schwalm et al., 2010). Existing forests in Wisconsin may have the capacity to sequester another 69 Tg C, while reforestation of less-optimal agricultural lands in north-central Wisconsin could sequester an additional 150 Tg C (Rhemtulla et al., 2009). Thus, Wisconsin forests appear to have been partially offsetting current greenhouse gas emissions from fossil fuel use in Wisconsin, estimated at 123 Tg CO_2 equivalents per year in 2003 (Governor's Task Force on Global Warming, 2008), and forestry practice has the potential to partially mitigate future emissions.

However, climate change is expected to alter the composition and distribution of Wisconsin's forests and thereby alter the amount of carbon sequestered in Wisconsin ecosystems. Trees are expected to shift their ranges northwards, with boreal trees decreasing in abundance and possibly becoming minor elements or disappearing altogether (Swanston et al., 2011; WICCI, 2011). In this section, we use the Lund-Potsdam-Jena dynamic global vegetation model (LPJ), driven by the WICCI downscaled climatologies, to simulate potential changes in vegetation structure and the terrestrial carbon budget for Wisconsin. This section summarizes analyses and results originally reported in Notaro et al. (in press).

4.2 Data and Methods

The Lund-Potsdam-Jena dynamic global vegetation model (LPJ) is designed to simulate vegetation structure and functioning at regional to global scales and across a range of timescales. It combines a mechanistic representation of 'fast' physiological processes such as photosynthesis, respiration, and transpiration, and 'slow' processes such as plant establishment, plant growth, mortality, post-fire recovery, and soil biogeochemistry (Gerten et al., 2004; Sitch et al., 2003). The basic unit in LPJ, as with other dynamic global vegetation models, is the plant functional type (PFT), which represents a group of species sharing similar functional traits and life history strategies. LPJ has 10 PFTs, including eight tree PFTs (e.g. boreal broadleaved summergreen tree, temperate needleleaved evergreen tree) and C3 and C4 grasses (Sitch et al., 2003). LPJ accurately simulates global-scale vegetation (Sitch et al., 2003), interannual vegetation responses to climate variability (Lucht et al., 2002), fire (Thonicke et al., 2001), and vegetation hydrology (Gerten et al., 2004; Sitch et al., 2003). Key processes not included in the version of LPJ used here are a representation of agricultural plant types or anthropogenic land use, dispersal limitation on the migration of plant species, and nitrogen cycling.

In LPJ, terrestrial carbon can be sequestered in six pools: heartwood, sapwood, leaves, litter, intermediate soil organic matter, and slow organic matter. Plant photosynthesis, measured as net primary productivity (NPP), removes CO_2 from the atmosphere, while heterotrophic respiration and disturbance release CO_2 to the atmosphere; the net carbon balance of terrestrial is determined by the difference between these processes (Chapin et al., 2002). In LPJ, atmospheric CO_2 exerts a direct and positive effect on NPP by increasing the intracellular ratio of photosynthesis to photorespiration. Higher atmospheric CO_2 also affects water use efficiency by allowing plants to reduce stomatal conductance at the leaf scale and hence reduce transpiration losses, which can in turn alter the competitive balance among tree and grass and C_3 and C_4 PFTs (Field et al., 1995; Gerber et al., 2004; Harrison and Prentice, 2003). These direct effects of CO_2 on plant physiology are distinct from the radiative effect of CO_2 on the global climates, but the strength of the physiological effect of CO_2 at decadal and longer time scales remains uncertain (Norby et al., 2005); field experiments and historical observations suggest that the effect of CO_2 fertilization may be weaker than indicated by closed-chamber experimental manipulations (Gedalof and Berg, 2010; Long et al., 2006). Our experimental design (below) is intended in part to assess the effects of climate change on Wisconsin vegetation and carbon balance with and without a strong CO_2 fertilization effect.

We used WICCI downscaled climate projections from 9 GCMs to drive LPJ, for the A2 and B1 emission scenarios (Table 4.1). For each GCM simulation, the WICCI downscaling procedure creates a time-varying probability density function of daily temperature and precipitation (Notaro et al., 2010), that is determined by the statistical relationship between local meteorological station data and the large-scale state of the atmosphere. For each simulation, we sampled from these PDFs to create three random realizations of Wisconsin's projected climates to drive LPJ. This approach enables the simulation of local-scale daily variability in a manner consistent with the large-scale climatic forcing simulated by coarse-resolution GCMs (Notaro et al., in press). Climate inputs to LPJ are monthly mean surface air temperature, precipitation, and cloud cover fraction, and the number of days per month with more than 1 mm rainfall. We estimated cloud cover fraction, which is not available in the WICCI downscaled datasets, by regressing it against temperature and precipitation data from seven Wisconsin meteorological stations (Notaro et al., in press). Soil properties are based on State Soil Geographic (STATSGO) data compiled by the National Resources Conservation Service of the US Department of Agriculture. We regionally tuned LPJ by comparing its simulation of late-20th vegetation to observed maps, then adjusting the summer warmth limit for boreal tree PFTs from 23°C to 22°C.

We ran sets of LPJ simulations for four scenarios, designed to assess the joint effects of climate scenarios (A2 vs. B1) and the plant-physiological effects of rising atmospheric CO_2 on Wisconsin vegetation and terrestrial carbon balance. In the A2fixCO2 and A2 sets of simulations, LPJ was driven by the WICCI downscaled datasets for the A2 scenario. In the A2fixCO2 set, atmospheric CO_2 is fixed at 374 ppm for the entire simulation. For the A2 set, atmospheric CO_2 follows the trajectory used to drive the GCM simulations, rising to 820ppm by 2100 AD. Hence, the A2 set of LPJ simulations assesses the combined effects of climate change and rising CO_2 on Wisconsin vegetation, while the A2fixCO2 isolates the effect of climate change alone, in essence assuming that there is no long-term fertilization effect. The B1fixCO2 and B1 sets follow a parallel design, for the B1 climate-change scenario.

Twenty-seven LPJ simulations were run for each set (9 GCMs x 3 downscaled realizations per GCM). Because LPJ is designed to simulate potential vegetation dynamics, and does not include a representation of agricultural or urban vegetation, we ran LPJ for the entire state, then applied an anthropogenic land use mask based on the Agricultural Lands in the Year 2000 dataset (Ramankutty et al., 2008). When masking the LPJ simulations, we multiplied the projected change for a grid cell by the fraction of non-agricultural and non-urban land in that grid cell. Thus, a grid cell occupied entirely by agricultural and urban land cover would not contribute to the carbon sequestration estimates calculated here.

4.3 Results and Discussion

In the LPJ simulations, evergreen tree cover declines and deciduous tree cover increases in all scenarios (Table 4.2, Fig. 4.1), consistent with other predictions that climate change will lead to a reduced extent or disappearance of the northern evergreens and hardwoods of northern Wisconsin (Jones et al., 1994; Prasad et al., 2007-ongoing; Scheller and Mladenoff, 2008; WICCI, 2011). The simulated loss of evergreen tree cover ranges from 37% to 62% by 2050 and from 91% to 100% by 2100. In LPJ, the primary driver of evergreen loss is the bioclimatic limit of summer warmth, which causes PFT mortality when this limit is exceeded for that grid cell. By 2100 AD, the tension zone, marking the ecotone between the southern deciduous forests and northern hardwoods (Curtis, 1959), has either moved north of Wisconsin or across the northern part of the state (Fig. 4.1). Deciduous tree fraction tends to increase in northern Wisconsin, as thermophilous tree taxa expand their ranges northwards. However, some models simulate a decrease in deciduous tree cover in southern Wisconsin by 2050 and 2100 AD, in response to increased evaporative demand and soil drying that leads to prairie expansion. As a result, the gain in deciduous tree cover tends to be similar to or somewhat less than the loss in evergreen tree cover (Fig. 4.1).

The effect of these changes on total tree cover varies among scenarios and time periods (Table 4.2, Fig. 4.2). Tree cover declines and grass cover increases in the A2fixCO2 and B1fixCO2, with the largest decrease in tree cover (-0.08) simulated for the A2fixCO2 scenario, representing a potential loss of 12.6% of current Wisconsin forest cover by 2100AD. Conversely, there is no net change in forest cover by 2100 AD in the A2 and B1 scenarios (Table 4.2). Hence, in the LPJ simulations, the losses in tree cover caused by climate change are largely balanced by the physiological effects of $CO_{2,}$ although terrestrial carbon is still released to the atmosphere (Table 4.2). However, caution should be exercised in interpreting this result; the strength of the CO_2 physiological effect remains a significant source of uncertainty in terrestrial ecosystem modeling and a major frontier in ecosystems research (Long et al., 2006; Moorcroft, 2006).

In all scenarios, the amount of carbon stored in Wisconsin's natural ecosystems is predicted to decrease during the 21st century (Table 4.2). By 2050, the loss ranges from 318 gC m^{-2} (1.7%, B1) to 1975 gC m^{-2} (10.4%, A2fixCO2). By the late 21st century, the projected loss ranges from 1037 gC m^{-2} (5.4%, B1) to 5,083 gC m^{-2} (26.7%, A2fixCO2). In the LPJ simulations, carbon fertilization offsets roughly two-thirds of the carbon loss due to climate change. For the A2 scenario, the 'business as usual' scenario that includes both the effects of climate change and CO_2 physiological effects, the projected carbon loss is 834 gC m^{-2} (4.4%) by 2050 and 1,804 gC m^{-2} by the late 21st century, roughly double the losses projected for the B1 scenario in which CO_2 is stabilized in the atmosphere at 550 ppm.

Most of the carbon losses are caused by a decrease in the size of vegetation carbon pool, and can be primarily attributed to tree mortality and carbon respiration associated with the conversion of northern evergreen forests to deciduous forests (Table 4.2). In the A2 scenario, vegetation losses are responsible for 78% of the carbon lost from Wisconsin's natural vegetation by middle of this century, due to the rapid losses of evergreen forests. In the A2 scenario, the vegetation carbon pool stabilizes between the middle and late 21st century, but the amount of carbon loss triples for carbon loss, so that by the end of this century the proportion of terrestrial carbon losses attributable to above-ground vegetation decreases to 62%, with the remaining losses in the litter and soil carbon pools.

The projected loss of land carbon is seen in all simulations for individual GCMs, but is strongest for the models predicting the most warming and drying for Wisconsin. For example, under A2fixCO2, CSIRO MK3.0

simulates a modest warming of 4.3°C and increased precipitation (+9.5 cm/year), producing a simulated loss of 2875 gC m^{-2} by the late 21st century. Conversely, MIROC 3.2 (medres) simulates a dramatic warming of 8.8°C and a drying of 11.8 cm/yr, resulting in a simulated loss of 7350 gC m^{-2} by the late 21st century.

In summary, these results suggest that Wisconsin terrestrial ecosystems have the potential to shift from a carbon sink to a carbon source over the coming decades, with the most carbon released to the atmosphere for the higher-warming scenarios and for scenarios in which the fertilization effect of CO_2 is weak. For the high-end A2fixCO2 scenario, the 1975 gC m^{-2} mean projection for 2050 AD is equivalent to Wisconsin natural vegetation releasing 18.9 Tg CO_2 per year. By 2100AD, this amount increases to 29.7 TgCO_2 per year. The amount of carbon lost in the B1 scenario is about 40% of the A2 projections, suggesting a positive feedback in which efforts to mitigate global CO_2 emissions further reduces the emissions from Wisconsin terrestrial ecosystems.

A critical uncertainty for modeling the future carbon balance of Wisconsin forests is the rate of mortality for northerly tree species versus the rate of range expansion and growth of southerly tree species. LPJ does not consider seed dispersal or other limits to migration, so the northward expansion of temperate tree PFTs likely occurs at a rate faster than would occur naturally. Managed relocation of southerly species may be a management tool for facilitating range expansion and encouraging carbon sequestration, but its risks and benefits should be carefully weighed prior to implementation (Hoegh-Guldberg et al., 2008; Richardson et al., 2009). Conversely, the mortality rates of northern evergreen trees caused by climate change may be overemphasized by LPJ, which models bioclimatic limits to PFT ranges as a threshold (Sitch et al., 2003). However, a range of ecological models predict population declines and range contraction for northern evergreen trees (Prasad et al., 2007-ongoing; Scheller and Mladenoff, 2008), so the critical questions center on how quickly and when the expected decline of northern tree species will occur.

A second critical area of uncertainty is the parameterization of carbon-cycle processes in LPJ, especially with respect to the estimated strength of the CO_2 fertilization effect (Lucht et al., 2006; Zaehle et al., 2005). The scenarios reported here show a strong sensitivity to the physiological effect, as has been reported in other sensitivity experiments with LPJ (Gerber et al., 2004; Harrison and Prentice, 2003; Notaro et al., 2007). Free-air CO_2 enrichment (FACE) experiments have shown that adding CO_2 can lead to sustained gains in photosynthetic rates in C_3 plants, despite plant acclimation and downregulation of Rubisco enzymatic activity (Leakey et al., 2009). However, in FACE experiments in soybean and wheat croplands, the observed yield gain in the open-air agroecosystems is about half that observed in laboratory settings (Long et al., 2006). Similarly, analyses of 20th-century rates of tree growth suggest that a CO_2 fertilization effect is detectable at only about 20% of sites, with no evidence for changes in water use efficiency or drought tolerance (Gedalof and Berg, 2010). The CO_2 fertilization effect as simulated by LPJ appears to be consistent with the range of observations (Norby et al., 2005), but is likely on the higher end of what might occur. Hence, the A2 and A2fixCO2 (and the B1 and B1fixCO2) scenarios offer bracketing estimates of the CO_2 fertilization effect and the degree to which it may ameliorate projected losses of carbon from Wisconsin natural vegetation.

