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Land-use and climatic causes of environmental novelty in Wisconsin since 1890

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Abstract. Multiple global change drivers are increasing the present and future novelty of environments and ecological communities. However, most assessments of environmental novelty have focused only on future climate and were conducted at scales too broad to be useful for land management or conservation. Here, using historical county-level data sets of agricultural land use, forest composition, and climate, we conduct a regional-scale assessment of environmental novelty for Wisconsin landscapes from ca. 1890 to 2012. Agricultural land-use data include six cropland types, livestock densities for four livestock species, and human populations. Forestry data comprise biomass-weighted relative abundances for 15 tree genera. Climate data comprise seasonal means for temperature and precipitation. We found that forestry and land use are the strongest cause of environmental novelty ($Novelty_{Forest}$ = 3.66, $Novelty_{Ag}$ = 2.83, $Novelty_{Climate}$ = 1.60, with Wisconsin's forests transformed by early 20th-century logging and its legacies and multiple waves of agricultural innovation and obsolescence. Climate change is the smallest contributor to contemporary novelty, with precipitation signals stronger than temperature. Magnitudes and causes of environmental novelty are strongly spatially patterned, with novelty in southern Wisconsin roughly twice that in northern Wisconsin. Forestry is the most important cause of novelty in the north, land use and climate change are jointly important in the southwestern Wisconsin, and land use and forest composition are most important in central and eastern Wisconsin. Areas of high regional novelty tend also to be areas of high local change, but local change has not pushed all counties beyond regional baselines. Seven counties serve as the best historical analogues for over one-half of contemporary Wisconsin counties (40/72), and so can offer useful historical counterparts for contemporary systems and help managers coordinate to tackle similar environmental challenges. Multi-dimensional environmental novelty analyses, like those presented here, can help identify the best historical analogues for contemporary ecosystems, places where new management rules and practices may be needed because novelty is already high, and the main causes of novelty. Separating regional novelty clearly from local change and measuring both across many dimensions and at multiple scales thus helps advance ecology and sustainability science alike.

Key words: *agroecology; climate change; ecological management; environmental history; forest composition; land use; novel ecosystems; regional novelty; Wisconsin.*

Introduction

The novelty of many ecological systems relative to historical baselines is rising due to multiple factors, including climate change, current and past land use, introductions of exotic species, and altered biogeochemical cycling (Hobbs et al. 2013, Radeloff et al. 2015). Novelty occurs when either the abiotic or biotic conditions are outside the historical range of variability in a given place, resulting in local novelty (Hawkins and Sutton 2012, Mora et al. 2013), or anywhere within some broader area, resulting in regional- to global-scale novelty (Williams et al. 2007, Mahony et al. 2017).

Novelty is related to, but distinct from, local change, in that a location must experience at least some change to experience novelty, but change does not always lead to novelty (Radeloff et al. 2015). For example, in North America, expected temperature changes at Anchorage

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over the 21st century are large, but remain within the bounds of 20th-century North American climates (Mahony et al. 2017). Conversely, future climates for Acapulco and Prince Rupert Island are expected to have high novelty relative to late 20th-century North American climates, even though absolute changes in temperature are smaller (Mahony et al. 2017).

Rising novelty challenges ecological management (Bonebrake et al. 2017), partly because ecosystems with high novelty can exhibit unexpected behavior due to new species interactions (Blois et al. 2013, Silliman et al. 2018), placing ecosystem services at risk. The predictive ability of ecological forecasting models is typically low when future conditions are outside of the range of observations used to test and calibrate such models (Veloz et al. 2012, Seidl et al. 2015, Keeley and Syphard 2016, Maguire et al. 2016, Uribe-Rivera et al. 2017). In some cases, restoring novel ecosystems to historical states may not be practical (Hobbs et al. 2006, 2013). Hence, identifying whether an ecosystem is highly novel is a first-order step in ecological management decision-making (Barnosky et al. 2017).

Efforts to define, identify, and map novel ecosystems and novel climates have employed either categorical (an ecosystem is novel or not; Hobbs et al. 2013) or continuous, dissimilarity-based approaches (an ecosystem has high or low novelty; Williams et al. 2007, Radeloff et al. 2015). Categorical definitions of novelty have been controversial on both operational and conceptual grounds (Murcia et al. 2014, Simberloff et al. 2015, Kattan et al. 2016, Backstrom et al. 2018). Dissimilarity-based approaches have gained popularity because of their quantitative basis, flexibility, and applicability to a wide range of physical and ecological systems, for both anthropogenic and non-anthropogenic causes of environmental novelty. Examples include the expected novelty of future climates relative to those of 20th-century baselines (Williams et al. 2007, Mahony et al. 2017, LaSorte et al. 2018), the novelty of fossil assemblages relative to extant counterparts (Overpeck et al. 1992, Williams et al. 2001, Finsinger et al. 2017), spatial gradients in ecological novelty (Gandy and Rehage 2017), or the novelty of contemporary forests relative to historical (Goring et al. 2016) or late Quaternary baselines (Fyfe et al. 2018).

Most assessments of environmental novelty have focused on future climate change and analyzed continental to global scales. Climate novelty is part of an emerging suite of environmental metrics designed to provide ecoclimatic indices of climate exposure (Ackerly et al. 2010, Garcia et al. 2014, Ordonez et al. 2016), including novelty, local rates of change, velocity, and divergence. The large spatiotemporal extent of the reference baselines used in these analyses enables powerful statements about the novelty of future climates, such as that some portions of late 21st-century climates are projected to be entirely outside the bounds of 20th-century climates within North America (Mahony et al. 2017) or even globally (Williams et al. 2007, Li et al. 2018). Highly novel climates likely will profoundly affect a large range of ecological processes, including disturbance regimes and forest ecosystem adaptations (Kulakowski et al. 2017, Thom et al. 2017), ecosystem metabolism (Kraemer et al. 2016), and bird migration (LaSorte et al. 2018), and high novelty is expected to decrease the predictive strength of ecological forecasting models (Fitzpatrick et al. 2018). However, species, ecosystems, and land managers are faced with a host of concomitant environmental changes that can drive ecological novelty (Martinuzzi et al. 2015), yet only a few efforts have explored the integration of climate metrics with other drivers of environmental change, such as calculations of the joint velocities of projected climate and land use change in the coterminous United States over the coming decades (Ordonez et al. 2014), or the emergence of global future novelty based on projected temperature, precipitation, nitrogen deposition rates, and human population growth (Radeloff et al. 2015).

Furthermore, most past efforts to measure and map novelty lacked the spatial resolution to be useful for land management practices operating at local to landscape scales. This is unfortunate because over the past two centuries and at local to regional scales, the effects of climate change on ecosystems have been relatively muted while land-use changes have been large in most parts of the world (Ellis and Ramankutty 2008, Ellis et al. 2013, Martinuzzi et al. 2015). Furthermore, by zooming in to assess novelty within regions, additional dimensions of novelty can be explored, because historical data sets are rarely available at global scales (e.g., Goring et al. 2016). Moreover, the regional scale enables a richer contextualization and more detailed interpretation of the emergent patterns of change and novelty. Focusing on novelty at the level of regional-scale political units such as U.S. states or counties helps connect these efforts to management practice and policy, which tend to operate at local to regional scales and to have spatial domains set by regulatory, legal, or political boundaries.

