2017 Project Abstract
For the Period Ending June 30, 2021

PROJECT TITLE: Assessment of Public Benefits of Protecting Source Water
PROJECT MANAGER: Bonnie Keeler
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2017, Chp. 96, Sec.2, Subd. 03b as extended by M.L. 2020, First Special Session, Chp. 4, Sec. 2

APPROPRIATION AMOUNT: $ 320,000
AMOUNT SPENT: $ 319,992
AMOUNT REMAINING: $ 8

Sound bite of Project Outcomes and Results
Source Water protection is associated with multiple economic, environmental, and social benefits. We created new spatially-explicit datasets representing multiple socio-economic benefits of source water protection for all 821 drinking water management units in Minnesota. Our work gives practitioners a more complete picture of the outcomes of source water protection statewide.

Overall Project Outcome and Results
The goal of the project was to collect and synthesize economic, social, and environmental data relevant to source water protection in Minnesota. We created new spatially-explicit datasets representing multiple socio-economic benefits of source water protection for all drinking water supply management areas in Minnesota. Project outcomes include:

1) Mapping land use change and land protection costs for all 821 drinking water management areas.
- Estimated trends in land use change in each DWSMA in order to identify potential threats to source water from increasing agricultural expansion or development.
- Obtained new spatial data based on estimated market values of hundreds of thousands of parcels in the state in order to quantify the opportunity costs of source water protection in each DWSMA.

2) Valuation of the multiple public benefits of land protection for clean water.
- Applied best-available estimates for drinking water treatment to calculate potential costs of contamination in each DWSMA as a function of population served.
- Implemented a methodology for estimating the potential health damages and associated monetary costs of drinking water contamination.
- Generated 19 spatially-explicit environmental benefit maps that can be used to assess the potential for co-benefits of protection or restoration in each DWSMA.

3) Assessing the equity implications of source water protection and community capacity to protect land and improve water quality.
- Developed a technique for linking source water protection areas to municipalities served, allowing us to relate census data and demographic characteristics to each DWSMA.
- Administered and analyzed data from a statewide survey of water values in order to identify perceived threats to water quality and preferences for different water-quality related values and uses.

- Completed a series of participatory water valuation exercises using a Q-sort methodology to understand stakeholder preferences for water-related expenditures and tradeoffs among water quality objectives.

Project Results Use and Dissemination

We presented our work at venues targeting academic and state agency audiences, and held meetings with specialists at MDH and the interagency GRAPS team exploring application of the work in MN agency work. We shared findings with state agencies including MPCA, MDH, DNR, and BWSR, along with external stakeholders and advocacy groups such as Freshwater Society and the Environmental Working Group. Our work contributed to multiple students' master's theses and is being written up for publication in a peer-reviewed journal. Our work is summarized in a report (available on our website) and includes appendices with data useful for further analysis.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2017 LCCMR Work Plan Final Report

Date of Submission: Nov 11, 2021

Date of Next Status Update Report: Final Report

Date of Work Plan Approval: 06/07/2017

Project Completion Date: June 30, **2021**

PROJECT TITLE: Assessment of Public Benefits of Protecting Source Water

Project Manager: Bonnie Keeler

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Location: Statewide

Total ENRTF Project Budget:		
	ENRTF Appropriation:	**$320,000**
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	Balance:	**$8**

Legal Citation: M.L. 2017, Chp. 96, Sec.2, Subd. 03b as extended by M.L. 2020, First Special Session, Chp. 4, Sec. 2

Appropriation Language:
Assessment of Public Benefits of Protecting Source Water
$320,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota to map and quantify source water risks, determine ecosystem service valuation of clean water, and provide analyses of equity and community capacity to improve decisions about the protection and management of groundwater and surface water. This appropriation is available until June 30, 2020, by which time the project must be completed and final products delivered.

M.L. 2020 - Sec. 2. ENVIRONMENT AND NATURAL RESOURCES TRUST FUND; EXTENSIONS. [to June 30, 2021]

I. PROJECT TITLE: What are the public benefits of protecting sourcewater?

II. PROJECT STATEMENT:

Access to clean safe water is essential for health, recreation, and economic development in Minnesota. However, many of our state's most pressing water quality problems remain unsolved. More than 40% of our lakes and rivers are rated as "impaired," and a growing number of households and communities face rising costs and health risks because of contaminated drinking water. If we hope to reverse current trends of water quality decline and preserve the valuable ecosystem services provided by clean water, we need to change how we account for the value of our water resources. Current systematic *undervaluation* of water is contributing to the overuse of water and degradation of water quality in Minnesota and elsewhere.