Section 5: Conclusions and Recommendations

Several common themes emerge from these analyses. First, the higher-end climate-change scenarios (A2, A1B) are projected to have transformative effects on Wisconsin's ecosystems by the end of this century. Under the A2 scenarios, the closest analogs for Wisconsin's 2100AD climates extend as far southwest as eastern Kansas and Oklahoma, with little or no overlap between the late-20th-century climates of Wisconsin and those projected for the state by the end of the century. Northern evergreen tree species such as white spruce, red pine, and balsam fir would be expected to experience extensive range contractions or disappear from the state by the end of this century. The spatial velocities of temperature-related variables are as high as 5.6 km/yr, about 4 times faster than estimated rates of tree species migration (0.1 to 1 km/yr) during past glacial-interglacial climate changes (Davis, 1976; Pearson, 2006; van der Knaap et al., 2005). Recent latitudinal range shifts are on the order of 1.7 km per year (Chen et al., 2011). The mean simulated loss of carbon from Wisconsin terrestrial ecosystems by 2100 AD may be as high as 29.7 TgCO2 per year, if there is no long-term CO_2 fertilization effect.

Second, the differences in climatic impacts between the B1 and A2 scenarios are large, with respect to Wisconsin species and ecosystems and the services that they provide. In the B1 scenarios, northern evergreen trees are projected to persist in Wisconsin, although with reduced ranges and abundances. The carbon losses associated with the B1 scenarios in the LPJ simulations are about 40% of those associated with the corresponding A2 scenarios. Under the B1 scenario, end-century Wisconsin climates are projected to resemble those found in southern Wisconsin, northern Illinois, eastern Iowa, and southern Michigan –a significant change, but less extreme than those projected for the A2 and A1B scenarios. Similarly, the maximum climate velocities expected for the B1 scenario, which are associated with mean seasonal and annual temperatures, are about two-thirds of the values projected for the A2 scenarios (Appendix 2), reducing the risk posed to dispersal-limited species. In short, efforts to mitigate carbon emissions are expected to substantially reduce the rate and magnitude of projected climate changes, and thereby reduce the vulnerability of Wisconsin's natural resources to climate change.

Third, given that climate change is underway and that some further amount of climate change appears inevitable, there is a critical need to develop and test management strategies for adaptation (WICCI, 2011). Climate change and its intersection with new patterns of land use, new species introductions, and other drivers of ecological change pose a strong likelihood that novel ecosystems will emerge this century, characterized by the resorting of existing species into strange new arrangements and interactions (Hobbs et al., 2006; Hobbs et al., 2009; Williams and Jackson, 2007). This prospect poses a new set of challenges to decision makers, resource managers, and other stewards of Wisconsin's natural resources. Adaptation strategies will have to account for the dynamism inherent to species responses to climate variability and should be designed to increase the resistance, resilience, and response options for Wisconsin's ecosystems (Millar et al., 2007). Because it is likely that novel management solutions will be required to manage this time of transition, there is a critical need now to experiment with alternate management strategies, and establish the capacity to assess the effects of these management strategies over the next several decades (Seastedt et al., 2008). Other critical scientific needs include improved monitoring capacity in order to detect changes or signals of imminent change, and the continued development and application of predictive models (Clark et al., 2001), while recognizing that there may be limits to ecological forecasting capacity (Beckage et al., 2011).

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Tables and Figures

Table 2.1: List of climate models used in the WICCI downscaled dataset

Originating group	Country	Model ID	Reference	20C3M	A2	B1	A1B
Canadian Centre for Climate Modelling & Analysis	Canada	CGCM3.1 (T47)	(Flato et al., 2000)		X	X	X
Canadian Centre for Climate Modelling & Analysis	Canada	CGCM3.1 (T63)	(Flato et al., 2000)			X	X
Météo-France / Centre National de Recherches Météorologiques	France	CNRM-CM3	(Déqué et al., 1994)		X	X	X
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.0	(Gordon and O'Farrell, 199		X	X	X
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.5	(Gordon et al., 2002)		X	X	X
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.0	(Delworth et al., 2006)		X	X	X
NASA / Goddard Institute for Space Studies	USA	GISS-AOM	(Lucarini and Russell, 2002			X	X
LASG / Institute of Atmospheric Physics	China	FGOALS-g1.0	(Yu et al., 2004)			X	X
Instituto Nazionale di Geofisica e Vulcanologia	Italy	INGV-ECHAM4	(Valcke et al., 2000)		X		X
Institut Pierre Simon Laplace	France	IPSL-CM4	(Dufresne and Friedlingste		X	X	X
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan	MIROC3.2(hires)	(Hasumi and Emori, 2004)			X	X
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan	MIROC3.2(medres)	(Hasumi and Emori, 2004)		X	X	X
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group	Germany / Korea	ECHO-G	(Roeckner et al., 1996)		X	X	X
Max Planck Institute for Meteorology	Germany	ECHAM5/MPI-OM	(Giorgetta et al., 2002)		X	X	
Meteorological Research Institute	Japan	MRI-CGCM2.3.2	(Kitoh et al., 1995)		X	X	X

Table 2.2: Wisconsin's 20 most populous cities and the locations of their climatic 'sister cities,' i.e. the US cities with late 20th-century climates analogous to the projected future climates for Wisconsin cities. Results are shown for the low-end B1 and upper-end A2 scenarios, for the late 21st-century. Results are based on Wisconsin's Climate Analog Mapping tool http://www.wicci.wisc.edu/climate-map.php and are expanded on results shown in Table 1 of Veloz et al. (2012).

	A2 Scenario (higher end scenario)					B1 Scenario (lower end scenario)			
WI City	**Analog City**	**Analog State**	**Distance (km)**	**Distance (miles)**		**Analog City**	**Analog State**	**Distance (km)**	**Distance (miles)**
Appleton	Barry	IL	552	343		Toledo	OH	516	321
Beloit	Winfield	MO	886	551		Barry	IL	363	226
Brookfield	St Louis	MO	510	317		Petersburg	WV	883	549
Eau Claire	Salina	KS	1239	770		Des Moines	IA	395	245
Fond du Lac	Wichita	KS	1006	625		Spencerville	OH	476	296
Green Bay	Harrisonburg	WV	1005	624		Toledo	OH	505	314
Greenfield	St Louis	MO	506	314		Akron	OH	573	356
Janesville	Winfield	KS	1269	789		Barry	IL	372	231
Kenosha	Charlestown	WV	940	584		Russelldale	WV	835	519
La Crosse	Wichita	KS	826	513		Grant City	MO	448	278
Madison	Howard	KS	886	551		Mason City	IL	318	198
Milwaukee	St Louis	MO	519	322		Akron	OH	573	356
New Berlin	St Louis	MO	503	313		Russelldale	WV	867	539
Oshkosh	Wichita	KS	1028	639		Pontiac	IL	343	213
Racine	Akron	OH	555	345		Chicago	IL	96	60
Sheboygan	Harrisonburg	VA	946	588		Toledo	OH	424	263
Waukesha	Waukesha	MO	497	309		Springfield	WV	884	549
Wausau	Kirksville	MO	565	351		Dubuque	IA	273	170
Wauwatosa	St Louis	MO	513	319		Petersburg	WV	876	544
West Allis	St Louis	MO	506	314		Russelldale	WV	867	539

Table 2.3: The average geographic distance (km) between Wisconsin locations and their closest climatic analogs, for the three 21st-century socioeconomic scenarios (B2, A1B, A2) and time periods (2046-2065 and 2081-2100). Results drawn from Table 2 in Veloz et al. (2012).

	B1	**A1B**	**A2**
2046-2065	460	639	570
2081-2100	562	861	926

Table 4.1: The list of GCMs used in for the LPJ dynamic vegetation modeling. From Table 1 in Notaro et al. (in press).

Originating group	**Country**	**Model ID**	**Reference**
Canadian Centre for Climate Modelling & Analysis	Canada	CGCM3.1 (T63)	Flato *et al*. (2000)
Météo-France / Centre National de Recherches Météorologiques	France	CNRM-CM3	Déqué *et al*. (1994)
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.0	Gordon and O'Farrell (1997)
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.5	Gordon *et al*. (2002)
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.0	Delworth *et al*. (2006)
Institut Pierre Simon Laplace	France	IPSL-CM4	Dufresne and Friedlingstein (2000)
Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan	MIROC3.2(medres)	Hasumi and Emori (2004)
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group	Germany, Korea	ECHO-G	Roeckner *et al*. (1996)
Meteorological Research Institute	Japan	MRI-CGCM2.3.2	Kitoh *et al*. (1995)

Table 4.2: Projected changes in Wisconsin vegetation and carbon for the four sets of LPJ simulations (A2, A2fixCO2, B1, B1fixCO2). Variables shown are tree cover fraction (on a 0 to 1 scale, where 1 indicates 100% cover of a grid cell), grass cover fraction, total vegetation cover fraction (tree+grass fractions), evergreen tree cover fraction, deciduous tree cover fraction, total land carbon (gC m^{-2}), vegetation carbon (gC m^{-2}), litter carbon (gC m^{-2}), soil carbon (gC m^{-2}), and the fraction water content in the upper and lower soil layers. Each cell in the table reports the mean change across the 27 LPJ simulations for that set, the standard deviations across the simulations, and the percent change. Change is calculated based on linear regression of the LPJ simulations for 2001-2050 and 2001-2100. Cell shading indicates the number of LPJ simulations that predict a negative trend in the specified variable: 22-27 (robust decline; pink), 16-21 (majority decline; yellow), 12-15 (little change; white), 6-11 (majority increase; green), 0-5 (robust increase; blue). For each variable, the scenario with the largest predicted change is highlighted in bold. From Table 4 in Notaro et al. (in press)

Mid-21st Century	A2fixCO2	B1fixCO2	A2	B1
Tree cover fraction	**-.05±.04 -7.6%**	-.04±.05 -5.6%	-.03±.03 -4.1%	-.02±.04 -3.1%
Grass cover fraction	**+.05±.03 +90.7%**	+.03±.05 +59.0%	+.03±.03 +50.3%	+.02±.04 +31.6%
Vegetation cover fraction	-.00±.01 -0.3%	**-.01±.01 -0.8%**	-.00±.01 -0.1%	-.00±.01 -0.5%
Evergreen tree cover fraction	**-.14±.07 -62.0%**	-.09±.07 -38.9%	-.14±.07 -60.8%	-.09±.07 -37.9%
Deciduous tree cover fraction	+.09±.04 +22.0%	+.05±.03 +12.5%	**+.11±.05 +26.7%**	+.07±.04 +15.9%
Land carbon gC/m^2	**-1975±841 -10.4%**	-1224±841 -6.4%	-834±831 -4.4%	-318±814 -1.7%
Vegetation carbon gC/m^2	**-1848±1092 -28.0%**	-1127±1252 -17.1%	-1156±1120 -17.5%	-566±1249 -8.6%
Litter carbon gC/m^2	+20±154 +1.5%	+32±229 +2.4%	**+185±166 +14.0%**	+162±230 +12.2%
Soil carbon gC/m^2	**-147±252 -1.3%**	-129±369 -1.2%	+136±262 +1.2%	+85±383 +0.8%
Upper soil water fraction	-.002±.018 -0.5%	-.006±.030 -1.4%	**+.006±.018 +1.4%**	+.001±.031 +0.3%
Lower soil water fraction	**-.052±.031 -10.5%**	-0.041±.057 -8.3%	-.039±.033 -7.8%	-.030±.060 -6.1%

Late-21st Century	A2fixCO2	B1fixCO2	A2	B1
Tree cover fraction	**-.08±.10 -12.6%**	-.02±.03 -2.8%	-.01±.05 -2.1%	+.00±.03 +0.5%
Grass cover fraction	**+.06±.08 +121.8%**	+.01±.03 +27.1%	+.01±.04 +22.1%	-.00±.02 -5.1%
Vegetation cover fraction	**-.02±.03 -2.6%**	-.00±.01 -0.6%	-.00±.01 -0.3%	+.00±.01 +0.0%
Evergreen tree cover fraction	-.25±.06 -100%	-.21±.08 -91.5%	**-.25±.06 -100%**	-.21±.08 -91.6%
Deciduous tree cover fraction	+.17±.11 +39.4%	+.19±.09 +45.5%	**+.24±.07 +55.7%**	+.22±.09 +50.6%

Land carbon gC/m^2	**-5083±1415 -26.7%**	-3269±1313 -17.1%	-1804±1340 -9.5%	-1037±1274 -5.4%
Vegetation carbon gC/m^2	**-2985±1082 -45.2%**	-2203±1081 -33.4%	-1113±1112 -16.9%	-944±1086 -14.3%
Litter carbon gC/m^2	**-554±228 -41.8%**	-301±188 -22.7%	-205±249 -15.5%	-64±185 -4.9%
Soil carbon gC/m^2	**-1543±527 -13.8%**	-765±388 -6.9%	-486±525 -4.4%	-28±377 -0.3%
Upper soil water fraction	+.002±.044 +0.4%	-.001±.024 -0.3%	**+.019±.044 +4.4%**	+.007±.025 +1.7%
Lower soil water fraction	**-.101±.059 -20.5%**	-.085±.048 -17.3%	-.077±.078 -15.7%	-.070±.052 -14.2%