Here, we seek to (1) conduct a regional-scale comprehensive, multi-dimensional analysis of the historical rise of environmental novelty from the late 19th century to present day based on changes in agricultural land use, biomass-weighted forest composition, and climate, (2) compare change vs. novelty, and (3) identify which of the three is the major cause of novelty across the state of Wisconsin. We draw on a broad mixture of historical and contemporary data resources, including agricultural census records, human census data, forestry surveys from the Public Land Survey and Forest Inventory and Analysis, and historical climate data from the PRISM Climate Group (Methods). We integrate three dimensions of environmental change that strongly predict ecological community composition and function: agricultural land use (including cropland area, livestock densities, and human population), forest composition, and climate. This is, to our knowledge, the first integrated analysis across all three sets of environmental variables. Methodologically, this integration enables new forms of interdisciplinary analysis from ecological, climatological, and historical perspectives. We review the major trends in each of these three environmental dimensions, contextualizing them with discussions of the historical record, and assess the emergence of novelty in each separate dimension. We then assess the relative importance of changes in agricultural land use, forest composition, and climate upon the magnitude and timing of the rise of environmental novelty in Wisconsin. We distinguish and identify areas of high local change vs. areas of high emergent novelty, and discuss implications for science and management in a world of rising novelty.

Study Area and History

Wisconsin landscapes have been profoundly transformed by agricultural land use, forestry, and, increasingly, climate change over the past 150 yr, making this region a useful case study for understanding multiple causes of environmental novelty. Taken in aggregate, these changes are greater than any experienced since the glaciers retreated (Waller and Rooney 2008). These changes affected southern, central, and northern Wisconsin ecosystems differently, creating regionally varying patterns of ecological and environmental change. The changes that occurred in Wisconsin are similar to those experienced in large parts of the northern United States and Canada.

Wisconsin's forests were transformed in both structure and composition during and following the mid-19th century by intensive timber harvesting and slash burning, spurred by the nation's growing dependence on timber resources to support urban development, and by the clearance of land for agriculture (Schulte et al. 2002, Mladenoff et al. 2008). The white pine forests of northern Wisconsin, part of a broader band of similar forests throughout the northern Great Lakes, fed Chicago's rapid growth during the "Cutover," an industrial-scale landscape transformation that was unlike any prior indigenous land use. During the middle to late 19th century, teams of woodmen felled trees in the north and used Wisconsin's rivers and Lake Michigan to transport logs to the lumber mills of Milwaukee and Chicago and from there to wider national markets via the railroad (Cronon 1991:148–206). The Wisconsin Legislature, concerned that such intensive logging would eventually exhaust the state's timber industry, allocated 50,000 acres of state park land in northern counties such as Vilas and Iron in 1879, thus preceding the federal Forest Reserve Act and Forest Management Act by over a decade (Dombeck 2008:359–360). The patchwork of federal, state, and county land designations that resulted in northern counties from such policies generally reflected the areas where forests were prioritized. Florence County, for example, contains mostly federal land, whereas neighboring Marinette contains none. Nevertheless, through the early decades of the 20th century, Wisconsin markets for hardwoods expanded, and the oak, ash, and beech trees that had previously been spared in favor of pines became commodified. Once the Cutover had cleared large swaths of these forests, the logging industry waned, resulting in a mass migration of workers from the region that would not revive until the post-WWII planting of successional forests for recreation, wise use, and restoration (Rhemtulla et al. 2009). Today, as a result of post-Depression-era public land designations in the 1940s, forestry and restoration have resulted in a patchwork of homogenous coniferous and deciduous stands (Radeloff et al. 1999, 2001, Schulte et al. 2007).

Agricultural transformations of Wisconsin landscapes were concentrated in central and southern Wisconsin, where mesic deciduous forests, oak savannas, and prairies were largely converted to agriculture (Curtis 1956, 1959, Meine 2004). General Land Office surveys during the mid-19th century had commodified land by imposing upon it a gridded pattern that could be enclosed, cleared, plowed, and cultivated (Johnson 1976). By the time Frederick Jackson Turner declared the frontier "closed" in 1893 (Turner 1920), Wisconsin's settlers were cultivating a diverse portfolio of crops. In the 1930s, federal agricultural programs such as the Farm Security Administration, spurred by the Dust Bowl, launched scientific conservation of agricultural ecosystems to prevent soil erosion. Gradually, agricultural land use intensified and industrialized through the 1910s introduction of tractors and the 1920s adoption of synthetically produced fertilizers, although the horse remained essential through Depression years (Leigh 2004). Between 1890 and 1950, farms increased acreage by only 10%, but nevertheless by 1930, wheat, corn, oats, barley, hay, and soybeans covered 99% of Wisconsin's original prairie vegetation (Curtis 1959). The 1930s drought and the stock market crash of 1929 sapped agricultural income and property values so severely that New Deal revitalization programs were largely ineffective (Kasparek et al. 2004). Thus, the early 1930s mark an apex moment in pre-Depression industrial agriculture that would not become fully mechanized until after World War II. The introduction of swales, contour plowing, and other conservation measures to prevent soil erosion bolstered the efficiency of intensive agriculture from mid-century to present.

Historical climate trends in Wisconsin reflect those recorded elsewhere in the central United States over the past 150 yr. Rising winter temperatures are well documented by historical instrumental data sets (WICCI 2011, Goring and Williams 2017) and are linked to the progressive decline in ice-cover duration at Lake Mendota (1.87 d/decade) between 1855 and 2005 (Benson et al. 2012) and to phenological trends (Leopold and Jones 1947, Bradley et al. 1999, WICCI 2011). Rainfall amount and variability have also increased in recent decades (Kunkel et al. 1999, 2013).

Methods

All of the above changes are well documented by historical and instrumental records spanning the last 100 to 150 yr. Because each of these historical and instrumental records varies in spatial and temporal resolution, we use counties as a common spatial grain of analysis, and we select the dates 1890, 1930, 1960, and 2012 as historical benchmarks to assess the emergent patterns of environmental novelty in time and space.

Land use data

We obtained county-level agricultural land use data from United States agricultural census records for 1890, 1930, 1959, and 2012. Agricultural census records were collated by the National Agricultural Statistics Service of the United States Department of Agriculture and were tabulated by Haines et al. (2016). Human population data were obtained from Waisanen and Bliss (2002) for the census years of 1890, 1930, and 1959, and from the Wisconsin Department of Administration for 2010 (data *available online*).[7]

Agricultural land use data comprise 11 variables representing croplands, pasturelands, and human population. Crops are represented as the areal percentage of each county covered by each of six types: barley, corn, hay, oats, soybean, and wheat. We analyzed percentages rather than absolute area to account for differing county sizes, and we included all crops that occupied ≥1% of Wisconsin land area during any census year. The crop type "hay" represents a combination of leguminous and graminoid plant species, and cannot be parsed further based on census records. The crop type "soybean" does not appear in census records until 1920, so soybean areas were set to zero for earlier census periods.

The area of pastureland could not be readily or reliably estimated from census records, so we used instead livestock densities (animals per acre [1 acre = 0.40 ha) for four domesticated species: cattle, horses, sheep, and swine. We acknowledge that the relationship between animal density and land area in pasture is imperfect and may be decoupled in recent history, particularly for cattle and swine, due to the emergence of concentrated animal feeding operations (Hurd 2002).

For variables that represent a density (i.e., livestock, human population) we apply a Yeo-Johnson power transformation (Yeo and Johnson 2000) to each variable, at each time step, prior to our analyses to normalize their distributions (Appendix S1: Fig. S1). This is particularly important for human population, which exhibits positive skewness due to high population densities concentrated in a few counties. We included human populations both as a signal of agricultural activity during the 19th and early 20th century, and as a signal of increasing land use intensity. We experimented with removing human population data from the data set of agricultural land use variables and found only a small effect on overall novelty patterns (Appendix S1: Fig. S2), with the biggest change in Milwaukee County.