The emphasis of the proposed work is on the value of sourcewater in Minnesota - the surface and groundwater resources that supply households and communities with their drinking water. Approximately 75% of Minnesota households rely on groundwater for household use and the majority of the land area in sourcewater areas is under private ownership. Land use and management actions on these lands that increase nutrients and other contaminants can affect the health and welfare of millions of Minnesotans. There are successful examples of private and public partnerships that have worked together to protect sourcewater and enhance valuable ecosystem services while supporting agricultural and rural economic development (e.g. Worthington Wells Wildlife Management Area). At the same time, other communities in Minnesota are facing known or unknown threats to their water supply with consequences for health and rising treatment costs.

Agency leaders and Gov. Dayton have identified an urgent need to map and quantify the risks facing sourcewater areas in Minnesota, better articulate the ***true value of clean water***, and develop practical approaches that enhance community capacity to protect sourcewater and ensure safe and equitable access to clean water for all Minnesotans. This project responds to that need with investments in three activities:

1) **Mapping land use change and risks to clean water for all 584 drinking water management areas.**
2) **Valuation of the multiple public benefits of land protection for clean water.**
3) **Assessing the equity implications of sourcewater protection and community capacity to protect land and improve water quality.**

These activities highlight potential risks and opportunities to protect water quality and provide multiple public benefits, identify financial practices or incentive programs that protect the value of clean water, and build capacity among citizens and decision-makers to take action in sourcewater protection areas to improve water quality and realize additional public benefits from land protection.

The proposed work builds on the LCCMR-funded project "Understanding Water Scarcity, Threats, and Values to Improve Management" awarded in 2015 to PI Keeler. The water scarcity project will assess how changes in precipitation and temperature interact with alternative scenarios of water demand to predict where there is likely to be water depletion in the future. These scenarios of water quantity will be used as inputs into the sourcewater protection analysis proposed here. Whereas the water scarcity project emphasizes water quantity, this project emphasizes water quality. In Minnesota, quantity and quality are related and this project will benefit from data on trends in both quality and quantity to estimate the risks and opportunities for sourcewater protection.

The project will focus on the 1.22 million acres in Minnesota designated as sourcewater protection areas, including both groundwater and surface water catchments. Outcomes of the work include maps and risk assessments for each drinking water management area, including evaluating current assumptions about travel time, threats and delineation of management zones. Additional products include spatially-explicit information about the benefits and costs of changes in water quality and distribution of costs to Minnesotans and assessments and recommendations for how to enhance community capacity to protect sourcewater.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of August 3, 2018:
Due to staffing shortages, we have not been able to hire the research capacity needed to move forward with project deliverables at our anticipated pace. Less than 15% of the project total budget has been spent in the first year of the work plan. We are in the process of transferring GIS capacity to this project to complete Activity 1. Currently no progress has been made to this activity as no funds have been allocated to the task.

Work on Activity 2 and 3 are progressing as planned. We assembled biophysical, social and demographic data on sourcewater vulnerability, risk, and impacts to ecosystem services. We completed and distributed a statewide survey to Minnesota households to better understand values and perceptions about water risks and identify regions of high community capacity to adopt sourcewater protection activities.

Next steps include integrating the biophysical data collected in Activity 2. with updated risk modeling and analysis and follow-up engagements related to the survey.

Amendment request as of August 20, 2018:
To extend the project end date to June 30, 2020 and adjust completion dates for Activity 1. This request is being made given an almost 12 month delay in being able to staff the project to full capacity. We have now brought staff onto this project and expect to make steady progress on Activity 1. There is no change to the outcomes or activities, rather a shift in timeline given a shortage in staff capacity during 2017-2018.

Amendment approved by LCCMR by August 8, 2018.

Amendment request as of February 28, 2019:
Our records show that we have $13,400 remaining from general supplies, focus groups, and travel expenses combined, which was originally budgeted to our statewide survey effort. Since we were able to co-produce and co-administer the Minnesota Water Values survey and focus groups with CWC funds, those remaining funds are not needed. Instead, we would like to re-budget the full amount ($13,400) toward personnel (wages and benefits) to support staff in Activity 3. We will need staff time to analyze and report on the data as well as to plan and conduct focus groups. Below are the budget changes made stating the sources and budget transferred to personnel.

- $8,000 from “Supplies” was moved to “Personnel”.
- $4,000 from “Other” (Focus groups) was moved to “Personnel”.
- $1,400 from “Travel expenses in Minnesota” was moved to “Personnel”.

Amendment Approved by LCCMR April 17, 2019.

Project status as of February 28, 2019:
Our initial analysis of the spatial data associated with sourcewater areas was completed and presented to MDH for their feedback. Our meeting with MDH yielded several new lines of inquiry, which we will be incorporating into our analysis. For example, we will identify what authorities have jurisdiction over source water areas, expand our database with information on co-benefits such as solar and pollinators and estimate the cost of protection and the human health costs of failing to protect source drinking water. We will incorporate this feedback and continue to refine our assessment of threats to sourcewater and co-benefits of protection.