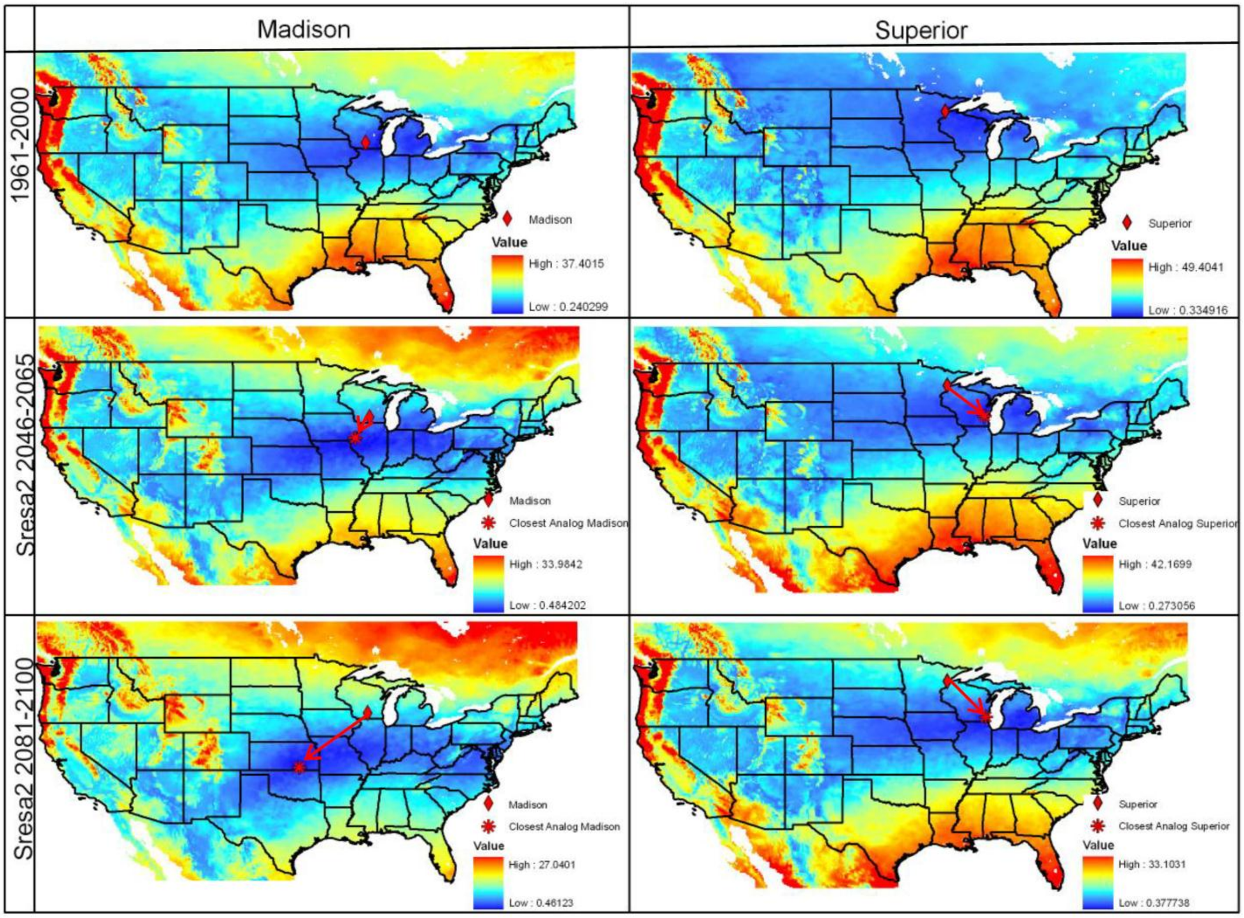


Figure 2.1: Maps of the climatic dissimilarity between two Wisconsin cities – Madison and Superior – when compared to the late 20th-century climates elsewhere in North America. Climatic dissimilarity is based on the standardized Euclidean Distance (SED) for seasonal temperature and precipitation. Low dissimilarities (blue) indicate a close match between the climates at a North American location and the Wisconsin target. In these climate-analog analyses, three climate states are used for Madison and Superior: their observed late-20th-century climates (a,b), their projected mid-21st-century climates (c,d), and their projected late-21st-century climates (e,f) using the higher-end A2 warming scenario. Arrows connect the location of each city with its closest climatic analog. Note the differing trajectories for the two cities. Because Superior's local climates are strongly influenced by its proximity to Lake Superior, the closest analogs for its future climates are consistently in the Milwaukee area. Madison, which is situated at the historical transition between prairie and forest in south-central Wisconsin, tends to draw mid-century analogs from northwestern Illinois and late-century analogs from eastern Kansas, under this climate-change scenario. From Veloz et al. (2012).

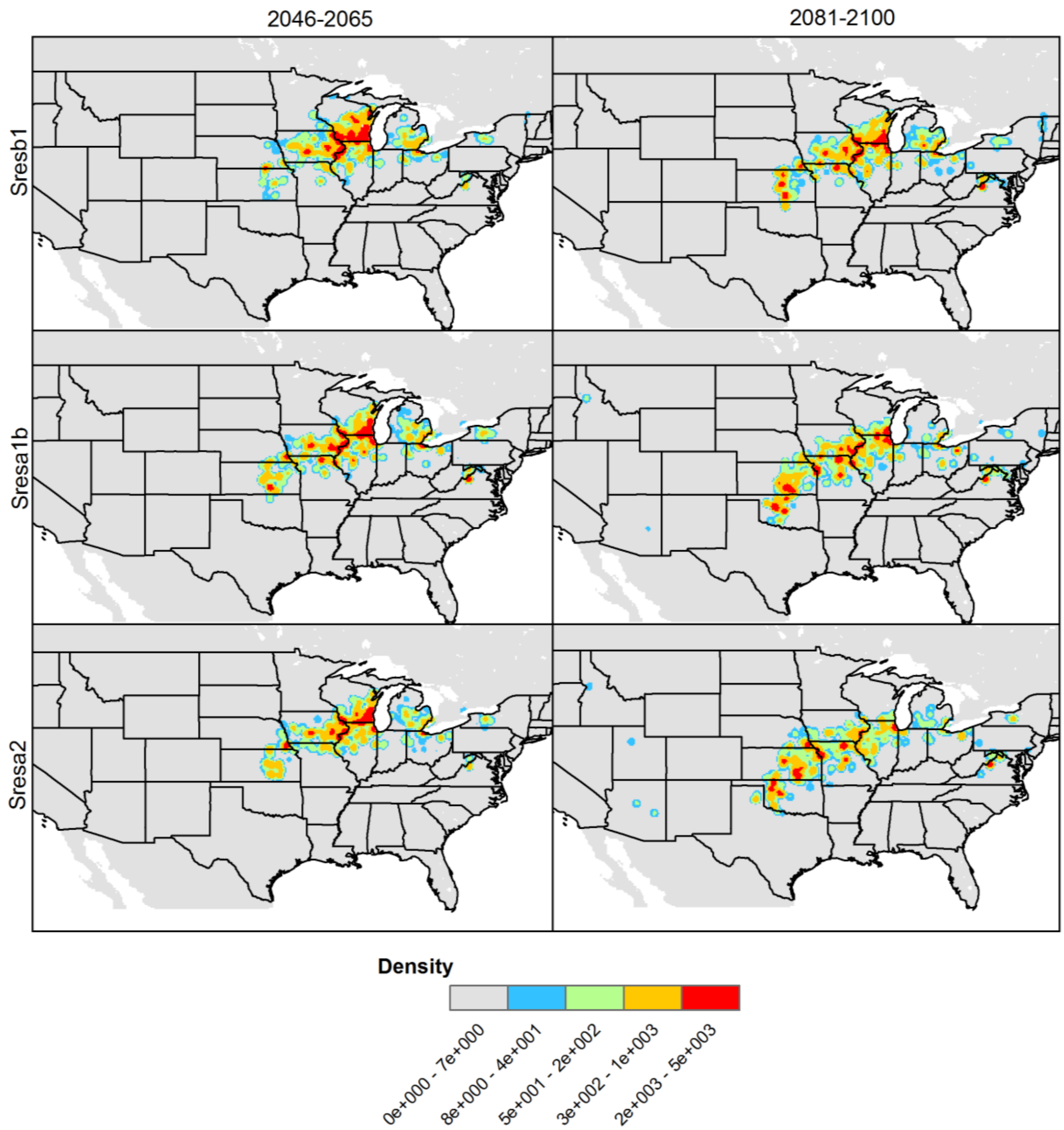


Figure 2.2: Maps of the density of late-20th-century (1961-2000) climatic analogs for future Wisconsin climates. The density estimates represents the closest analog locations for all WI grid cells for all GCMs for a particular scenario and time period. Reds indicate higher densities of climate analogs. Results are shown for the B1 (a,b), A1B (c,d), and A2 (e,f) climate-change scenarios. The bottom maps (g,h) show mean annual temperature and precipitation for late 20th-century North America, from Maurer et al. (2007; 2002). From Veloz et al. (2012).

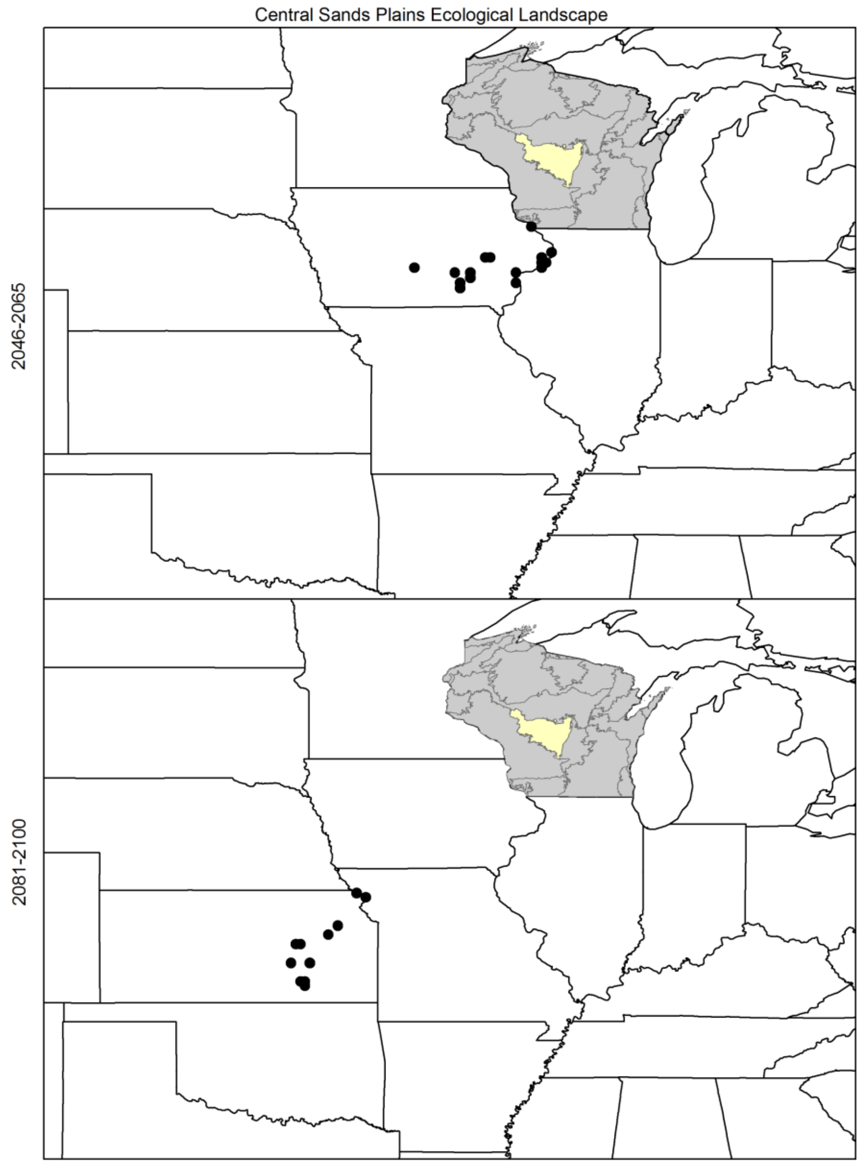


Figure 2.3: Maps of the location of the closest late-20th-century analog for future Wisconsin climates within the Central Sands Plains ecological landscape (http://dnr.wi.gov/landscapes/). Each dot represents the closest analog for a single WI grid cell within the central sands ecological landscape, and the set of dots includes all grid cells within the central sands plains ecological landscape. This analysis used an 11 member ensemble of GCM's using the SRES A2 emission scenario. The top map shows the climate analogs for Wisconsin climates for the middle of the 21st-century (2046-2065) while the bottom map shows the climate analogs for Wisconsin climates for the late 21st-century (2081-2100). From Veloz et al. (2012).