County boundaries have changed from 1840 to 2012, particularly in early decades, as larger units were broken up into the modern configuration. For example, La Pointe County in 1850 encompassed the current Bayfield County, Douglas County, and portions of Ashland, Burnett, Sawyer, and Washburn Counties. Additional minor changes to county boundaries are due to mapping corrections and adjustments. By 1910, the modern distribution of Wisconsin counties was largely in place. We calculated county areas separately for each time period, using United States county boundary files available from the National Historical Geographic Information System (Minnesota Population Center 2016) using the "Field Calculator" tool in ArcMap (ESRI, Redlands, California, USA). These county areas were associated with agricultural variables with custom R scripts (R Core Team 2017) and archived on GitHub (see *Data Availability*).

To allocate historical agricultural statistics to 2012 counties, we assumed that agricultural land use was distributed evenly within counties and proportionally reallocated historical productivity to modern counties by area overlap. Area overlap was calculated using the tabulate intersection tool in ArcMap. County agricultural production values were rescaled for each historical census year, each 2012 county, and each agricultural variable, as follows (Eq. 1):

$$\sum_{i=1}^{n} a_i \times p_i \quad (1)$$

where n is the number of counties from the historical census period that overlaps the 2012 county, a_i is the value of the agricultural variable (divided by county area) in county i, and p_i is the proportion of county i that overlaps the 2012 county. Human population estimates had been previously matched to 2012 county boundaries by Waisanen and Bliss (2002), so did not need to be reallocated.

Forestry data

Biomass-weighted estimates of forest composition are based on Public Land Survey System (PLSS) records (Schulte et al. 2007, Liu et al. 2011, Goring et al. 2016, Cogbill et al. 2018) and United States Forest Service Forest Inventory and Analysis (FIA) data (Forest Inventory Analysis Program 2007, Gray et al. 2012). PLSS records provide an estimate of mid- to late-1800s forests, while FIA observations are from the most recent full plot inventory (2007–2011) (Goring et al. 2016). Hence, the PLSS estimates serve as a record of forest composition and biomass prior to major Euro-American land-use and clearing. We used the PLSS data as a proxy for

[7] https://doa.wi.gov/Pages/LocalGovtsGrants/Population_Estimates.aspx

forest composition in 1890, although many observations were collected up to several decades previously, so there is some temporal misregistration. The FIA observations serve as a modern estimate of composition and biomass and are used for the 2012 data. For both periods, we included 15 tree genera that are prevalent throughout the Midwest, using genera rather than species to minimize ambiguities in PLSS surveyor identifications (Mladenoff et al. 2002, Goring et al. 2016): *Abies* (fir), *Acer* (maple), *Betula* (birch), *Fagus* (beech), *Fraxinus* (ash), *Juniperus*/*Thuja* (juniper/cedar), *Larix* (larch), *Ostrya* (ironwood), *Picea* (spruce), *Pinus* (pine), *Populus* (poplar), *Quercus* (oak), *Tilia* (basswood), *Tsuga* (hemlock), and *Ulmus* (elm).

Goring et al. (2016) developed 8-km gridded data sets of composition, stem density, and biomass for the PLSS and FIA data, aggregating the PLSS data from their native resolutions of individual trees sampled at corner points at 1 mile spacing (1 mile = 1.61 km) and FIA data from their native resolutions of individual trees within 7.2 m fixed-radius plots. Biomass estimates for the PLSS data were calculated by first calculating point-level stem densities at each survey location, using the two nearest trees and stem-density estimators described by Goring et al. (2016) and Cogbill et al. (2018), then multiplying the stem density estimates by average stem basal area, calculated using diameter at breast height (DBH) and allometries from Jenkins et al. (2004). Biomass estimates for the FIA data were also calculated using DBH and allometries for all individual trees with DBH > 20.32 cm (8 inches), to match the PLSS data (Goring et al. 2016). We aggregated these gridded estimates to the county level by summing for each taxon its biomass across all grid cells in a county. Based on the total biomass for all taxa in each county, we then derived a biomass-weighted estimate of relative composition at the county level for the novelty calculations.

Climate data

Climate data are from the PRISM Climate Group (Daly et al. 2002, 2008), a 4-km resolution historical data set spanning 1895 to 2015. Based on these data, we created 25-yr mean climatologies that we temporally aligned with the U.S. agricultural census records as follows: 1890 census, 1895–1920 climates; 1930 census, 1920–1945 climates; 1959 census, 1945–1970 climates; 2012 census, 1990–2015 climates. For each these periods, we included eight variables: mean precipitation and mean temperature for winter (December–February), spring (March–May), summer (June–August), and fall (September–November) and spatially averaged each variable from the 4-km resolution to the county.

Novelty analyses

We quantified the rise of novelty in Wisconsin ecosystems across all three sets of variables (agricultural land use, forest composition, and climate) and for each set individually. All analyses used the county as the basic spatial unit, with the forestry and climate data aggregated to the county level as described above. For the climate data, available at 4-km resolution, we experimented with spatial grain, conducting novelty analyses at 4-km resolution; averaging 4-km novelty results to county; and for climate variables averaged to the county level (Appendix S1: Figs. S3, S4). We measured novelty among four time periods (1890, 1930, 1960, and 2012) for each time step relative to its precursor time period (decadal-scale novelty) and for 2012 relative to 1890 (century-scale novelty). Because forestry data were available for only 1890 and 2012, the century-scale novelty calculation was based on all three sets of variables while the decadal-scale novelty calculations for each time step relied on agricultural land use and climate data only. Temporal co-registration among data sets is imperfect for the earliest time period (1890) because of differences in temporal extent among data sets. This time period comprises agricultural census data from 1890, climate data from 1895 to 1920, and PLS survey data collected between the 1830s and 1890s.

In all novelty analyses, we calculated the environmental dissimilarity between a county for one time period and all counties for an earlier reference time period, then retained the minimum dissimilarity (i.e., the dissimilarity between a county and its closest analogue in the reference baseline) as the indicator of environmental novelty (Radeloff et al. 2015). We ran four temporal comparisons for novelty: 1930 vs. 1890, 1960 vs. 1930, 2012 vs. 1960, and 2012 vs. 1930 (Fig. 1), and examined patterns of novelty in regional management units defined by the Wisconsin Department of Natural Resources (Appendix S1: Table S1). Most measures of environmental novelty use standardized Euclidean dissimilarity (SED) or Mahalanobis dissimilarity (Williams et al. 2007, Mahony et al. 2017, LaSorte et al. 2018). Mahalanobis distance corrects for covariance among input variables, while SED does not. Here we use SED because it better preserves the signal of individual variables for later analysis and attribution, does not lose information with dimension reduction, and because some environmental variables used here are statistically correlated yet fundamentally differ in their ecological signals and effects, e.g., fall temperature (T_{SON}) and horse distributions, winter temperatures (T_{DJF}) and birch distributions, oak and corn distributions (Appendix S1: Fig. S5). Hence, we measured novelty by calculating, for each county, its SED to all counties in the reference baseline

$$\mathrm{SED}_{ij} = \sqrt{\sum_{k=1}^{n} \frac{\left(b_{kj} - a_{ki}\right)^2}{s^2{}_k}} \tag{2}$$

and retaining the minimum ($\mathrm{SED}_{\min}$). Here k indexes the environmental variables (n = 34 for analyses with