We have begun analyzing data from the 1,498 responses to the statewide survey on resident water values, activities, and investment priorities. We have created a first round of data summary tables and presented them to MDH staff. The threats and vulnerabilities identified in Activity 1 will be used to target sourcewater areas and communities “at risk” in which to carry out focus groups to further our research on community capacity to protect water sources. We have presented preliminary survey findings to the Clean Water Council.

Project Status as of August 1, 2019:

Our analysis of the public benefits of protecting source water is progressing on several fronts simultaneously. A recently hired senior scientist is enabling us to rapidly generate estimates of the probability of land use change throughout the state. Predicting changes of land that will influence the surrounding drinking water supply is essential for preventing threats before they occur and to ensure resources are prioritized on the areas with the most urgent threats.

We also made significant progress in linking consumption of drinking water with elevated nitrate levels to impacts on human health. Our model now links well-level nitrate data to municipality level changes in the incidence of three types of cancer. We can then estimate human health costs using the standard value of a statistical life approach, and compare that to the cost of interventions. We also made progress assessing public benefits beyond human health. In particular, we demonstrated that data and methods we developed to assess the environmental benefits of any parcel in MN can be used to identify parcels with known co-benefits of drinking water protection and pheasant habitat. Now that we have demonstrated we can identify parcels with known co-benefits, we are sharing our data and methods with Pheasants Forever so they can identify promising parcels they are not aware of yet.

Our analysis on the MN value of water survey continued, including the completion of a master’s thesis titled “Communicating risk and increasing civic engagement in water protection in Minnesota” (included as an attachment to this update). We are working to combine insights from the survey with demographic data on MN communities and biophysical data on the threats to their drinking water. These data sets will inform the selection of vulnerable communities for a follow up focus group.

Project Status as of February 19, 2020:

As we enter the final 6 months of this project, we are turning from data collection and analysis to synthesis and communication. Under activity 1 we have created a new statewide risk of conversion metric. While we will only be assessing risk within sourcewater protection areas, this new dataset has applications to any conservation activity in the state. We are continuing to leverage graduate student effort to add more samples to the training dataset, and plan to publish and make available the resulting data products.

Due to shared objectives on a similar project for the Lessard-Sams Outdoor Heritage Council, we were able to leverage a collaboration with the Natural Resources Research Institute to create new datasets on habitat quality for a variety of bird and mammal species and include these in our analysis for sourcewater protection analysis. Similarly, we were able to include sourcewater protection in the analysis of their programs, furthering the consideration of sourcewater protection co-benefits to programs beyond the scope of this project.

We also made progress in quantifying the cost of protection. We recently obtained new and detailed data on estimated market values of hundreds of thousands of parcels in the state. While the data doesn’t provide complete statewide coverages, it is a large improvement over the township-level averages we planned to use. Land value data is critical for assessing the tradeoffs between the environmental and health benefits of sourcewater protection, and the lost productivity of protected land.

While our focus was predominantly on activities 1 and 2, we continued to collect data while presenting our work at various venues throughout the state. Using a simple instrument called ‘Q-sort’ we are collecting data on how groups value a suite of benefits related to water. The results often differ from traditional economic assessments and provide a valuable point of comparison when we integrate the costs and benefits of sourcewater protection.

Project extended to June 30, 2021 by LCCMR 6/18/20 as a result of M.L. 2020, First Special Session, Chp. 4, Sec. 2, legislative extension criteria being met.

Project Status as of August 1, 2020:
As is the case with nearly everything, the covid-19 pandemic caused some disruption to work on this project. Fortunately, the major components of the project were able to be done remotely. It is only the focus group activity which will not proceed as originally planned. After further review of a statewide value of water survey and additional 'Q-sort' exercises completed before the pandemic, we plan to use these instruments to address our original questions on how sub-groups value and consider risks to water. Our typical dissemination activities through presentations to practitioners and stakeholders were initially disrupted, but quickly transitioned to similar activities in an online format.

Work continued on the drinking water supply management area risk and environmental co-benefit model development. We completed 21 environmental benefit maps that will be used to assess the potential for co-benefits in each sourcewater protection area. We also completed refinements to techniques for linking sourcewater protection areas to all municipalities served, including both the primary public water supply and consecutive connections to typically smaller municipalities that purchase that water.

Finally, we have begun drafting a manuscript that will synthesize all of the components of this, and other, research. We have added recent developments in methodology from valuing health costs associated with elevated drinking water nitrate to our modeling framework and will include the results for Minnesota in the upcoming manuscript. As the funds from this project are now almost entirely spent, we will not be allocating effort to it directly any more. However, we are delaying closing out the project because a manuscript synthesizing the findings of this work is continuing under the support of other projects. We will continue to update the work plan and overall project outcomes with the data and figures developed for the manuscript.