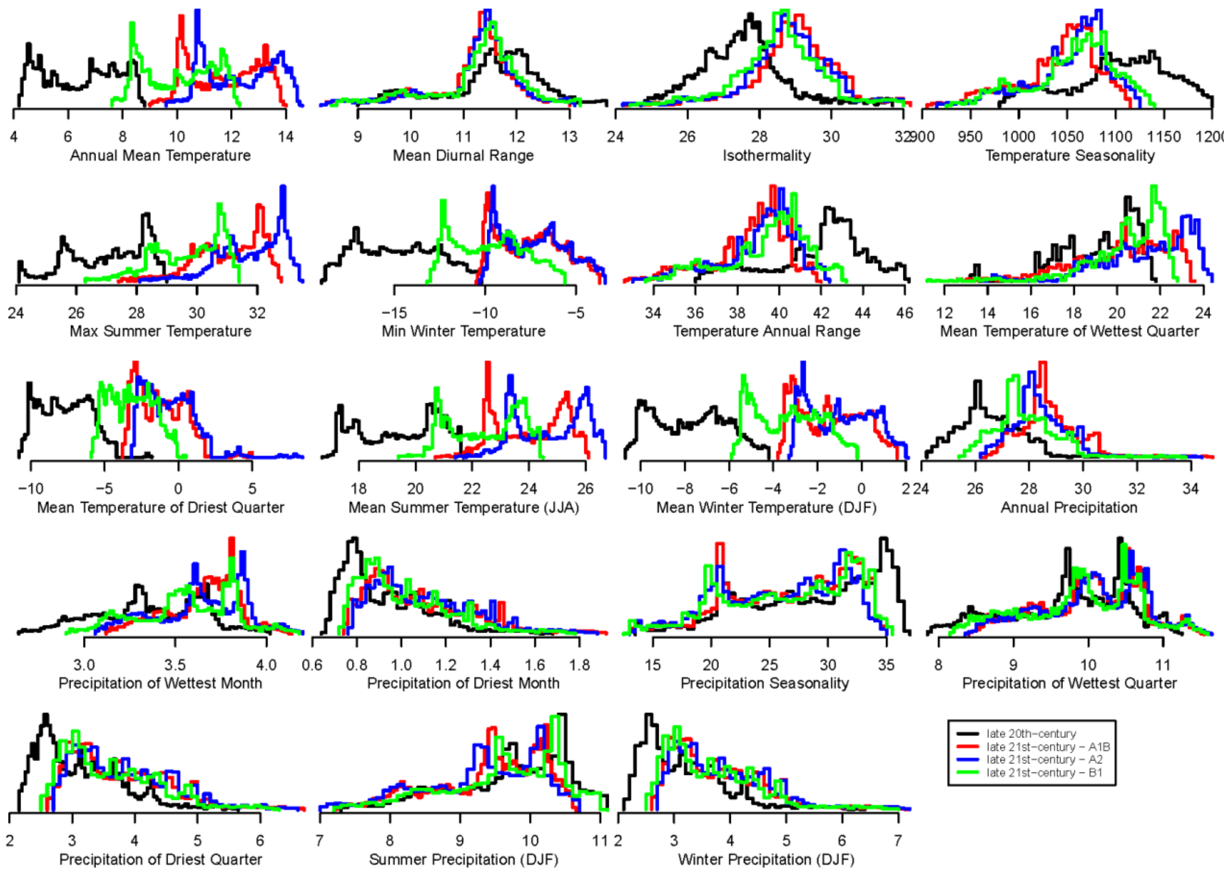


Figure 3.1: Histogram of current and future climatic availability for 19 bioclimatic variables. Height of the line at each point corresponds to the proportion of the area in Wisconsin for that climate variable. Late 20th-century climates (1961-2000) are represented with the black line, and projected future climates (derived from WICCI downscaled predictions for the late 21st century) are the ensemble prediction of 15 GCMs under three IPCC emission scenarios (A1B-red; A2-blue and B1-green). Temperature is measured in Celsius degrees, precipitation in millimetres. Temperatures seasonality was determined as the standard deviation of monthly temperatures, and Precipitation Seasonality as the coefficient of variation in monthly precipitation over the year. From Ordonez et al. (in review).

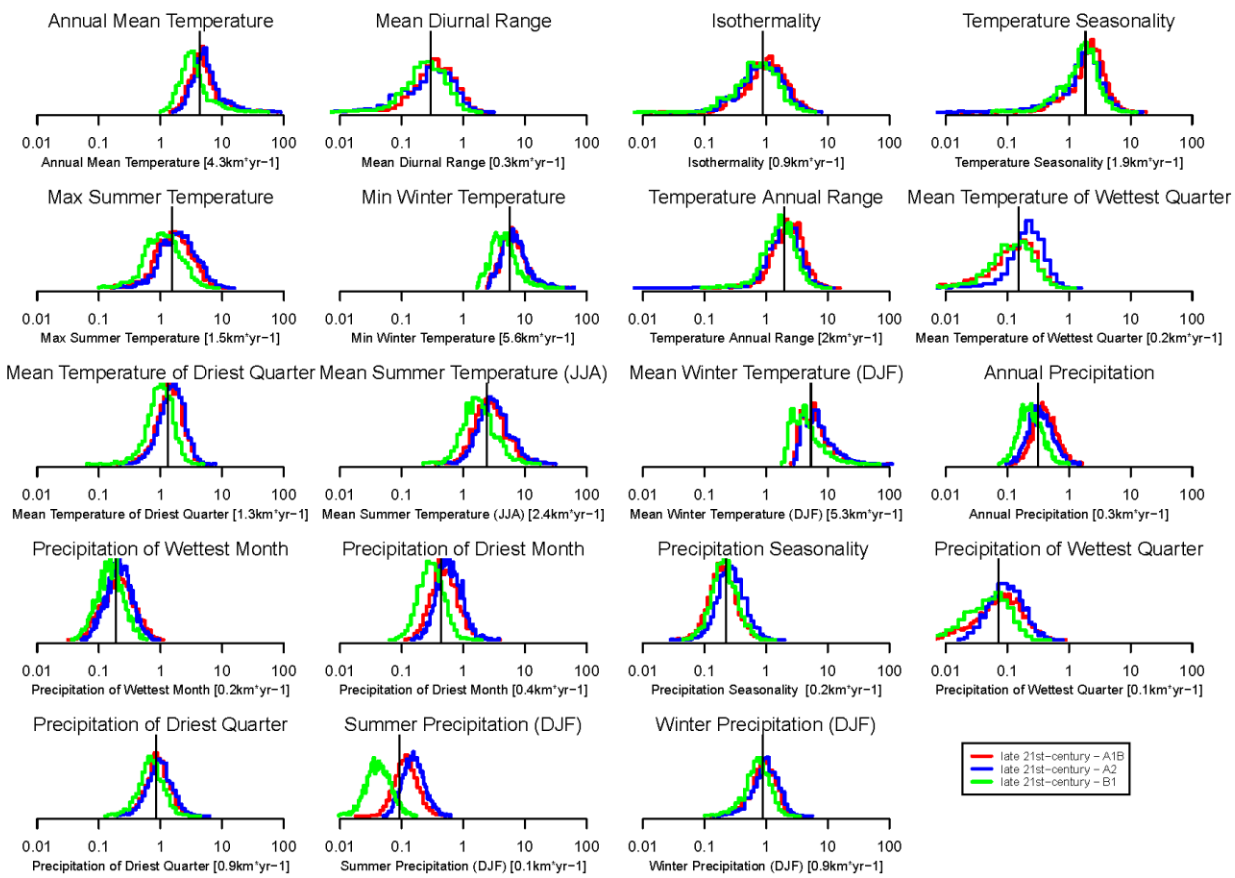


Figure 3.2: Histograms of the velocity of change (km*y^{-1}) for 19 bioclimatic variables. Plotted predictions are based on three IPCC climate scenarios (A1B-red; A2-blue and B1-green). Velocity is estimated as the ratio between spatial and temporal rates of change as specified by Loarie et al., (2009). Mean velocity (across scenarios) for each variable in Wisconsin is marked with a black vertical line, and displayed in the x-axis label. From Ordonez et al. (in review).

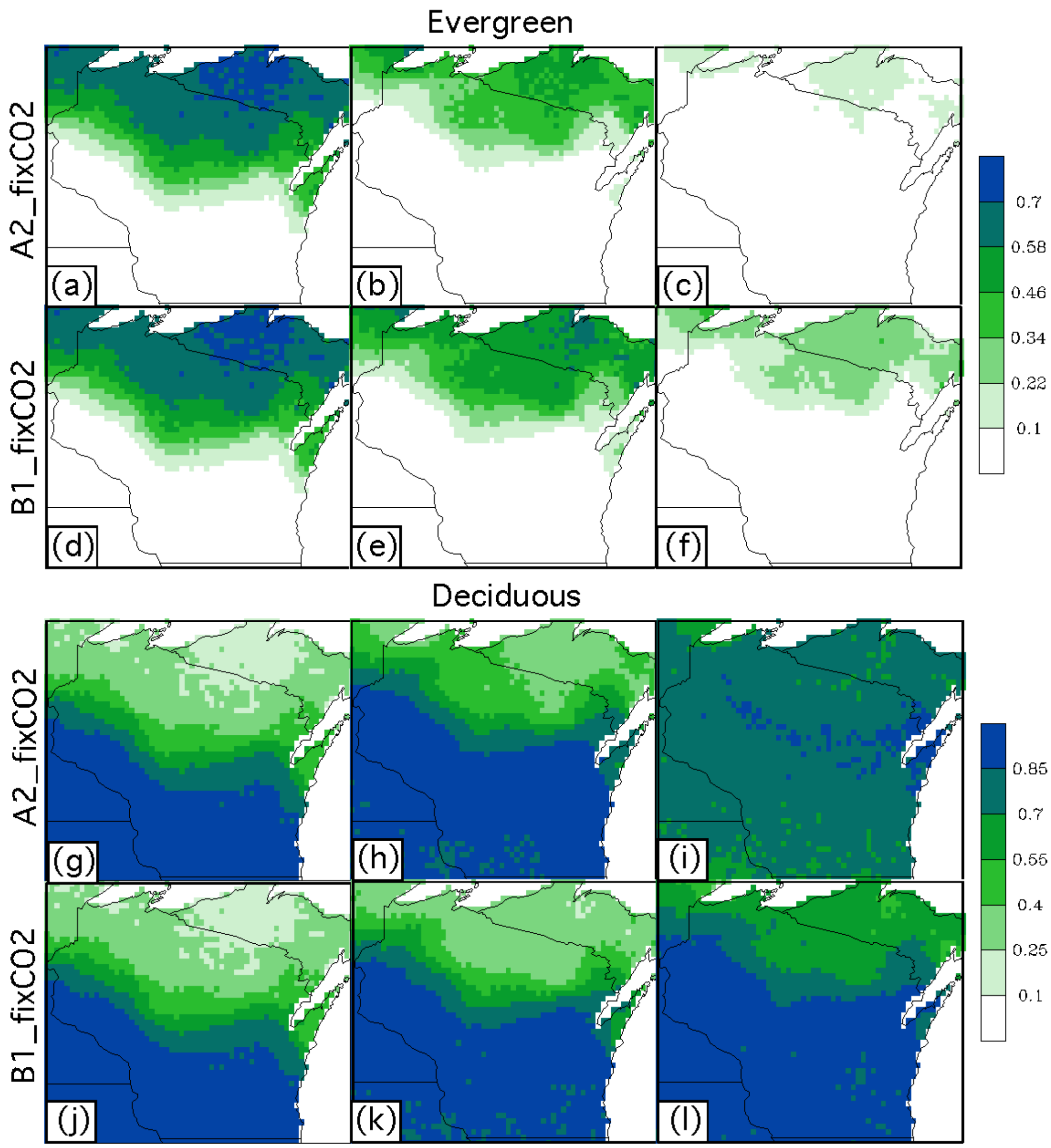


Figure 4.1: Projected distribution of deciduous and evergreen tree cover in Wisconsin for the late 20th century (1981-2100; left column of maps), the middle 21st century (2041-2060; middle column), and late 21st century (2081-2100, right column). Results are averaged across 9 GCMs and 3 downscaled realizations per GCM for each scenario. From Notaro et al. (in press).

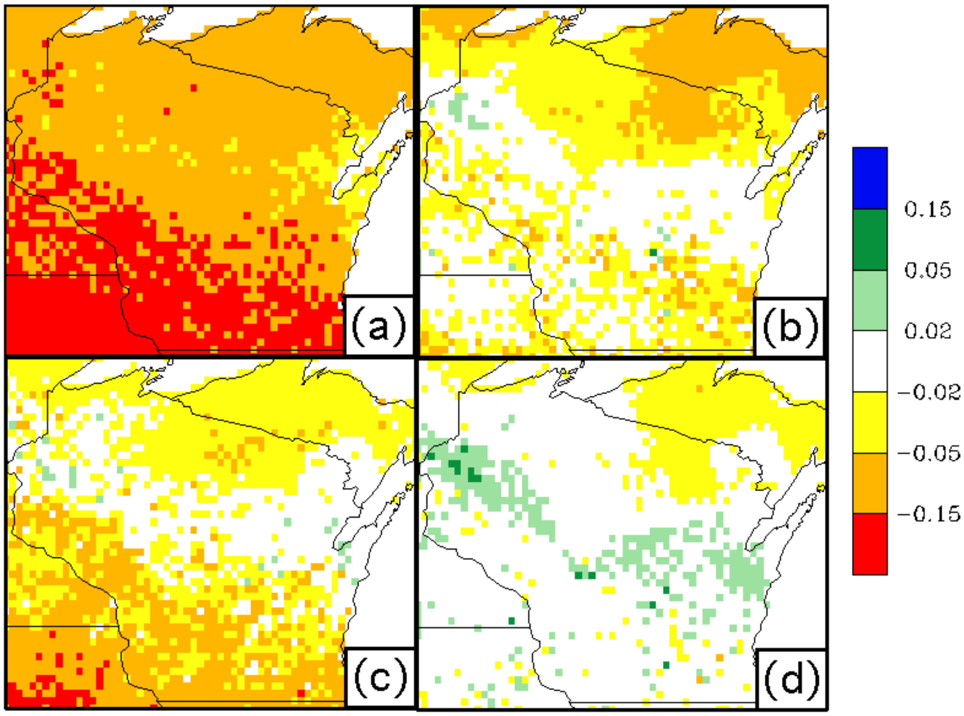


Figure 4.2: Projected changes in tree cover during the 21st century for the a) A2fixCO2, b) B1fixCO2, c) A2, and d) B1 scenarios. Changes in tree cover are expressed as the difference between mean tree cover for 2081-2011 and 1981-2000, averaged across 9 GCMs and 3 realizations per GCM. From Notaro et al. (in press).