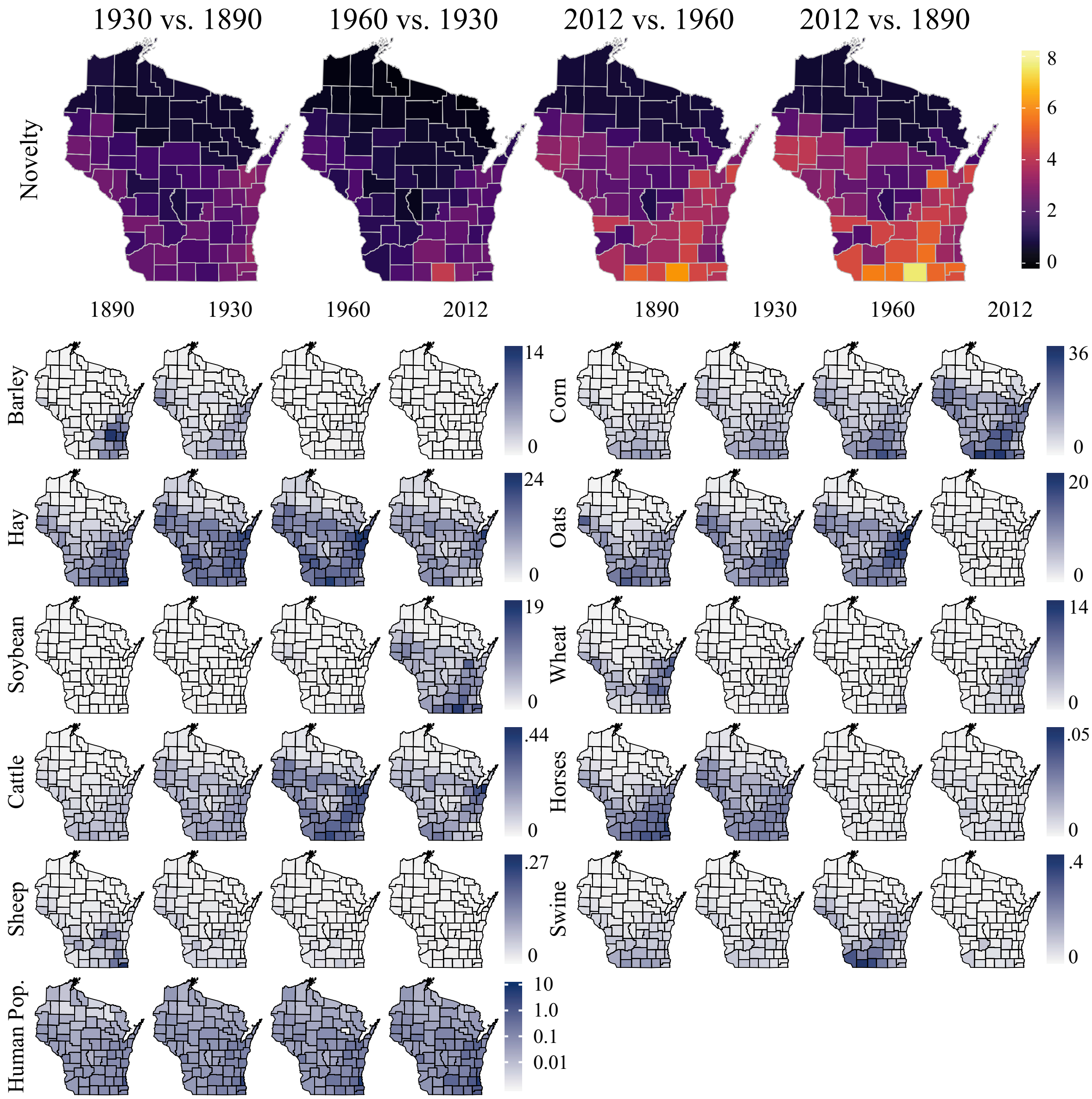

Fig. 1. Agricultural land use novelty (top row) and patterns of agricultural land use for four time periods, 1890, 1930, 1960, and 2012, based on agricultural census data. Novelty maps show minimum standardized Euclidean dissimilarities (SEDs; unitless) for each county, for analogue analyses in which each county was matched to its closest analogue from the earlier time period. Zero novelty indicates a perfect match to a historical counterpart; high novelty indicates that a county does match closely to any historical counterpart. The first three maps are comparisons between adjacent time periods (1930 vs. 1890, 1960 vs. 1930, 2012 vs. 1960) and the last map is from the most recent to earliest times considered in this study (2012 vs. 1890). Agricultural land use maps are shown as distributions of individual crop types, densities of domesticated animals, or human population densities (other rows, blue-shaded maps). The linear color gradients are bounded by variable minima and maxima. In order to better see spatial patterns in human population density, we plot human population density using a log scale.

climate, forestry, and agriculture, or n = 19 for analyses with only climate and agriculture); a refers to the value of variable k at focal county i (drawn from the reference baseline data set); b refers to the value of variable k at focal county j (drawn from the period for which novelty is being assessed); and s refers to the standard deviation of variable k. Dividing each variable by its variance standardizes the values to a common scale. Indices of climate novelty usually use temporal variability to calculate s, under the theory that, to be ecologically important, environmental changes must be large relative to background environmental variability (Williams et al. 2007). However, because the number of time periods is fairly small in our analysis, we calculate s as spatiotemporal variability, using all observations for all times and locations, and following this procedure for all variables. Higher SED_{min} values correspond to counties with no close analogue in the earlier reference baseline (high novelty), while lower SED_{min} values correspond to counties that have a close analogue (low novelty).

Lastly, we calculate local change as the environmental dissimilarity between a county and itself for the two time periods under comparison (i.e., $i = j$). Note that novelty will always be less or equal to local change ($SED_{min} \leq SED_{ii}$).

Results

Maps of agricultural land use and novelty (Fig. 1) show how Wisconsin landscapes have been transformed by multiple waves of agricultural innovation and obsolescence. As expected, these changes are strongest in southern and central Wisconsin, with southern counties having the largest agricultural novelty. Some crops, such as wheat, barley, and oats, flourished for brief periods, then gave way (Fig. 1). Of these, the rise and decline of wheat in the middle to late 19th century represents the gradual abandonment of unirrigated dryland wheat farming, while the declines in barley and oats, and corresponding reductions in fodder crops, can be traced to the reduced reliance on draft horses for transportation and farm work (Cronon 1991). The rotation of soybeans and corn is relatively recent, with corn-based agricultural area steadily increasing from 1890 to 2012, and soybeans present only at trace levels in the surveys from 1960 and prior decades. Similarly, high horse densities prevailed in the latter 19th and early 20th century, dropping to near-zero levels by the 1960s, while sheep densities peaked in the 1890s and swine densities peaked in the 1960s in southwestern Wisconsin. Cattle densities increased from the late 19th century until the 1960s, but have decreased in more recent decades. Human densities have steadily increased, with the highest densities in southeastern Wisconsin, representing the growth of Milwaukee and surrounding areas.

These changes are closely reflected in the assessments of land use novelty (Fig. 1). Novelty from land use is consistently highest in southwestern and eastern Wisconsin. Pairwise novelty between 1890 and 1930 is relatively low, suggesting relatively minor changes in the mix of crop types grown by farmers over this time period, while land-use novelty steadily increases for both the 1930 vs. 1960 and 1960 vs. 2012 pairwise combinations, suggesting the introduction of new crop types and abandonment of others. Total land-use novelty is high for 2012 relative to 1890, showing that land use and agricultural innovations in Wisconsin have continued to move these landscapes further from historical baselines.