Project Status as of February 12, 2021:
In this period our work was focused on two main areas. First, we built the framework for attributing cases of disease to drinking water nitrate contamination. This entailed implementing methods recently developed and applied in Wisconsin (Mathewson 2020), and collecting data on incidences of disease in Minnesota, and the association of those diseases with drinking water nitrate contamination. We have not yet linked these cases to values of statistical life methodologies, but anticipate completing that this month. The second major area is the drafting of a manuscript that synthesizes the results from our analysis of health impacts from drinking water nitrate from an equity standpoint, informed by our value of water survey. We have submitted an abstract for this paper for an upcoming conference.

While we are focused on a peer-reviewed publication in the short term, we are cognizant that scientific publications are not always the most useful format for the public, or for the specific questions of state agencies. Our dissemination plan includes datasets and communications that are tailored to state agencies and the public, respectively.

Overall Project Outcomes and Results:

The goal of the project was to collect and synthesize economic, social, and environmental data relevant to source water protection in Minnesota. We created new spatially-explicit datasets representing multiple socio-economic benefits of source water protection for all drinking water supply management areas in Minnesota. Project outcomes include:

1) Mapping land use change and land protection costs for all 821 drinking water management areas.

- Estimated trends in land use change in each DWSMA in order to identify potential threats to source water from increasing agricultural expansion or development.

- Obtained new spatial data based on estimated market values of hundreds of thousands of parcels in the state in order to quantify the opportunity costs of source water protection in each DWSMA.

2) Valuation of the multiple public benefits of land protection for clean water.

- Applied best-available estimates for drinking water treatment to calculate potential costs of contamination in each DWSMA as a function of population served.
- Implemented a methodology for estimating the potential health damages and associated monetary costs of drinking water contamination.
- Generated 19 spatially-explicit environmental benefit maps that can be used to assess the potential for co-benefits of protection or restoration in each DWSMA.

3) Assessing the equity implications of source water protection and community capacity to protect land and improve water quality.

- Developed a technique for linking source water protection areas to municipalities served, allowing us to relate census data and demographic characteristics to each DWSMA.
- Administered and analyzed data from a statewide survey of water values in order to identify perceived threats to water quality and preferences for different water-quality related values and uses.
- Completed a series of participatory water valuation exercises using a Q-sort methodology to understand stakeholder preferences for water-related expenditures and tradeoffs among water quality objectives.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Mapping land use change and risks to clean water

Description: In partnership with the Minnesota Department of Health (MDH), we will conduct a comprehensive risk assessment for all 584 drinking water supply management areas in Minnesota. We will improve and expand upon MDH's current approach to risk assessment by including new data on land use change and other potential threats to water quality or quantity such as population growth and expected changes in precipitation patterns. The work on land use change will build upon existing tools and approaches developed by the Natural Capital Project. We will adapt these tools to Minnesota and run alternative scenarios of the extent and intensity of future land use change in each sourcewater area. We will also assess how changing assumptions about aquifer vulnerability class and travel time of pollutants currently used by MDH affect the acreage of lands needing protection and potential costs of treatment or protection. Finally, we will account for uncertainty and develop management-relevant storylines that reflect a range of plausible futures for Minnesota sourcewater areas and communities. These activities will expand upon and enhance tools used by MDH to map sourcewater areas and identify risks to water quality.

Summary Budget Information for Activity 1: **ENRTF Budget: $ 104,000**
Amount Spent: $ 104,000
Balance: $ 0

Outcome	Completion Date
1. New risk maps and data on future land use trends and threats in each of the 584-sourcewater areas.	January 2019
2. Evaluation of current MDH approaches to assessing sourcewater vulnerability and recommendations for improved management and delineation of management areas. For example, we will evaluate how MDH estimates the travel time for pollutants and produce updated maps of sourcewater protection areas based on different assumptions of travel time and geologic vulnerability.	June 2019

Activity 1. Status as of August 3, 2018:

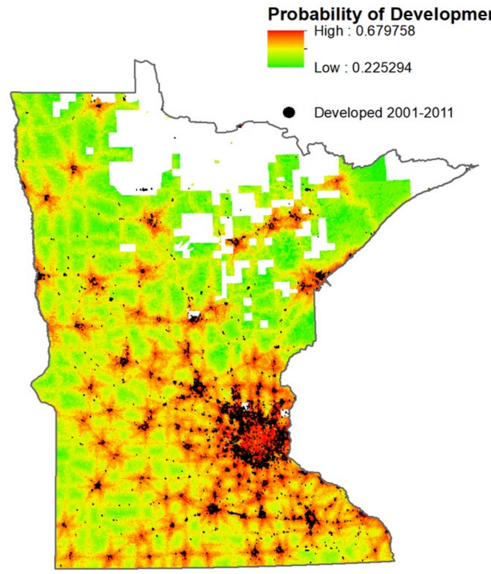
No budget has yet been allocated to this activity. Research staff working on other projects have now been assigned to this task and their efforts will be reflected in the next status update.