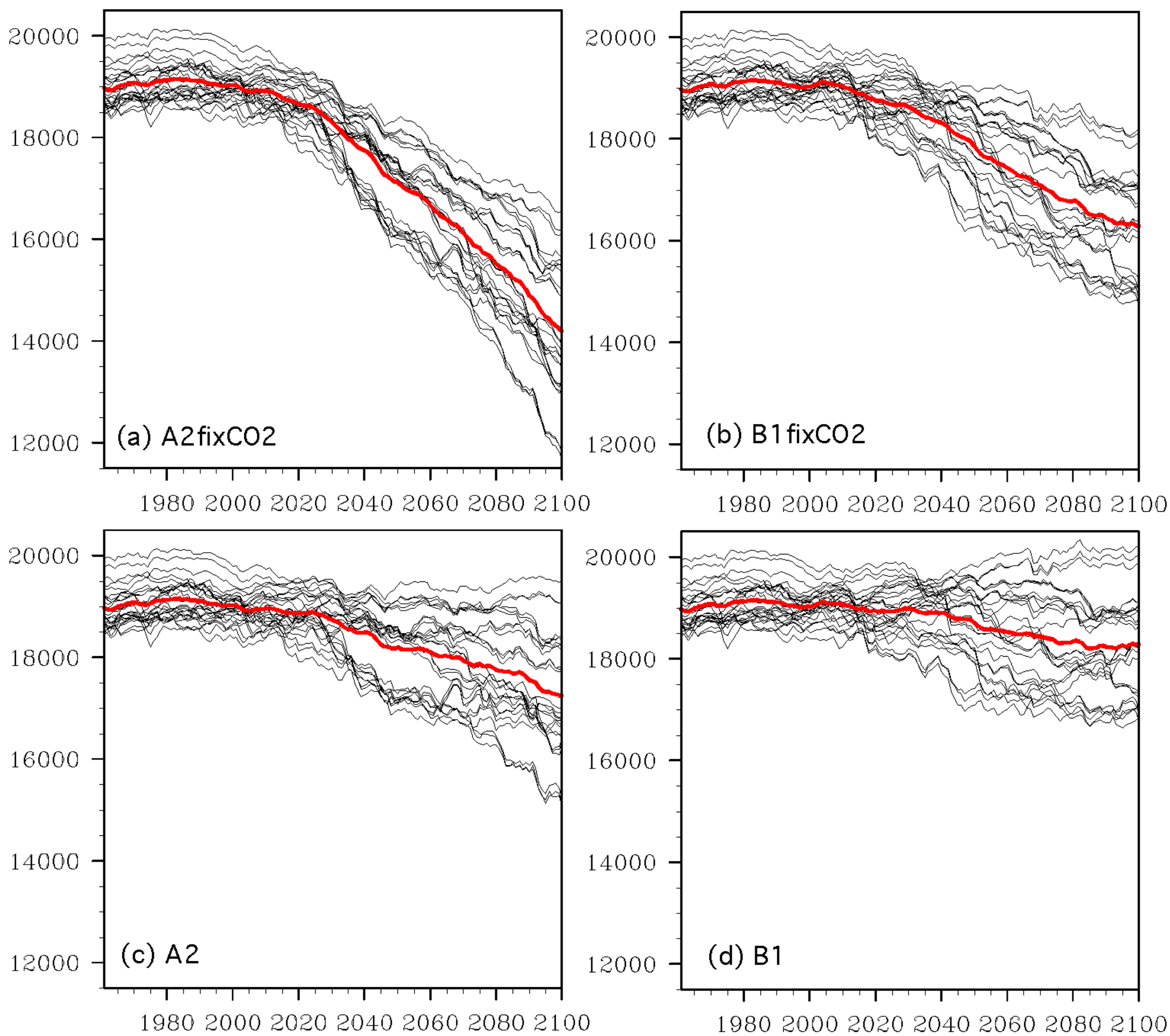
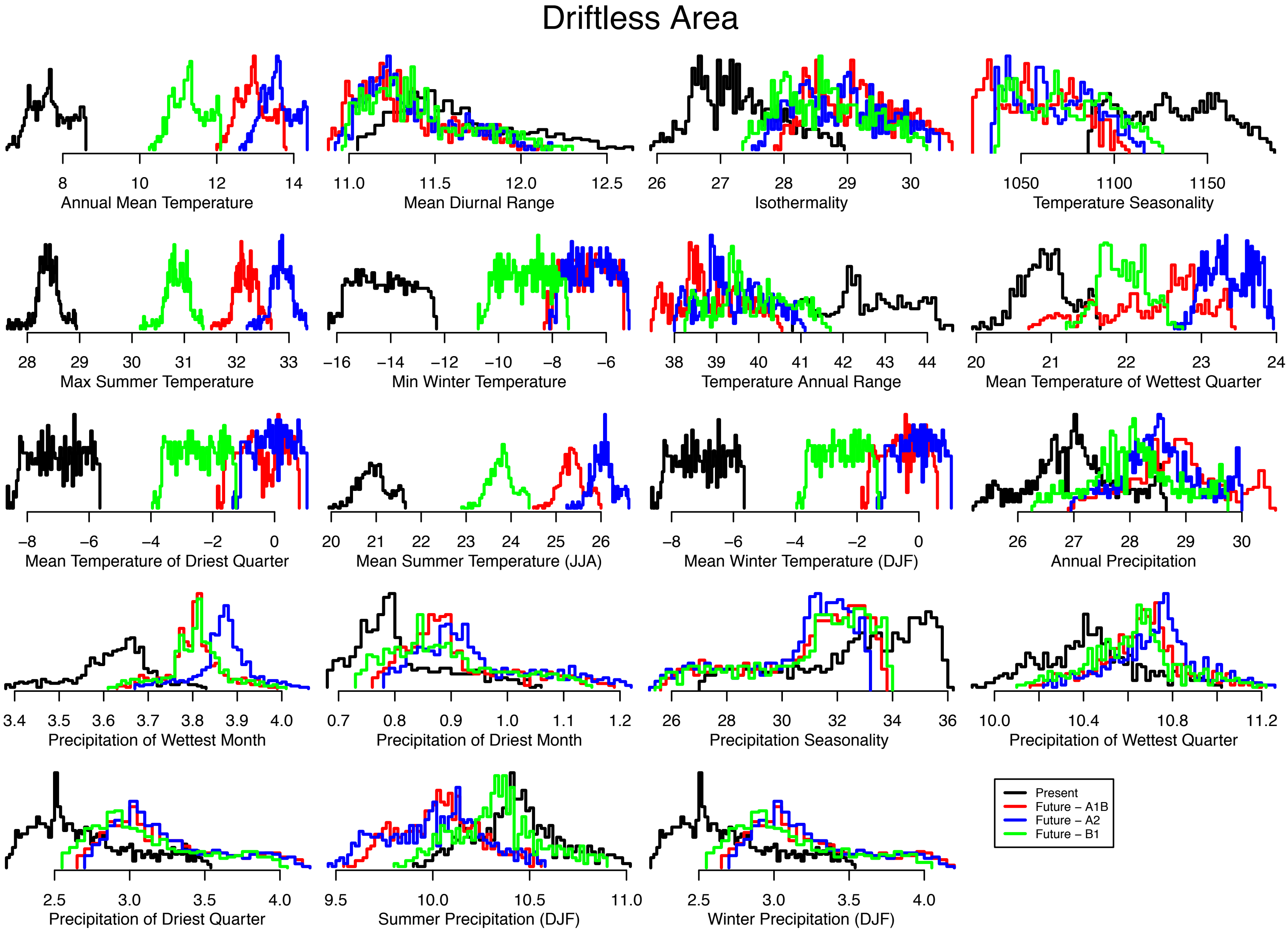


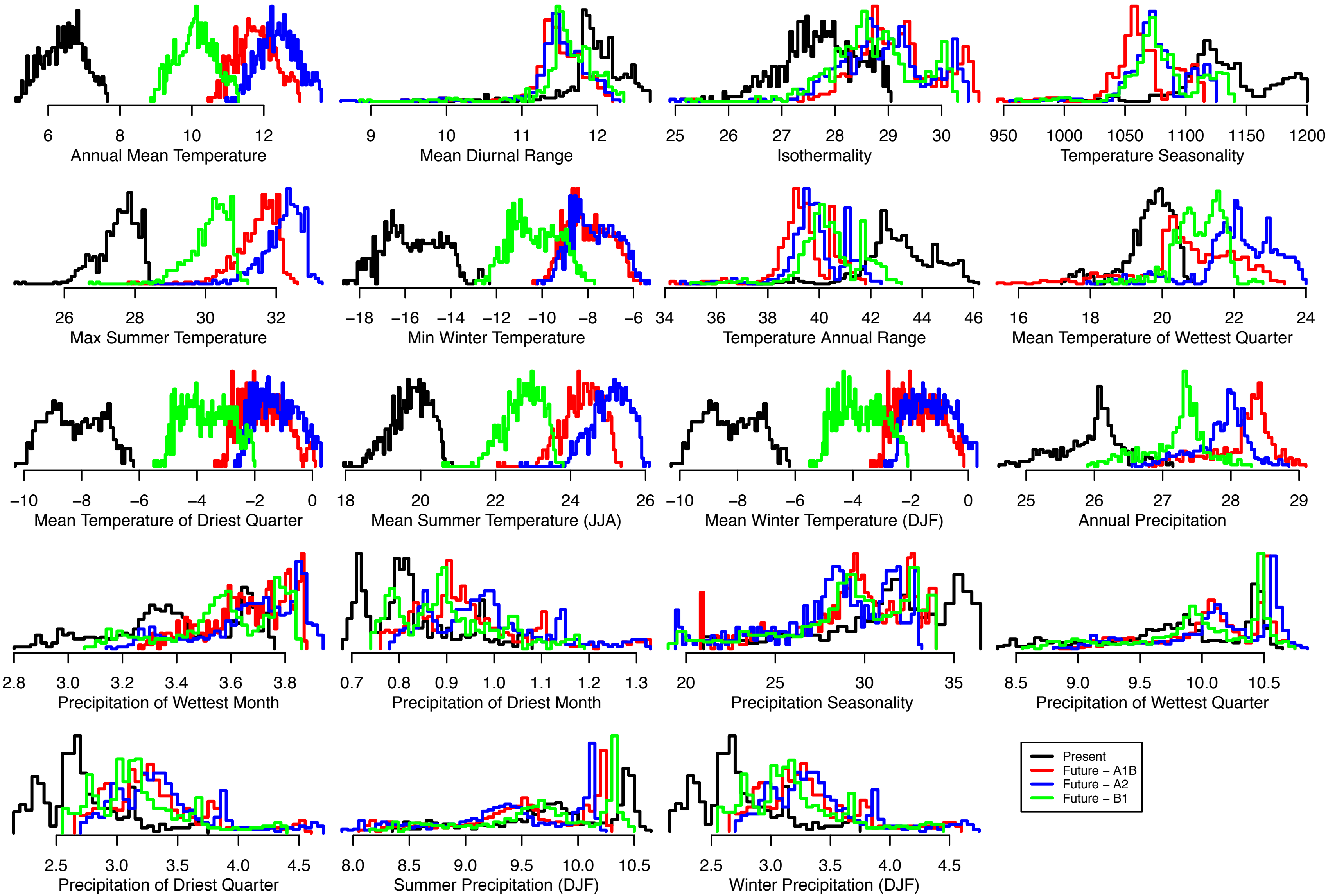
Figure 4.3: Projected trends in terrestrial carbon (including vegetation, litter, and soil C) in Wisconsin's natural vegetation from 1960 to 2100 AD, for the four LPJ scenarios: A2fixCO2, B1fixCO2, A2, and B1. Black lines represent each of the 27 individual LPJ simulations per scenario, with the mean projection shown by the red line.

Appendices

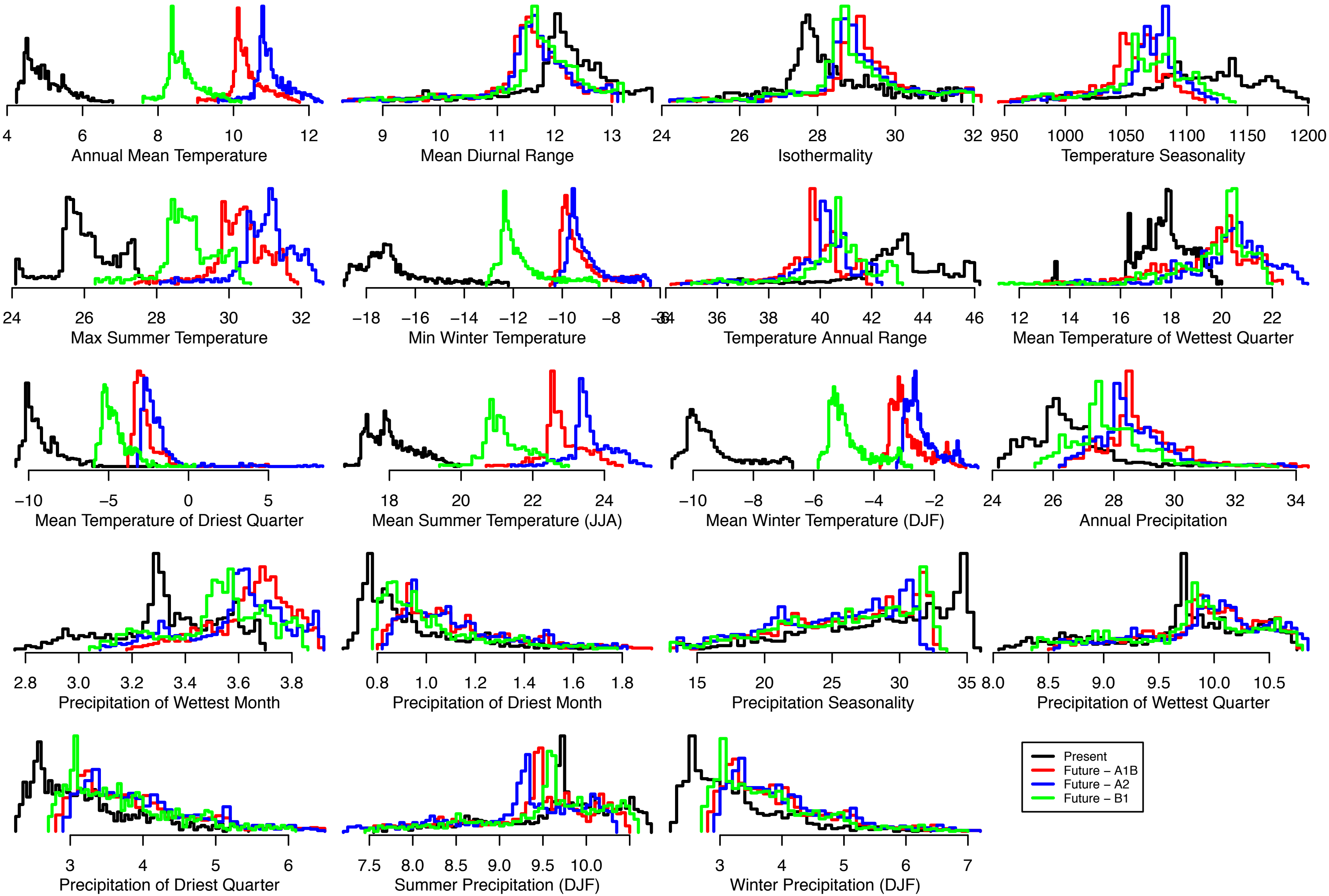
Appendix 1: Histograms of the current and projected future distribution of 19 climatic variables for 5 EPA ecoregions in Wisconsin, for the B1, A1B, and A2 socioeconomic scenarios. From Ordonez et al. (in review).