For Wisconsin forests, patterns of novelty (Fig. 2) reflect the legacies of the late 19th- and early 20th-century cutover in northern and eastern Wisconsin, combined with ongoing forest harvesting, land use, and fire suppression. These historical forest changes have been well described previously (Schulte et al. 2007, Mladenoff et al. 2008, Goring et al. 2016) so are only briefly summarized here. Key changes between the present and 19th century include the homogenization of Wisconsin forests (Schulte et al. 2007), with a weakening of the classic delineation between northern mixed forests and southern hardwoods, separated by the tension zone (Curtis 1959). Formerly prevalent taxa in Wisconsin's Northwoods, such as birch, sugar maple, pine, tamarack, and hemlock, are still present, but at lower relative biomass, while other taxa such as poplar, basswood, and red maple are more common now. Oak is still widespread across Wisconsin, but has declined in relative biomass in the south, where oak savannas and woodlands have been mostly replaced by agricultural lands and closed mesic deciduous forests. Beech, formerly common in eastern Wisconsin, has declined, while ash has increased.

Novelty in biomass-weighted forest composition is highest along the shore of Lake Michigan, caused mainly by the decline of beech and the increase of ash (Fig. 2). Forest novelty is also high in northeastern Wisconsin but here the cause is the decline in fir, spruce, and tamarack, and concomitant increase in poplar (trembling and big-toothed aspen, two early-successional species). Hence, patterns and causes of forest novelty are heterogeneous due to heterogeneity in both presettlement and contemporary species composition.

Major climatic trends in Wisconsin from the late 19th century to present include an increase in winter temperatures (T_{DJF}) and spatially variable but increasing precipitation in winter, spring (T_{MAM}), and summer (T_{JJA}; Fig. 3). Increases in winter temperature are strongest in southern Wisconsin and increases in precipitation strongest in northern and southwestern Wisconsin. Fall climate trends differ from the other seasons, with areas of cooling in northeastern Wisconsin and drying in south-central Wisconsin. Climate novelty is generally low relative to other environmental factors (the maximum novelty values for climate are only one-quarter of the maxima for agricultural land use and forest composition, Figs. 1–3) but highest in southern and southwestern Wisconsin. This pattern of climatic novelty is produced by temperature rises and large precipitation increases in this border region, which means that closer climatic analogues may lie outside the study area, likely to the southwest.

When the three different dimensions of novelty are combined (agricultural land use, forest composition, climate), total novelty is highest in eastern and southern Wisconsin (Fig. 4a), indicating that these regions have moved farthest from the suite of late-19th-century baselines. Attribution of novelty among these three dimensions (Fig. 4b) shows a clear separation of Wisconsin into three regions, with novelty in southwestern Wisconsin attributable to both climatic changes and agricultural land use, and novelty in northern Wisconsin due almost entirely to changes in forest composition and

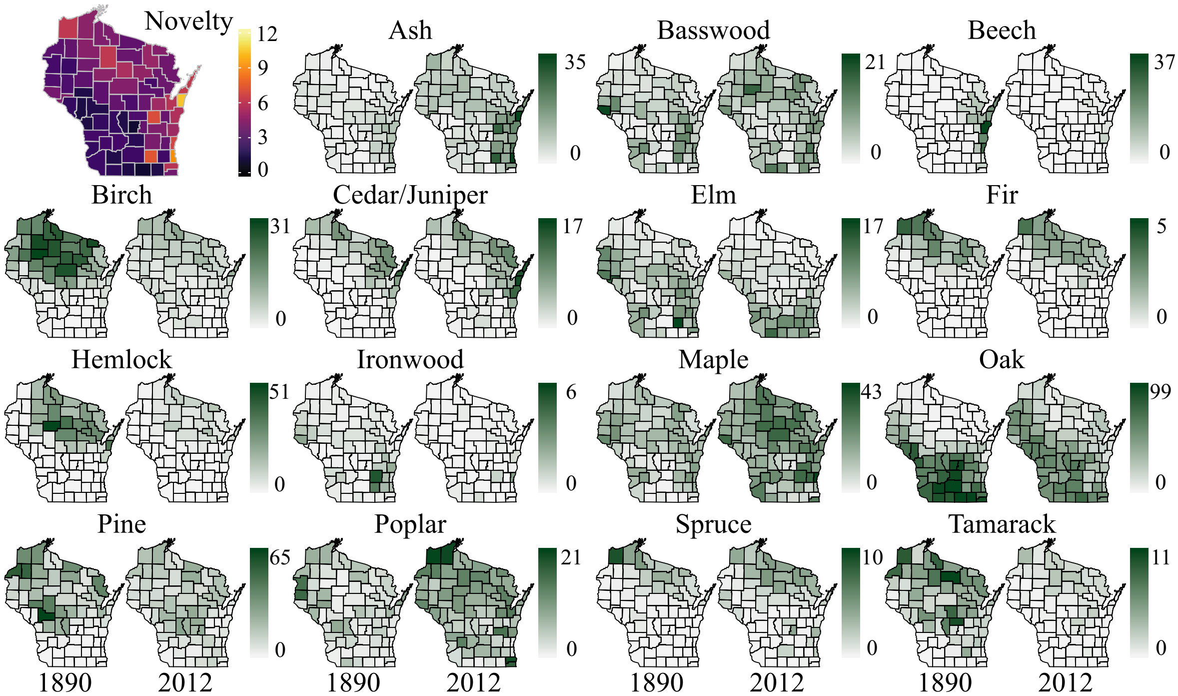

Fig. 2. Forest novelty and forest composition for 2012 and the mid-19th century, based on Public Land Survey and Forest Inventory and Analysis data sets, as compiled by Goring et al. (2016). Novelty map design follows Fig. 1. Individual tree taxa are mapped using a biomass-weighted estimate of relative composition, using a color ramp that encompasses minimum and maximum values.

secondarily to climate change. In the third region, extending from southeastern Wisconsin into central and western Wisconsin, the primary causes of novelty are agricultural land use and changes in forest composition. These three dimensions of novelty are no more than modestly correlated to each other, based on ordinary linear regression for the novelty of 2012 relative to 1890 ($\text{Novelty}_{\text{Forest}}$ vs. $\text{Novelty}_{\text{Climate}}$, $r = 0.0005$, $P = 0.971$; $\text{Novelty}_{\text{Forest}}$ vs. $\text{Novelty}_{\text{Ag}}$, $r = 0.036$; $P = 0.00914$; $\text{Novelty}_{\text{Climate}}$ vs. $\text{Novelty}_{\text{Ag}}$, $r = 0.435$; $P < 0.001$).

The maps of local change (Fig. 4c) resemble those of total novelty (Fig. 4a), showing how high levels of local change are a first-order predictor of which areas have become most novel. However, the ratio of local change to regional novelty (Fig. 5) highlights areas where the two diverge. Counties where the ratio is low (light shading) have low levels of emergent novelty relative to local change. In these counties, 20th- and 21st-century environmental change may be large, but the counties still have good analogues somewhere in historical Wisconsin. The arrows in Fig. 5, which connect each contemporary county to its 19th-century closest analogue, show that a few 19th-century counties serve as the best analogues for many contemporary counties. These counties hence may serve as particularly important historical baselines or references for contemporary ecosystem managers.

Places where the ratio is close to 1 (dark shading) indicates counties that have similar levels of local change and regional novelty (Fig. 5). These also tend to be counties that match to themselves, i.e., they are their own closest 19th-century analogue. This pattern suggests that as environments have changed from the 19th to 21st centuries, these counties were at the leading edge of 19th-century realized environmental space, and so now serve as the closest analogues for themselves and for other, similar counties.