Activity 1. Status as of February 28, 2019:
The research under Activity 1. consists of an iterative process of compiling and analyzing data on the potential threats to source water areas, and soliciting feedback from MDH on how threats are considered in their vulnerability assessments. We have completed the first iteration of this process by constructing a database that contains changes in land cover data over the last 10 years for all source water areas. The database also includes information on the proportion of publicly held versus private land, environmental benefit scores created by previous ENRTF-funded research, and threat metrics derived from trends in each agricultural area, undeveloped land, and geologic vulnerability. In addition, we have also begun to explore the possibility for including demographic data from census data; however, further manual processing of the data is necessary to achieve a one-to-one match between census data and sourcewater areas.
We presented this database to senior MDH staff to solicit their feedback on the approach we took to analyze the data we compiled and to learn more about their existing data and approaches. Feedback from the MDH included the suggestion to expand our analysis to include data on the different jurisdictional authorities represented in sourcewater areas and add a proxy for land value. In addition, we learned that income is the only demographic data being explored by MDH and that it would be helpful to their assessments to incorporate a larger set of demographic data. Working closely with MDH, out team will work to integrate demographic data into our dataset in a way that aids with the assessment of sourcewater areas. Finally, we learned that the current assumptions around travel time reflect the difficulties of protection at large scales. Further analysis will explore the trade-offs associated with manageable planning efforts and capture threats beyond the current travel time assumptions.
We will continue to refine our analysis and metrics of threats while communicating with the MDH and expanding our understand of how assessment and prioritization of sourcewater areas happens at regional levels where MDH works.

Activity 1 Status as of August 1, 2019:
Recently hired senior scientist Christina Locke developed a prototype statewide risk of development metric. The metric assesses which drinking water management supply areas are more likely to experience stressors to water quality from future land use changes. Our work improves upon existing threat prioritization used by MDH and other state agencies by considering likely future changes rather than a snapshot of what the risks and vulnerabilities exist currently. State agencies and local governments can then use more cost effective protective actions, rather than reacting to threats after groundwater quality is already degraded.

The approach we developed uses a logistic regression model to associate variables such as slope, distance to water bodies, distance to roads, soil type, land value, distance to urban areas, and others with observed recent land use change. We then use this model to identify other areas of the state with characteristics associated recent changes. A model for urban expansion is complete and an agriculture expansion model is under development. Agriculture expansion is especially difficult to model because satellite based data often struggle to differentiate between natural grass, pasture, and fallow cropland, thus providing misleading training data. We are addressing this by manually reviewing historical aerial imagery to create better training data.

Prototype probability of development metric:

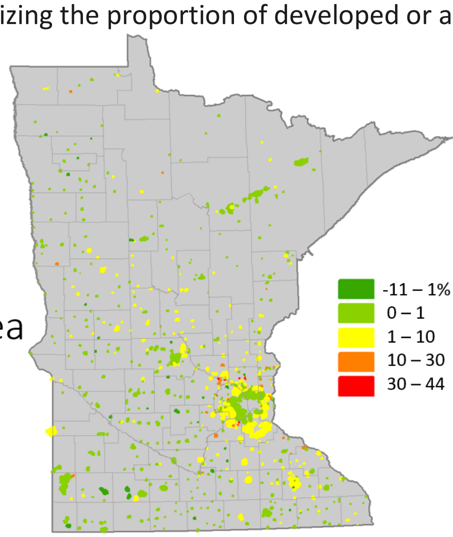


Activity 1 Status as of February 19, 2020:

A first round of manual review of historical aerial imagery and a statewide model for land conversion to cropland is now complete. Along with the previously completed model for urban expansion, we can now prioritize drinking water management supply areas (DWSMAs) based on risk of land conversion to agricultural and urban uses.

We also provided a summary to MDH on land-use change trends over the period of 2001 – 2016. MDH staff were mostly interested in how much land has changed between unprotected (urban development and agriculture) and protected (vegetated – not hay or grass) status over time. We found there to be 9,000 fewer acres of protected land and 30,000 more acres of unprotected land in DWSMAs over this time period, representing 0.7% and 2.3% of the total area in DWSMAs, respectively. The DWSMAs where most land changed to "unprotected" status were also some of the largest DWSMAs, like Hastings, Rochester Central, and Shakopee. See below for figure summarizing the proportion of developed or agricultural land uses.

Change in area of unprotected land 2001 – 2016 as % of DWSMA area



Activity 1 Status as of August 1, 2020:

In this period we updated the social cost of nitrogen methods with those that have been developed in the last two years. In addition to existing methods for bladder, colorectal and kidney cancers, new advancements include methodologies for estimating increases in very preterm and very low weight births, neural tube defects, miscarriages, and two types of cancer associated with elevated nitrate in drinking water.

The new methods required not just population served by a given water supply, but also demographic data used to identify sub-populations at elevated risk. In the past we have established a one to one link between major municipality census data and water suppliers. However, distribution is often more complex, with small communities buying water from larger suppliers through consecutive connections. Using data on consecutive connections from MDH, we identified the population and demographic characteristics of communities that buy their water from a larger municipal supply.