Driftless Area
8 10 12 14
Annual Mean Temperature
11.0 11.5 12.0 12.5
Mean Diurnal Range
26 27 28 29 30
Isothermality
1050 1100 1150
Temperature Seasonality
28 29 30 31 32 33
Max Summer Temperature
−16 −14 −12 −10 −8 −6
Min Winter Temperature
38 39 40 41 42 43 44
Temperature Annual Range
20 21 22 23 24
Mean Temperature of Wettest Quarter
−8 −6 −4 −2 0
Mean Temperature of Driest Quarter
20 21 22 23 24 25 26
Mean Summer Temperature (JJA)
−8 −6 −4 −2 0
Mean Winter Temperature (DJF)
26 27 28 29 30
Annual Precipitation
3.4 3.5 3.6 3.7 3.8 3.9 4.0
Precipitation of Wettest Month
0.7 0.8 0.9 1.0 1.1 1.2
Precipitation of Driest Month
26 28 30 32 34 36
Precipitation Seasonality
10.0 10.4 10.8 11.2
Precipitation of Wettest Quarter
2.5 3.0 3.5 4.0
Precipitation of Driest Quarter
9.5 10.0 10.5 11.0
Summer Precipitation (DJF)
2.5 3.0 3.5 4.0
Winter Precipitation (DJF)
Present
Future – A1B
Future – A2
Future – B1