Temporal trends in novelty across all counties are smooth, but differ among regions and dimensions (Fig. 6; Appendix S1: Fig. S6), with some regions and dimensions showing steady accruals in novelty and others showing no long-term trends. The single largest increase in novelty is for agricultural variables in south-central Wisconsin, which show large increases between 1930 and 1960 (1.8 SED) and 1960 and 2012 (0.8 SED). The centennial-scale increase in agricultural novelty (1890—2012) in this region is larger than for any individual pairwise comparison. This pattern signifies a directional trend to novelty, in which contemporary Wisconsin agricultural systems have continued to accumulate novelty and have become increasingly dissimilar to late 19th-century baselines. A similar pattern occurs in southeast, northeast, and west-central Wisconsin, but at lower levels of novelty. Although trends are not available, forest novelty is also an important contribution in all regions, with changes in forest novelty the single biggest contributor to total novelty in all regions except

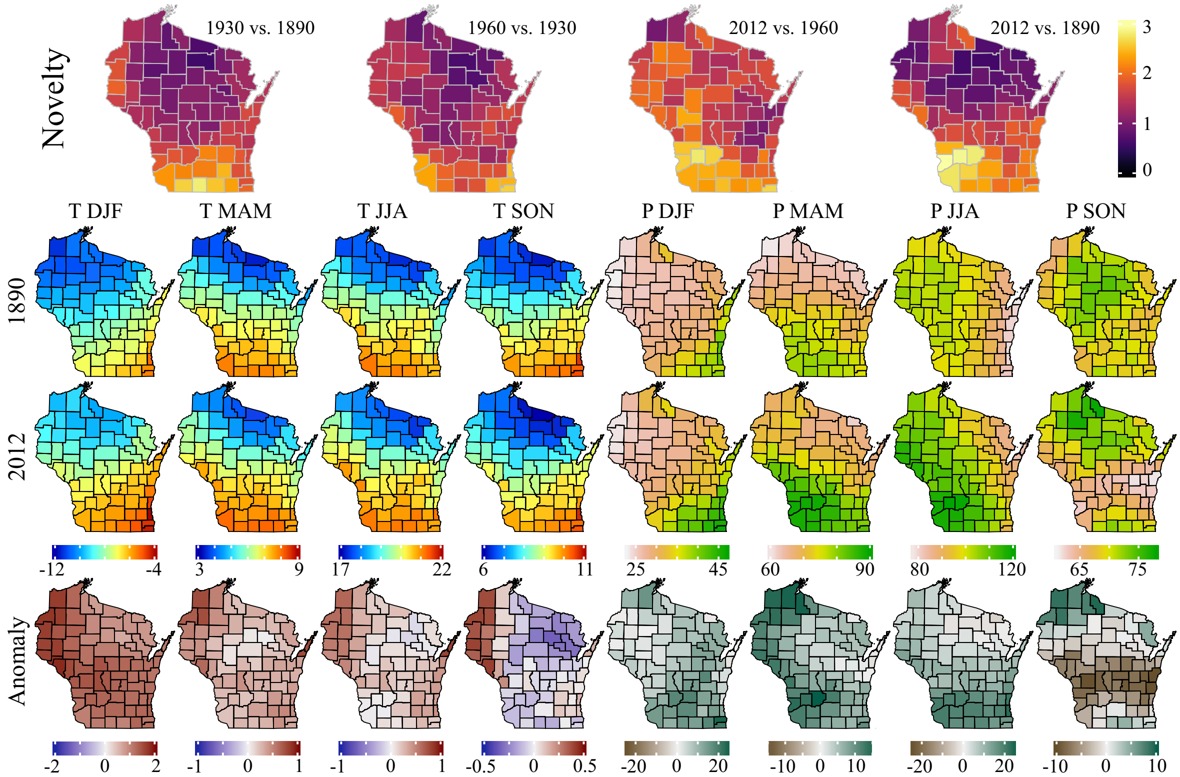

Fig. 3. Climate novelty and individual climate variables, using eight variables (seasonal means of temperature and precipitation for 1895–1920 [1890] and 1990–2015 [2012]). Novelty map design follows Fig. 1. Individual climate variables are shown as interannual means for the respective climate periods, for mean seasonal temperature (°C) and mean seasonal precipitation (mm/month). Climate anomalies are shown in the bottom row, expressed as differences for temperature ($T_{2012}-T_{1890}$) and percentage change for precipitation ($(P_{2012}-P_{1890})/P_{1890}$).

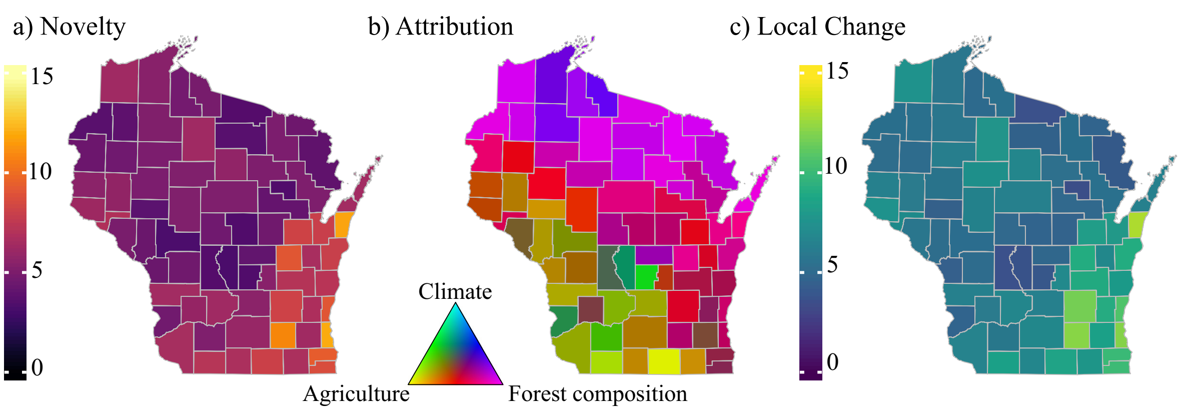

Fig. 4. (a) Novelty of contemporary Wisconsin landscapes relative to 19th-century baselines, when assessed across all three major environmental dimensions (agricultural land use, forest composition, climate). (b) The contribution of each of these three dimensions to total environmental novelty. (c) The local change for individual counties.

south-central Wisconsin. Trends in climate novelty between adjacent periods tend to be flat or slightly increasing, suggesting that, so far, climate change has not been a strong contributor to environmental novelty in Wisconsin.

The strongest individual contributors to the novelty of current Wisconsin landscapes relative to 19th-century baselines are agricultural land use and forest composition (Fig. 7). Indeed, the single biggest contributor is the increase in ash (Fig. 7), especially in eastern Wisconsin

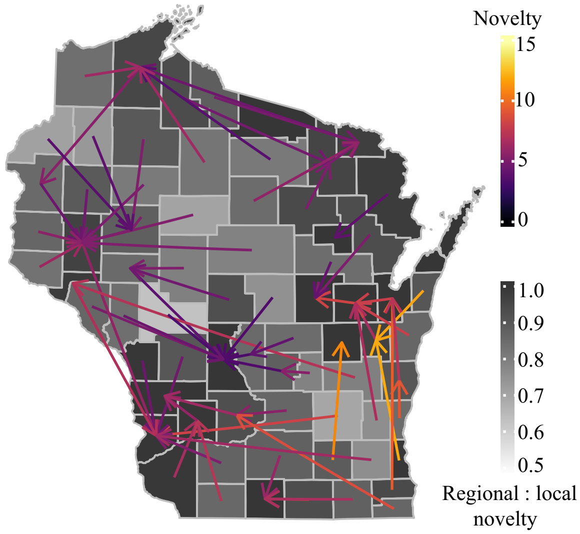

FIG. 5. This figure shows three variables: the ratio of local change to novelty (background shading), the match between current counties and their closest 19th-century analogues (arrow direction, arrow points from current county to closest 19th-century analogue), and level of dissimilarity within each pairing (arrow color).