These methodological advancements enable us to integrate data on risks from land use change with a wide range of research on the health impacts of elevated drinking water nitrate.

Activity 1 Status as of February 12, 2021:
Now that we have linked demographic information to municipal public water supplies in the state, the next step is to calculate the nitrate-attributable cases of diseases associated with elevated nitrate levels. We continued to build out the methods developed for Wisconsin in Mathewson (2020)[1] and apply them to Minnesota data. Specifically, we have been collecting the relative risk ratios from studies that examine links between drinking water nitrate exposure and health impacts. We also compiled disease incidence rates at the county level from the Minnesota Department of Health. These baseline rates are important for being able to distinguish how many cases of disease are in the population regardless of nitrate exposure, and the number of additional cases.

For identifying risks to human health at the DWSMA level, our focus is on the five cancers and three types of birth defects mentioned in the last update because they have strong links to drinking water nitrate and public health data is available for them. Our literature review also includes approximately 50 other diseases which can be included if there is sufficient data on baseline incidence in Minnesota and sufficient sample sizes in the literature.

Final Report Summary:
The outcomes of Activity 1 are documented in section 1 of our synthesis report. We also note that previous status updates under this activity have described estimating health costs associated with exposure to drinking water nitrate. We carried out that research, but believe it is most appropriate to discuss it in the context of other valuation analyses in section 2 of our synthesis report, and Activity 2 of this work plan. The outcomes of Activity 1 are summarized here as follows:

1.) Summarize past land use change trends and project risk of development in all DWSMAs

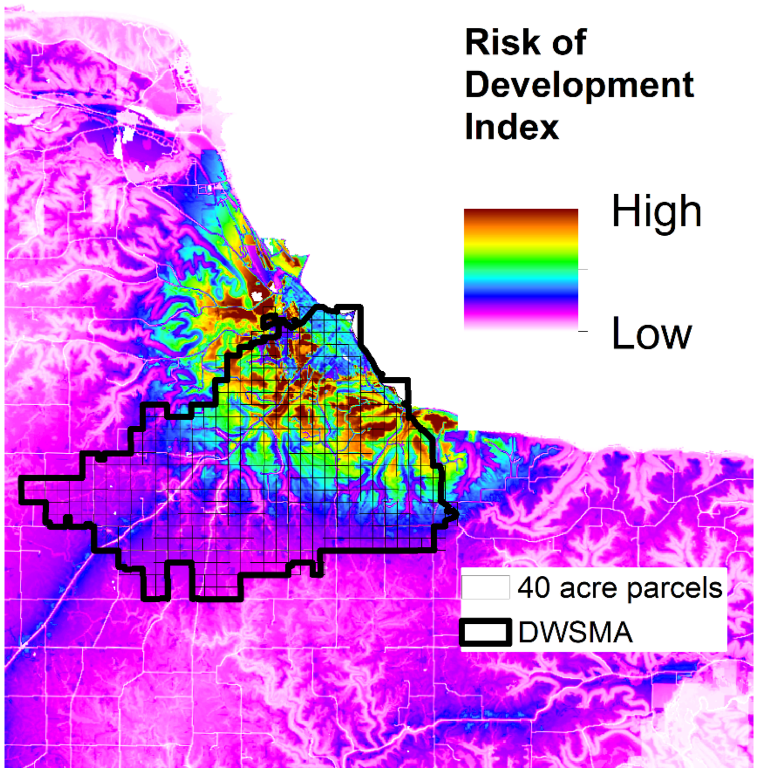
Outcomes: We applied two land use change analyses to capture threats from both observed and potential land use change. We used best-available data from the National Land Cover Dataset (NLCD) to quantify land use change trends in every DWSMA from 2001-2019 (Figures 2 and 3, Appendix B). We created Python scripts capable of analyzing DWSMAs independently to allow for assessment of land use changes in overlapping DWSMA over time, an approach not possible using traditional tools like ArcGIS. We created a spreadsheet with filter, aggregation, and visualization functions to allow users to calculate statistics and visualize land use change trends for individual, or collections of DWSMAs without specialized software.

We also created a risk of development layer (described in the August 2019 update above) to capture the threat of future changes. Because the layer is 30m resolution and DWSMAs are typically very large, we opted not to

[1] Mathewson, P.D., Evans, S., Byrnes, T., Joos, A., Naidenko, O. V., 2020. Health and economic impact of nitrate pollution in drinking water: a Wisconsin case study. Environ. Monit. Assess. 192. https://doi.org/10.1007/s10661-020-08652-0

average the results at the DWSMA level because it can hide variability between high and low risk areas. Instead, we only provide average risk of development scores at the parcel level in Appendix C. We also created a summary of risk of development across all DWSMAs using a simplified version of our risk layer and visualized our results in figures 9 and 10 or our synthesis report.