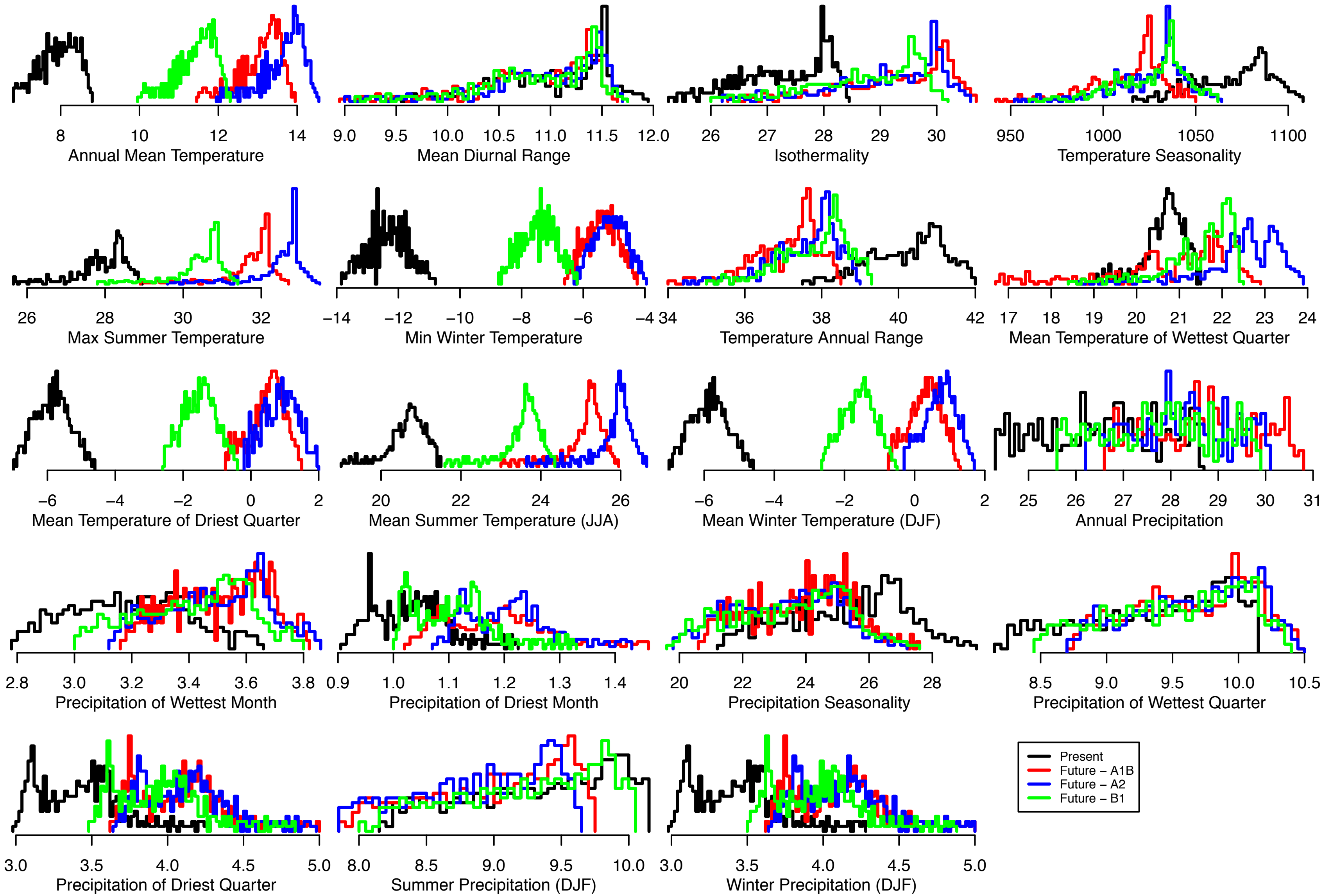
North Central Hardwood Forests

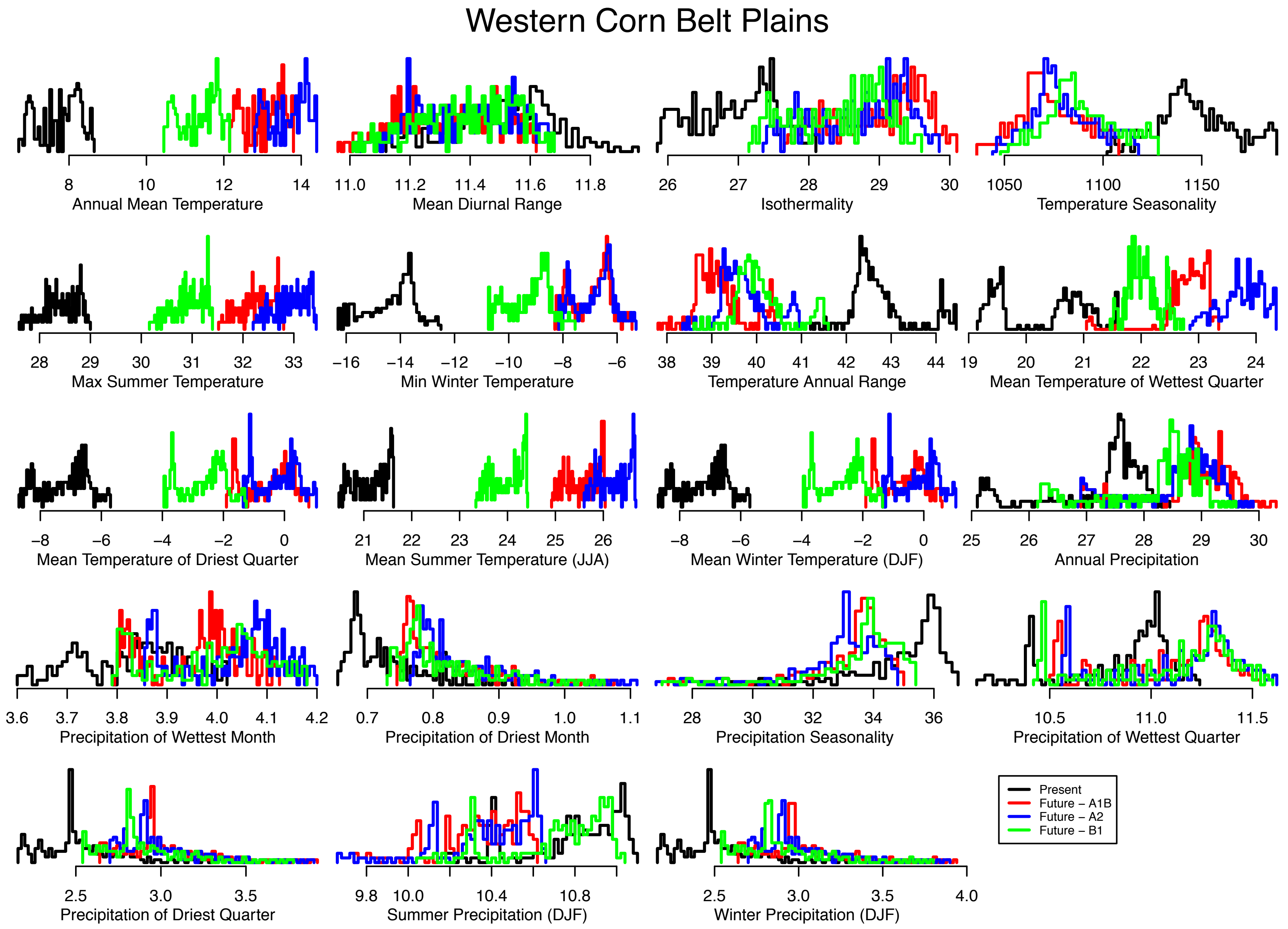


Northern Lakes and Forests

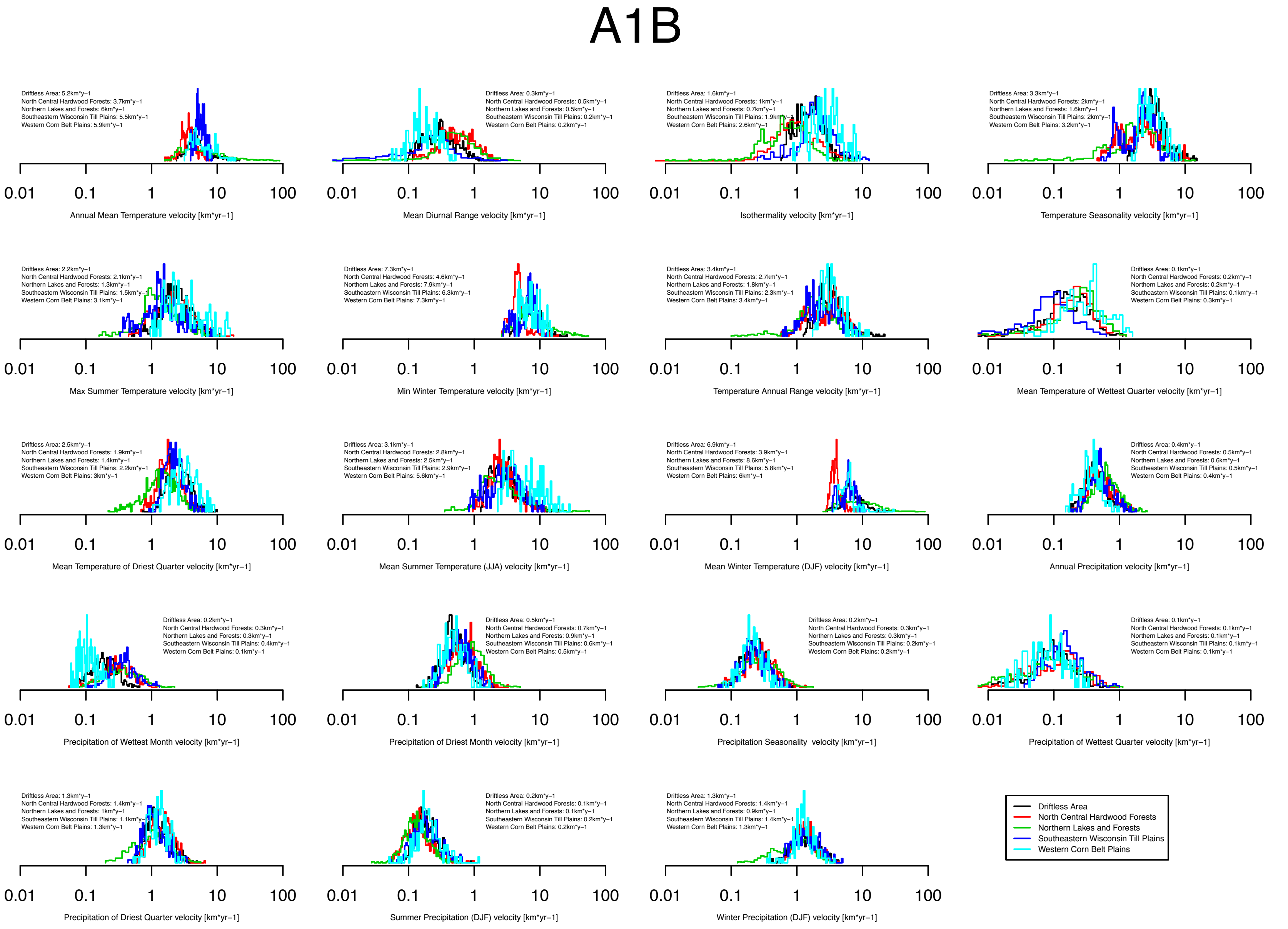


Southeastern Wisconsin Till Plains

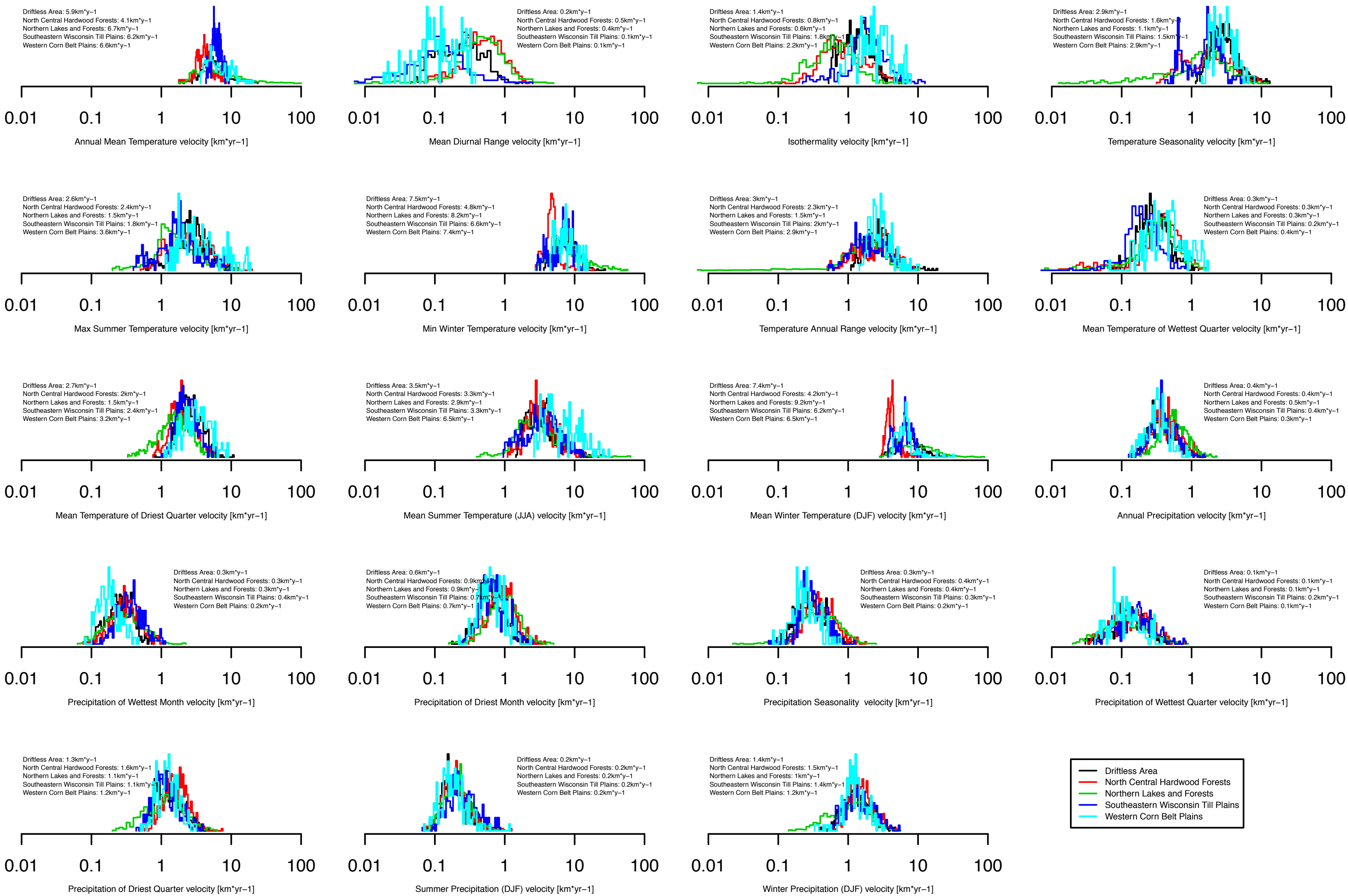



Western Corn Belt Plains
Annual Mean Temperature
Mean Diurnal Range
Isothermality
Temperature Seasonality
Max Summer Temperature
Min Winter Temperature
Temperature Annual Range
Mean Temperature of Wettest Quarter
Mean Temperature of Driest Quarter
Mean Summer Temperature (JJA)
Mean Winter Temperature (DJF)
Annual Precipitation
Precipitation of Wettest Month
Precipitation of Driest Month
Precipitation Seasonality
Precipitation of Wettest Quarter
Precipitation of Driest Quarter
Summer Precipitation (DJF)
Winter Precipitation (DJF)
Present
Future – A1B
Future – A2
Future – B1

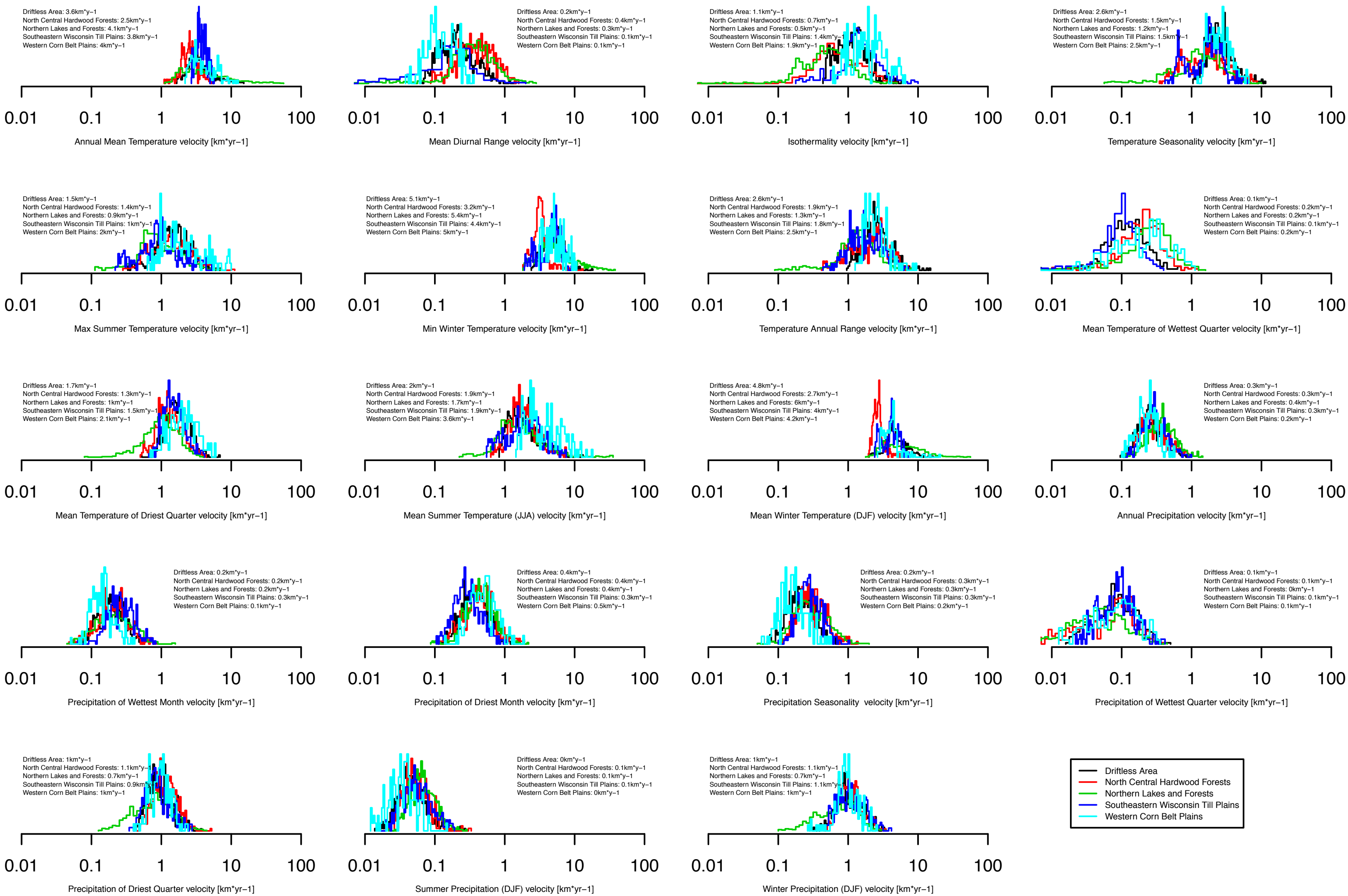
Appendix 2: Histograms of the spatial velocity for 19 climatic variables, for 5 EPA ecoregions in Wisconsin, for the B1, A1B, and A2 socioeconomic scenarios. From Ordonez et al. (in review).


A1B
Driftless Area: 5.2km*y−1
North Central Hardwood Forests: 3.7km*y−1
Northern Lakes and Forests: 6km*y−1
Southeastern Wisconsin Till Plains: 5.5km*y−1
Western Corn Belt Plains: 5.9km*y−1
Annual Mean Temperature velocity [km*yr−1]
Driftless Area: 0.3km*y−1
North Central Hardwood Forests: 0.5km*y−1
Northern Lakes and Forests: 0.5km*y−1
Southeastern Wisconsin Till Plains: 0.2km*y−1
Western Corn Belt Plains: 0.2km*y−1
Mean Diurnal Range velocity [km*yr−1]
Driftless Area: 1.6km*y−1
North Central Hardwood Forests: 1km*y−1
Northern Lakes and Forests: 0.7km*y−1
Southeastern Wisconsin Till Plains: 1.9km*y−1
Western Corn Belt Plains: 2.6km*y−1
Isothermality velocity [km*yr−1]
Driftless Area: 3.3km*y−1
North Central Hardwood Forests: 2km*y−1
Northern Lakes and Forests: 1.6km*y−1
Southeastern Wisconsin Till Plains: 2km*y−1
Western Corn Belt Plains: 3.2km*y−1
Temperature Seasonality velocity [km*yr−1]
Driftless Area: 2.2km*y−1
North Central Hardwood Forests: 2.1km*y−1
Northern Lakes and Forests: 1.3km*y−1
Southeastern Wisconsin Till Plains: 1.5km*y−1
Western Corn Belt Plains: 3.1km*y−1
Max Summer Temperature velocity [km*yr−1]
Driftless Area: 7.3km*y−1
North Central Hardwood Forests: 4.6km*y−1
Northern Lakes and Forests: 7.9km*y−1
Southeastern Wisconsin Till Plains: 6.3km*y−1
Western Corn Belt Plains: 7.3km*y−1
Min Winter Temperature velocity [km*yr−1]
Driftless Area: 3.4km*y−1
North Central Hardwood Forests: 2.7km*y−1
Northern Lakes and Forests: 1.8km*y−1
Southeastern Wisconsin Till Plains: 2.3km*y−1
Western Corn Belt Plains: 3.4km*y−1
Temperature Annual Range velocity [km*yr−1]
Driftless Area: 0.1km*y−1
North Central Hardwood Forests: 0.2km*y−1
Northern Lakes and Forests: 0.2km*y−1
Southeastern Wisconsin Till Plains: 0.1km*y−1
Western Corn Belt Plains: 0.3km*y−1
Mean Temperature of Wettest Quarter velocity [km*yr−1]
Driftless Area: 2.5km*y−1
North Central Hardwood Forests: 1.9km*y−1
Northern Lakes and Forests: 1.4km*y−1
Southeastern Wisconsin Till Plains: 2.2km*y−1
Western Corn Belt Plains: 3km*y−1
Mean Temperature of Driest Quarter velocity [km*yr−1]
Driftless Area: 3.1km*y−1
North Central Hardwood Forests: 2.8km*y−1
Northern Lakes and Forests: 2.5km*y−1
Southeastern Wisconsin Till Plains: 2.9km*y−1
Western Corn Belt Plains: 5.6km*y−1
Mean Summer Temperature (JJA) velocity [km*yr−1]
Driftless Area: 6.9km*y−1
North Central Hardwood Forests: 3.9km*y−1
Northern Lakes and Forests: 8.6km*y−1
Southeastern Wisconsin Till Plains: 5.8km*y−1
Western Corn Belt Plains: 6km*y−1
Mean Winter Temperature (DJF) velocity [km*yr−1]
Driftless Area: 0.4km*y−1
North Central Hardwood Forests: 0.5km*y−1
Northern Lakes and Forests: 0.6km*y−1
Southeastern Wisconsin Till Plains: 0.5km*y−1
Western Corn Belt Plains: 0.4km*y−1
Annual Precipitation velocity [km*yr−1]
Driftless Area: 0.2km*y−1
North Central Hardwood Forests: 0.3km*y−1
Northern Lakes and Forests: 0.3km*y−1
Southeastern Wisconsin Till Plains: 0.4km*y−1
Western Corn Belt Plains: 0.1km*y−1
Precipitation of Wettest Month velocity [km*yr−1]
Driftless Area: 0.5km*y−1
North Central Hardwood Forests: 0.7km*y−1
Northern Lakes and Forests: 0.9km*y−1
Southeastern Wisconsin Till Plains: 0.6km*y−1
Western Corn Belt Plains: 0.5km*y−1
Precipitation of Driest Month velocity [km*yr−1]
Driftless Area: 0.2km*y−1
North Central Hardwood Forests: 0.3km*y−1
Northern Lakes and Forests: 0.3km*y−1
Southeastern Wisconsin Till Plains: 0.2km*y−1
Western Corn Belt Plains: 0.2km*y−1
Precipitation Seasonality velocity [km*yr−1]
Driftless Area: 0.1km*y−1
North Central Hardwood Forests: 0.1km*y−1
Northern Lakes and Forests: 0.1km*y−1
Southeastern Wisconsin Till Plains: 0.1km*y−1
Western Corn Belt Plains: 0.1km*y−1
Precipitation of Wettest Quarter velocity [km*yr−1]
Driftless Area: 1.3km*y−1
North Central Hardwood Forests: 1.4km*y−1
Northern Lakes and Forests: 1km*y−1
Southeastern Wisconsin Till Plains: 1.1km*y−1
Western Corn Belt Plains: 1.3km*y−1
Precipitation of Driest Quarter velocity [km*yr−1]
Driftless Area: 0.2km*y−1
North Central Hardwood Forests: 0.1km*y−1
Northern Lakes and Forests: 0.1km*y−1
Southeastern Wisconsin Till Plains: 0.2km*y−1
Western Corn Belt Plains: 0.2km*y−1
Summer Precipitation (DJF) velocity [km*yr−1]
Driftless Area: 1.3km*y−1
North Central Hardwood Forests: 1.4km*y−1
Northern Lakes and Forests: 0.9km*y−1
Southeastern Wisconsin Till Plains: 1.4km*y−1
Western Corn Belt Plains: 1.3km*y−1
Winter Precipitation (DJF) velocity [km*yr−1]
0.01 0.1 1 10 100
Driftless Area
North Central Hardwood Forests
Northern Lakes and Forests
Southeastern Wisconsin Till Plains
Western Corn Belt Plains