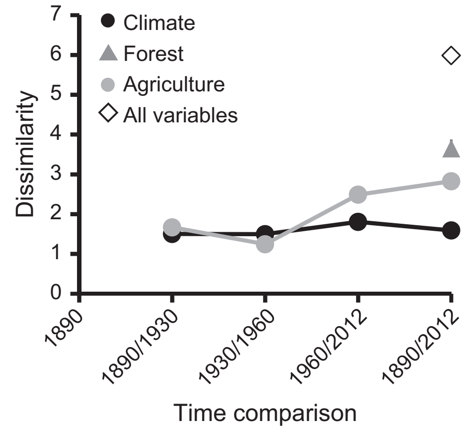

FIG. 6. Trends in novelty for Wisconsin across all counties. Each line indicates the trends for the three major dimensions (agricultural land use, forest composition, and climate. Standard error bars are included but are smaller than symbol size.

(Fig. 2). The next two are the increases in soybeans and corn, which occur most strongly in southern and eastern Wisconsin (Fig. 1). Other important individual contributors include maple and poplar (both increasing), winter and summer precipitation (increasing), and horses, basswood, elm, and wheat (all decreasing).

DISCUSSION

Causes of rising environmental novelty

Multiple factors are causing environmental novelty to rise, leading to on-going discussions about how best to conceptualize, describe, and manage the advent of novel environments and ecosystems (Hobbs et al. 2013, Murcia et al. 2014, Radeloff et al. 2015, Barnosky et al. 2017). Here, we show how to quantify novelty holistically, and attribute its causes across multiple dimensions of global change at a management-relevant scale, i.e., for one U.S. state at county resolution. We found that, in Wisconsin, land use has been the most important cause of the emergence of novel environments, due to both agricultural land use and the legacies of current and past forestry. We also found strong intra-state variability in causes, in which agricultural land use was clearly the most important cause of novelty in southern Wisconsin, forest composition was the most important in the north, and climate change was consistently a tertiary factor but locally important in southwestern Wisconsin. Patterns of novelty are related to patterns of local change (Fig. 4), but with important differences that both underscore the conceptual differences between novelty and change (Radeloff et al. 2015) and highlight individual counties that serve as 19th-century best analogues for contemporary counties. Over 100 yr of forestry and scientific research provides a rich historical record for studying these historical analogues and the transformation of Wisconsin landscapes over time (e.g., Wisconsin Chief Geologist 1883, Roth 1898, Curtis 1959, Waller and Rooney 2008). These novelty assessments add value by integrating across many kinds of environmental change, assessing their relative magnitude, and providing a new framework to understand the effects of multidimensional environmental change on ecological communities.

In these analyses, agricultural land use and forest change clearly are the most important causes of rising environmental novelty over the past 100 to 150 yr, with changing climate generally of secondary importance. The causes of rising novelty vary locally, with a strong zonal pattern (Fig. 4b) that is closely linked to patterns of land-use history and to the divide between agricultural land use in southern and central Wisconsin and forestry in the north. Indeed, the five largest individual contributors to contemporary novelty are all linked to agricultural land-use or forest composition (Fig. 7). Among the agricultural land use changes, the rise of corn and soybeans is a particularly notable late-20th-century phenomenon (Fig. 1) that follows several other waves of agricultural innovation and abandonment, including the abandonment of winter wheat in the early 20th century and the abandonment of oats and barley in the mid-20th-century as horses declined in importance (Fig. 1).

Contemporary forest composition is largely a legacy of widespread logging in the late 19th and early 20th century (Cronon 1991, Schulte et al. 2002, Mladenoff et al. 2008). The rise of poplar and maple in the north can be traced to post-clearance secondary growth and succession: both poplar and red maple grow quickly and are associated with post-disturbance primary growth.

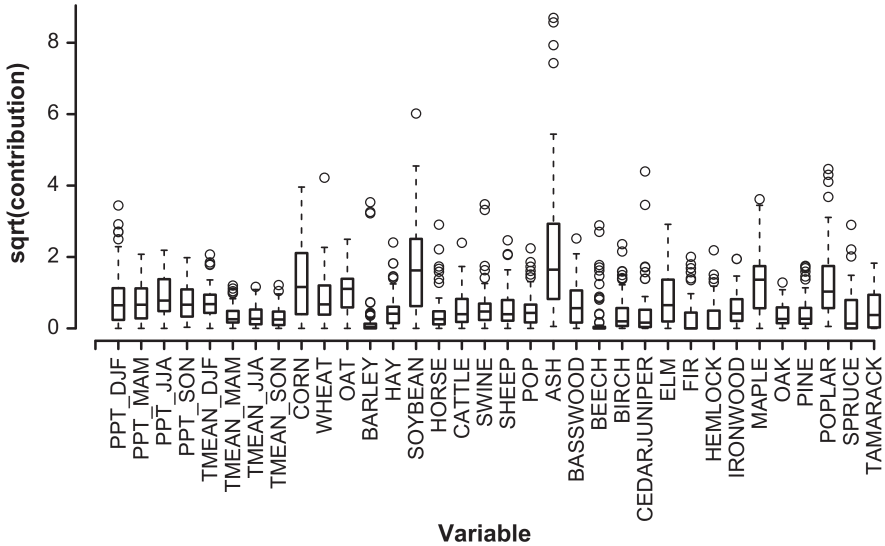

Fig. 7. Contributions of individual variables to total novelty, shown as box and whisker plots with boxes indicating medians, 25th, and 75th percentiles and whiskers indicating 95% intervals. Values outside of the 95% intervals are indicated by open circles. All variables have been square-root transformed (sqrt) for visualization purposes. Variables are sorted by type. See Methods for descriptions of climate, land use, and forestry variables.

Poplar also reproduces vegetatively, enabling fast spread and growth after disturbance. Similarly, green ash (*Fraxinus pennsylvanica*), the most common species of ash in Wisconsin (Curtis 1959), can rapidly establish in old fields and other disturbed environments. The large expansion of ash in eastern Wisconsin (Fig. 2) is likely also due to fire suppression and the replacement of oak savannas and woodlands with agricultural fields and closed-canopy mesic forests. Fire suppression began in Wisconsin in the 1930s, after several devastating fires, most notably the Great Peshtigo Fire of 1871 (Pyne 1982).

Climate change so far is a minor cause of environmental novelty in Wisconsin. Among the climate variables, temperature contributed less to novelty than did precipitation. These findings contrast with those from studies that focused solely on climate change and examined the expected future rise of novelty at continental to global scales (Williams and Jackson 2007, Mahony et al. 2017, LaSorte et al. 2018). In those analyses, rising temperatures are the largest cause of emerging environmental novelty relative to contemporary baselines, which in turn has raised questions about the adaptive capacity of species relative to temperatures outside the range of those experienced today (Feeley and Silman 2010, Buckley et al. 2013, Burke et al. 2018) and the predictive ability of ecological forecasting models (Williams et al. 2013, Fitzpatrick et al. 2018). To be clear, our new results do not call previous assessments of environmental novelty into question; this paper and those were conducted at different spatial scales (regional vs. global) and temporal domains (historical vs. 21st-century projections). Some of these papers also differ in choice of dissimilarity metric (e.g., SED vs. Mahalanobis) and standardization approach (e.g., temporal vs. spatiotemporal variance), so the results are not directly comparable. However, this contrast does emphasize how scale matters in assessments of novelty (see next section) and how the challenges of novelty faced by land managers today may be different from those expected for the coming decades. Ultimately, species are experiencing ecological and environmental novelty in far more dimensions than just climate (Ordonez et al. 2014, Martinuzzi et al. 2015) and, historically, land use has been a bigger driver of environmental and ecological change. Hence, analysis of environmental novelty ought to be based on multiple dimensions of environmental change whenever possible, not just climate. Land use merits particular attention in historical novelty analyses, because it has affected so many regions so drastically (Ellis et al. 2013).