An example of our risk of development map is included below. The thick black line is a DWSMA. Averaging the risk index across the entire DWSMA would include both very high and very low values, thus producing a misleading average. The small black squares are 40-acre public land survey parcels. We aggregated most of our data to these units for several reasons. They are small enough that averaging across them is unlikely to produce misleading results, tabular data is easier for practitioners to work with than raster data, and the parcels tend to follow roads, natural features, and existing ownership boundaries. These attributes make them a useful level of aggregation for analyzing our data while still being relevant and familiar for land protection activities.



The risk index is calculated statewide, but because of missing data in the national soil database (gSSURGO) there are limited areas of no data in north east MN. Approximately 12 DWSMAs out of 821 fall in the no data area, but we believe the predictive value of the variables in the gSSURGO data is worth the tradeoff of not being able to be applied in these areas.

Executive summary: On average, land use in source water protection areas remained relatively stable from 2001 to 2019, with built area increasing by 12% while natural vegetation and agricultural land use areas declined by 5% and 8%, respectively. Although the area covered by agriculture declined, agriculture is still the dominant land cover, covering 49% of areas with high or very high vulnerability to contamination. Most DWSMAs had little change in land cover over the last two decades, but the overall trend was an increase in developed land covers. Some smaller DWSMAs, such as Willow River, Minnetrista Central, and Woodland MHP, had a more than 20 percentage point in built area in 18 years. DWSMAs experiencing increases of built and/or agricultural land covers face more potential threats to water quality within their water supply.

2.) Estimate the opportunity cost of protection activities by mapping land value in all DWSMAs

Outcomes: We estimated the opportunity cost of protecting all of the non-built land in DWSMAs. Opportunity costs reflect lost revenue from agriculture or development as a result of land acquisition or the adoption of best management practices that reduce yields or take lands out of production. We estimated the value of unprotected land using a novel dataset (Nolte 2020) that improves on previous underestimates of opportunity costs of conservation by using machine learning techniques to harmonize tax assessor and other datasets nationwide. We summarized the total value of the land in all of the MDH DWSMA vulnerability classes in Table 2 of our synthesis report. We also visualized this data by showing the proportion of land that could be protected if acquired in order from least to most expensive in Figures 6 and 7.

Executive summary: We used a novel dataset of land value to calculate the opportunity cost of protecting unbuilt land in source water areas. Our analysis demonstrates the high opportunity cost of acquiring land for protecting source water. The total area of unprotected and unbuilt land in source water protection areas is over 634,000 acres, with a value of $8.8 billion. Targeting a subset of the lowest value, highest vulnerability land reduces the cost substantially, but the opportunity cost remains high. Protecting 15% of this subset would cost over $100 million, and would produce inequitable protection that excludes high land value DWSMAs. Our addition of land value data at the DWSMA and parcel levels provides insights on the opportunity costs of protection that will help practitioners prioritize projects with a high return on investment.

3. Evaluation of current MDH approaches to assessing sourcewater vulnerability

Our original plan was to examine sourcewater protection costs and co-benefits in a buffer of DWSMAs. We discussed this activity with the MDH because they are responsible for the groundwater flow modeling that is required to delineate the 10-year path of travel the defines a DWSMA. Their feedback was twofold. First, a buffer does not represent groundwater flow well in many locations. Each DWSMA is delineated individually by an expert groundwater modeler because of the complexity of the flows. Using a buffer approach would not add value to MDH because it is not in line with their established practices. Second, they indicated that a 10-year path of travel is their preferred analysis timeframe because of the balance between immediate impact and long-term planning. Going beyond 10 years adds uncertainty and is a larger scale than can be effectively managed by public water supply planning efforts. Our analysis indicated that a 10-year path of travel based DWSMA already contains land value exceeding 8 billion dollars and high environmental benefits scores across all our metrics. We determined expanding this would run contrary to the guidance of MDH and would detract from the analysis of costs and benefits of protection within MDH's defined DWSMAs.

ACTIVITY 2: Valuation of the multiple public benefits of clean water
Description: By not fully accounting for the value of clean water and land protection, we risk undervaluing and mismanaging our natural capital. We will build on ten years of experience at the Natural Capital Project to advance our understanding of the multiple public benefits or "ecosystem services" associated with land protection or restoration with a focus on the value of clean water.

The proposed work will consist of three phases of analysis. First, we will assemble a dataset on avoided treatment costs for nitrate and other contaminants based on data provided by MDH and a comprehensive literature review from national surveys and datasets. We will combine treatment cost data with information on the potential economic impacts of exposure to nitrate and other contaminants. Second, we will estimate the economic value of agricultural production in each sourcewater area and other land uses in order to estimate the "opportunity costs" of land protection. Opportunity costs reflect lost revenue from agriculture or development as a result of land acquisition or the adoption of best management practices that reduce yields or take lands out of production. Third, we will quantify other valuable public benefits related to recreation and tourism, cultural identity, wildlife and aquatic habitat, and reduced soil loss and erosion. We will not engage in new data collection to assess these services, but rather rely on literature estimates and previous approaches developed by the Natural Capital Project and elsewhere to estimate these values and how they compare to the values of water quality benefits. These activities will help to illuminate the true value of clean water and identify how this information can inform decisions ranging from payment programs or incentive schemes to evaluating the return on investment in land protection.