A2


Driftless Area: 5.9km*y−1
North Central Hardwood Forests: 4.1km*y−1
Northern Lakes and Forests: 6.7km*y−1
Southeastern Wisconsin Till Plains: 6.2km*y−1
Western Corn Belt Plains: 6.6km*y−1
0.01 0.1 1 10 100
Annual Mean Temperature velocity [km*yr−1]
Driftless Area: 0.2km*y−1
North Central Hardwood Forests: 0.5km*y−1
Northern Lakes and Forests: 0.4km*y−1
Southeastern Wisconsin Till Plains: 0.1km*y−1
Western Corn Belt Plains: 0.1km*y−1
0.01 0.1 1 10 100
Mean Diurnal Range velocity [km*yr−1]
Driftless Area: 1.4km*y−1
North Central Hardwood Forests: 0.8km*y−1
Northern Lakes and Forests: 0.6km*y−1
Western Corn Belt Plains: 2.2km*y−1
0.01 0.1 1 10 100
Isothermality velocity [km*yr−1]
Driftless Area: 2.9km*y−1
Northern Lakes and Forests: 1.1km*y−1
Western Corn Belt Plains: 2.9km*y−1
0.01 0.1 1 10 100
Temperature Seasonality velocity [km*yr−1]
Driftless Area: 2.6km*y−1
North Central Hardwood Forests: 2.4km*y−1
Northern Lakes and Forests: 1.5km*y−1
Southeastern Wisconsin Till Plains: 1.8km*y−1
Western Corn Belt Plains: 3.6km*y−1
0.01 0.1 1 10 100
Max Summer Temperature velocity [km*yr−1]
Driftless Area: 7.5km*y−1
North Central Hardwood Forests: 4.8km*y−1
Northern Lakes and Forests: 8.2km*y−1
Southeastern Wisconsin Till Plains: 6.6km*y−1
Western Corn Belt Plains: 7.4km*y−1
0.01 0.1 1 10 100
Min Winter Temperature velocity [km*yr−1]
Driftless Area: 3km*y−1
North Central Hardwood Forests: 2.3km*y−1
Northern Lakes and Forests: 1.5km*y−1
Southeastern Wisconsin Till Plains: 2km*y−1
Western Corn Belt Plains: 2.9km*y−1
0.01 0.1 1 10 100
Temperature Annual Range velocity [km*yr−1]
Driftless Area: 0.3km*y−1
North Central Hardwood Forests: 0.3km*y−1
Northern Lakes and Forests: 0.3km*y−1
Southeastern Wisconsin Till Plains: 0.2km*y−1
Western Corn Belt Plains: 0.4km*y−1
0.01 0.1 1 10 100
Mean Temperature of Wettest Quarter velocity [km*yr−1]
Driftless Area: 2.7km*y−1
North Central Hardwood Forests: 2km*y−1
Northern Lakes and Forests: 1.5km*y−1
Southeastern Wisconsin Till Plains: 2.4km*y−1
Western Corn Belt Plains: 3.2km*y−1
0.01 0.1 1 10 100
Mean Temperature of Driest Quarter velocity [km*yr−1]
Driftless Area: 3.5km*y−1
North Central Hardwood Forests: 3.3km*y−1
Northern Lakes and Forests: 2.9km*y−1
Southeastern Wisconsin Till Plains: 3.3km*y−1
Western Corn Belt Plains: 6.5km*y−1
0.01 0.1 1 10 100
Mean Summer Temperature (JJA) velocity [km*yr−1]
Driftless Area: 7.4km*y−1
North Central Hardwood Forests: 4.2km*y−1
Northern Lakes and Forests: 9.2km*y−1
Southeastern Wisconsin Till Plains: 6.2km*y−1
Western Corn Belt Plains: 6.5km*y−1
0.01 0.1 1 10 100
Mean Winter Temperature (DJF) velocity [km*yr−1]
Driftless Area: 0.4km*y−1
North Central Hardwood Forests: 0.4km*y−1
Northern Lakes and Forests: 0.5km*y−1
Southeastern Wisconsin Till Plains: 0.4km*y−1
Western Corn Belt Plains: 0.3km*y−1
0.01 0.1 1 10 100
Annual Precipitation velocity [km*yr−1]
Driftless Area: 0.3km*y−1
North Central Hardwood Forests: 0.3km*y−1
Northern Lakes and Forests: 0.3km*y−1
Southeastern Wisconsin Till Plains: 0.4km*y−1
Western Corn Belt Plains: 0.2km*y−1
0.01 0.1 1 10 100
Precipitation of Wettest Month velocity [km*yr−1]
Driftless Area: 0.6km*y−1
Northern Lakes and Forests: 0.9km*y−1
Western Corn Belt Plains: 0.7km*y−1
0.01 0.1 1 10 100
Precipitation of Driest Month velocity [km*yr−1]
Driftless Area: 0.3km*y−1
North Central Hardwood Forests: 0.4km*y−1
Northern Lakes and Forests: 0.4km*y−1
Southeastern Wisconsin Till Plains: 0.3km*y−1
Western Corn Belt Plains: 0.2km*y−1
0.01 0.1 1 10 100
Precipitation Seasonality velocity [km*yr−1]
Driftless Area: 0.1km*y−1
North Central Hardwood Forests: 0.1km*y−1
Northern Lakes and Forests: 0.1km*y−1
Southeastern Wisconsin Till Plains: 0.2km*y−1
Western Corn Belt Plains: 0.1km*y−1
0.01 0.1 1 10 100
Precipitation of Wettest Quarter velocity [km*yr−1]
Driftless Area: 1.3km*y−1
North Central Hardwood Forests: 1.6km*y−1
Northern Lakes and Forests: 1.1km*y−1
Western Corn Belt Plains: 1.2km*y−1
0.01 0.1 1 10 100
Precipitation of Driest Quarter velocity [km*yr−1]
Driftless Area: 0.2km*y−1
North Central Hardwood Forests: 0.2km*y−1
Northern Lakes and Forests: 0.2km*y−1
Southeastern Wisconsin Till Plains: 0.2km*y−1
Western Corn Belt Plains: 0.2km*y−1
0.01 0.1 1 10 100
Summer Precipitation (DJF) velocity [km*yr−1]
Driftless Area: 1.4km*y−1
North Central Hardwood Forests: 1.5km*y−1
Northern Lakes and Forests: 1km*y−1
Western Corn Belt Plains: 1.2km*y−1
0.01 0.1 1 10 100
Winter Precipitation (DJF) velocity [km*yr−1]
Driftless Area
North Central Hardwood Forests
Northern Lakes and Forests
Southeastern Wisconsin Till Plains
Western Corn Belt Plains

B1


Driftless Area: 3.6km*y−1
North Central Hardwood Forests: 2.5km*y−1
Northern Lakes and Forests: 4.1km*y−1
Southeastern Wisconsin Till Plains: 3.8km*y−1
Western Corn Belt Plains: 4km*y−1
0.01 0.1 1 10 100
Annual Mean Temperature velocity [km*yr−1]
Driftless Area: 0.2km*y−1
North Central Hardwood Forests: 0.4km*y−1
Northern Lakes and Forests: 0.3km*y−1
Southeastern Wisconsin Till Plains: 0.1km*y−1
Western Corn Belt Plains: 0.1km*y−1
Mean Diurnal Range velocity [km*yr−1]
Driftless Area: 1.1km*y−1
North Central Hardwood Forests: 0.7km*y−1
Northern Lakes and Forests: 0.5km*y−1
Southeastern Wisconsin Till Plains: 1.4km*y−1
Western Corn Belt Plains: 1.9km*y−1
Isothermality velocity [km*yr−1]
Driftless Area: 2.6km*y−1
North Central Hardwood Forests: 1.5km*y−1
Northern Lakes and Forests: 1.2km*y−1
Southeastern Wisconsin Till Plains: 1.5km*y−1
Western Corn Belt Plains: 2.5km*y−1
Temperature Seasonality velocity [km*yr−1]
Driftless Area: 1.5km*y−1
North Central Hardwood Forests: 1.4km*y−1
Northern Lakes and Forests: 0.9km*y−1
Southeastern Wisconsin Till Plains: 1km*y−1
Western Corn Belt Plains: 2km*y−1
Max Summer Temperature velocity [km*yr−1]
Driftless Area: 5.1km*y−1
North Central Hardwood Forests: 3.2km*y−1
Northern Lakes and Forests: 5.4km*y−1
Southeastern Wisconsin Till Plains: 4.4km*y−1
Western Corn Belt Plains: 5km*y−1
Min Winter Temperature velocity [km*yr−1]
Driftless Area: 2.6km*y−1
North Central Hardwood Forests: 1.9km*y−1
Northern Lakes and Forests: 1.3km*y−1
Southeastern Wisconsin Till Plains: 1.8km*y−1
Western Corn Belt Plains: 2.5km*y−1
Temperature Annual Range velocity [km*yr−1]
Driftless Area: 0.1km*y−1
North Central Hardwood Forests: 0.2km*y−1
Northern Lakes and Forests: 0.2km*y−1
Southeastern Wisconsin Till Plains: 0.1km*y−1
Western Corn Belt Plains: 0.2km*y−1
Mean Temperature of Wettest Quarter velocity [km*yr−1]
Driftless Area: 1.7km*y−1
North Central Hardwood Forests: 1.3km*y−1
Northern Lakes and Forests: 1km*y−1
Southeastern Wisconsin Till Plains: 1.5km*y−1
Western Corn Belt Plains: 2.1km*y−1
Mean Temperature of Driest Quarter velocity [km*yr−1]
Driftless Area: 2km*y−1
North Central Hardwood Forests: 1.9km*y−1
Northern Lakes and Forests: 1.7km*y−1
Southeastern Wisconsin Till Plains: 1.9km*y−1
Western Corn Belt Plains: 3.6km*y−1
Mean Summer Temperature (JJA) velocity [km*yr−1]
Driftless Area: 4.8km*y−1
North Central Hardwood Forests: 2.7km*y−1
Northern Lakes and Forests: 6km*y−1
Southeastern Wisconsin Till Plains: 4km*y−1
Western Corn Belt Plains: 4.2km*y−1
Mean Winter Temperature (DJF) velocity [km*yr−1]
Driftless Area: 0.3km*y−1
North Central Hardwood Forests: 0.3km*y−1
Northern Lakes and Forests: 0.4km*y−1
Southeastern Wisconsin Till Plains: 0.3km*y−1
Western Corn Belt Plains: 0.2km*y−1
Annual Precipitation velocity [km*yr−1]
Driftless Area: 0.2km*y−1
North Central Hardwood Forests: 0.2km*y−1
Northern Lakes and Forests: 0.2km*y−1
Southeastern Wisconsin Till Plains: 0.3km*y−1
Western Corn Belt Plains: 0.1km*y−1
Precipitation of Wettest Month velocity [km*yr−1]
Driftless Area: 0.4km*y−1
North Central Hardwood Forests: 0.4km*y−1
Northern Lakes and Forests: 0.4km*y−1
Southeastern Wisconsin Till Plains: 0.3km*y−1
Western Corn Belt Plains: 0.5km*y−1
Precipitation of Driest Month velocity [km*yr−1]
Driftless Area: 0.2km*y−1
North Central Hardwood Forests: 0.3km*y−1
Northern Lakes and Forests: 0.3km*y−1
Southeastern Wisconsin Till Plains: 0.3km*y−1
Western Corn Belt Plains: 0.2km*y−1
Precipitation Seasonality velocity [km*yr−1]
Driftless Area: 0.1km*y−1
North Central Hardwood Forests: 0.1km*y−1
Northern Lakes and Forests: 0km*y−1
Southeastern Wisconsin Till Plains: 0.1km*y−1
Western Corn Belt Plains: 0.1km*y−1
Precipitation of Wettest Quarter velocity [km*yr−1]
Driftless Area: 1km*y−1
North Central Hardwood Forests: 1.1km*y−1
Northern Lakes and Forests: 0.7km*y−1
Southeastern Wisconsin Till Plains: 0.9km*y−1
Western Corn Belt Plains: 1km*y−1
Precipitation of Driest Quarter velocity [km*yr−1]
Driftless Area: 0km*y−1
North Central Hardwood Forests: 0.1km*y−1
Northern Lakes and Forests: 0.1km*y−1
Southeastern Wisconsin Till Plains: 0.1km*y−1
Western Corn Belt Plains: 0km*y−1
Summer Precipitation (DJF) velocity [km*yr−1]
Driftless Area: 1km*y−1
North Central Hardwood Forests: 1.1km*y−1
Northern Lakes and Forests: 0.7km*y−1
Southeastern Wisconsin Till Plains: 1.1km*y−1
Western Corn Belt Plains: 1km*y−1
Winter Precipitation (DJF) velocity [km*yr−1]
Driftless Area
North Central Hardwood Forests
Northern Lakes and Forests
Southeastern Wisconsin Till Plains
Western Corn Belt Plains