Effects of scale and variable selection on emergent patterns of novelty

These results also show how quantitative approaches to measuring novelty provide ample flexibility to incorporate multiple dimensions of environmental change across a variety of spatiotemporal scales and domains. Novelty metrics can either be based on abiotic factors, such as climate; biotic factors, such as forest composition; or socioeconomic factors, such as land use and human populations (Radeloff et al. 2015). These approaches are also flexible in regard to the spatial scale and temporal domain and directionality. While prior quantifications of novelty focused on global- to continental-scale analyses (Ordonez et al. 2016, Mahony et al. 2017, LaSorte et al. 2018) or on the timing of emergence of locally novel conditions (Hawkins and Sutton 2012, Mora et al. 2013), we show here how novelty can be calculated at intermediate scales, using management units (counties) and domains (a single state) of particular relevance to managers. In regard to temporal domain, these analyses here compared contemporary novelty relative to a historical baseline, but the same approaches can be used to measure future novelty relative to present, or the novelty of now-vanished ecosystems relative to modern counterparts (Overpeck et al. 1992, Williams et al. 2001).

As with most ecological analyses, findings are scale dependent, and different patterns of novelty would emerge if spatially larger or temporally deeper baselines were used (Burke et al. 2018). Novelty measures depend on the baseline used to measure novelty (Radeloff et al. 2015). For example, wheat farming largely ceased in Wisconsin, but remains an important crop in Great Plains states such as Kansas, Montana, and North Dakota. Hence, analyzing a broader study area would have most likely reduced the contributions to novelty made by this crop type. Similarly, the rising winter temperatures in southern Wisconsin have no good state-level analogues, causing climatic novelties to be highest in the southwestern corner of Wisconsin (Figs. 3 and 4). Hence, many contemporary counties draw their best 19th-century analogues from the southwestern corner (Fig. 5). Inclusion of climates in Iowa or Illinois would have provided better historical analogues for contemporary climates, although perhaps these states would have been poor analogues for other dimensions of contemporary Wisconsin environments. This close relationship between novelty metrics and the spatial and temporal bounds of the chosen baseline needs to always be remembered when critically analyzing novelty analyses, but is generally a strength, because it allows novelty metrics to be flexibly targeted to the question, management context, or system of interest.

Furthermore, while U.S. states and counties are convenient units for regional-scale analyses of novelty like this one, they are not the only possible units for such analyses. Thus, the scale of what constitutes a “region” might look very different in different places, particularly in countries for which jurisdictional boundaries may or may not incorporate ecological regions, or for which ecological management may not be dictated by the jurisdiction of counties, states, or provinces. Indeed, state, county, and even national boundaries can just as easily conceal ecological regions as they can reveal the jurisdictional implications for management. Other locations across the globe will require their own regionally meaningful units of analysis, based on their administrative and ecological contexts, sourced from the joint political and ecological assumptions that make a region a region (Sayre 2005, 2017).

Our results also help clarify the distinction between high local rates of change from the emergence of regional novelty (Figs. 4 and 5; Radeloff et al. 2015). Locations (e.g., counties) can experience high rates of change without becoming novel, as long as there is historical precedent for the new conditions somewhere in the study area (Figs. 4 and 5). Similarly, relatively low rates of change can result in high levels of novelty if that change results in conditions for which there is no precedent anywhere in the historical baseline. Choice of environmental variables and standardization also affects patterns of emergent novelty and may confound some patterns. For example, because we analyzed genus-level forest composition, we could not detect emergent patterns of novelty at the species level, e.g., new compositional mixtures among *Quercus* or *Pinus* species. Similarly, the reliance on historical climate data adds potential uncertainty to these findings, given the sparseness of early 20th-century meteorological stations (Daly et al. 2008). When standardizing variables for multivariate assessments of novelty, it is ideal to use long-term time series with many time steps, so that the historical range of variability can be quantified separately for each location (Williams et al. 2007, Mahony et al. 2017). However, here such information was not available, so we instead quantified the range of variability across both time and space, i.e., across all counties in Wisconsin for four time periods. This approach drastically reduces the requirements for input data, making novelty analyses feasible in many settings and for variables for which historical data are only available for single points in time. However, this switch to using spatiotemporal variability to normalize variables instead of temporal variability will lead to different weightings of variables, because a variable’s spatial variance often differs from its temporal variance. Because variables with a high variance are downweighted in the novelty calculations, the choice of variance metric is important. The use of spatiotemporal variance may contribute, for example, to the relatively low importance of temperature in these analyses, because regional spatial gradients in temperature are large relative to decadal-scale trends over the last 100 yr.

Regional-scale novelty analyses: implications for management

We chose to analyze novelty for a state, rather than an ecoregion or other ecologically defined unit, to make our analyses more relevant for land management. In the United States, many land management actions are carried out at the state level. Managers often build up deep bodies of practical and lived experience in their home regions and ecosystems (Mahony et al. 2018), making state-level novelty challenging for management, because neither rules nor practices were developed with such novel conditions in mind. Climate change is forcing a re-evaluation of these practices (Prober et al. 2019), as species conservation and ecosystem management may increasingly require moving beyond frameworks that assume that local populations are best adapted to their local environments. For example, similar analogue-based approaches are being developed for foresters to pick best (and possibly non-local) seed sources for maximizing yields and to assess the spatial speed of environmental change (Isaac-Renton et al. 2014, Hamann et al. 2015, Ordonez et al. 2016).

The fact that a small subset of counties that provide the best analogues for a large number of contemporary ecosystems (Fig. 5) may be of particular interest to local managers faced with the complexities of multidimensional and simultaneous global change processes. First, these maps help local managers to find historical counterparts to where their area is heading, and so help managers to more easily visualize multidimensional changes. To this end, we have included in the Supporting Information a summary table and visualization of the seven counties from 1890 that provide the most common analogues for contemporary counties (Appendix S1: Table S2, Fig. S7). Second, management experiences gained in the best-analogue counties provides a starting point for discussion about management decisions in other counties that have become more like them. Third, managers in counties that all have the same best analogue can coordinate to tackle what are likely similar management challenges.

The rates of environmental change, in all dimensions, are likely to further increase in the future, and some of these changes will cause novelty to rise. High rates of change and emergence of novel states pose unique challenges for both species and land managers. Wisconsin, our study area, is emblematic of the environmental changes that many parts of the temperate latitudes have experienced or will experience in the future. By measuring novelty in multiple dimensions, and with high spatial resolution for a specific region, we identify areas where novelty is high in a way that is holistic, clearly defined, quantifiable, and closely tied to local reference conditions. In other words, our approach offers a flexible way to study changes in the environment, provides a continuous metric of novelty, and enables assessment of which dimensions of environmental change are the primary cause for novelty in a given spatial and historical context. These are the kinds of information that can both guide management actions and predict species responses to a world quickly departing from historical baselines.

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Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.1955/full

Data Availability

Data and code are available on the Dryad Digital Repository: https://doi.org/10.5061/dryad.7k2526d. County areas with associated agricultural variables and custom R scripts are archived on GitHub https://github.com/kdburke/EnviroNoveltyWI.