Summary Budget Information for Activity 2:

ENRTF Budget:	**$ 107,705**
Amount Spent:	**$ 107,697**
Balance:	**$ 8**

Outcome	Completion Date
1. Collection, visualization, and dissemination of ecosystem services valuation data for each sourcewater area (agricultural production, agricultural management practices, treatment costs, health, property values, recreation and tourism, cultural identity, habitat)	January 2018
2. Data and summary reports on the costs and public benefits associated with clean water and land protection and recommendations for mainstreaming these values in policy and agency decision making	December 2018

Activity 2 Status as of August 3, 2018:
As described in this activity, we are working on the collection and visualization of ecosystem services valuation data for each drinking water supply management area. We worked with MDH to obtain boundaries for each sourcewater area and have begun analyses to link each area to population and demographic data. We have assembled data on agricultural production, treatment costs, and the potential health impacts of exposure to nitrate. We are working with MDH to identify other contaminants of concern and track down data to quantify risks and potential impacts of exposure in sourcewater.

The first product of this work is a storymap based on spatial data collection and interviews with public health officials and rural water suppliers. For a copy of the blog and associated story map, see the link here: http://environment.umn.edu/discovery/natural-capital-project/integrative-approach-protecting-minnesotas-drinking-water/

We have met with MDH several times to better understand their needs for data and economic assessments of sourcewater costs and public benefits associated with clean water and land protection and recommendations for mainstreaming these values in policy and agency decision making. These insights are informing the literature and data collection tasks that are ongoing as part of this activity.

Activity 2 Status as of February 28, 2019:
Our meeting with MDH also revealed a strong interest in better accounting for the co-benefits of source water protection. Our preliminary work on this consisted of compiling existing data sources and creating an all new a dataset that is the first to estimate the number of people served by groundwater and surface water per public water supply (PWS) and on a statewide basis. Creating this dataset involved collecting information from 513 individual sourcewater assessments and contacting major water suppliers in the state that provide a blend of ground and surface water in order to determine the right assumptions about the proportions of people dependent on ground water versus surface water.

We have also identified lakes and trout streams that are hot spots for visitation using social media data, compiled MPCA's SPARROW modeling of nutrient export, and incorporated previous ENRTF-funded work on environmental benefits of conservation easements. Going forward we will analyze this information on a sourcewater area basis, so we can identify the unique co-benefits found in each sourcewater area. The data we are compiling will also allow us to identify the hotspots for environmental benefits within sourcewater areas so that planners can maximize the public benefits of their protection activities.

Activity 2 Status as of August 1, 2019:
We made extensive progress in linking the presence of nitrate in drinking water to changes in life expectancy based on previous studies. The code we are developing starts by aggregating records for individual wells up to the PWS and DWSMA level. This novel step makes it possible to link wells with census data to determine the demographics and of the communities with elevated nitrate levels. Our code then calculates the number people served by DWSMAs where the nitrate level is above previously studied thresholds, but typically below the Federal standard, giving use the population that would be affected by interventions which reduce nitrate loading in the groundwater.

Next, we use published factors that associate consumption of water with elevated nitrate levels with three types of cancer. Exposure increases the likelihood of an individual contracting these diseases by relatively small amount, but over the entire population, mortality increases with exposure. We use the value of a statistical life to value these marginal changes. We are working to compare the cost to human health to the cost and efficacy of various interventions.

In addition to refining estimates of human health impacts, we are also quantifying the other environmental benefits of interventions used to protect drinking water. A successful example of this type is a partnership between Pheasants Forever and the state to protect the city's water supply and restore pheasant habitat. We met with MDH and Pheasants Forever to discuss what made that partnership work, and how we can identify similar opportunities. In preparation of the meeting, we adapted a previous ENRTF sponsored research project, the Parcel Environmental Benefit Assessment Tool (pebat.umn.edu), to allow us to analyze all of the privately held undeveloped parcels in the state for both drinking water protection and pheasant habitat benefits. Using a series of queries, we were able to quickly identify the parcels that were included in the Worthington Wells project, as well as several dozen others elsewhere in the state that offered similar benefits. We will provide these and other data products to Pheasants Forever so they can better target multiple benefits in their acquisitions.

Activity 2 Status as of February 19, 2020:
We have created several new environmental benefit metrics, including bird species of greatest conservation need, upland game birds, and waterfowl game. We now have 14 metrics that can be used to assess parcels within sourcewater protection areas and will likely add several more before the end of the project. In particular we want to expand our metrics to make them applicable for restoration as well as protection.

In addition to environmental benefits, we are also considering cost. We have previously described methods for assessing human health cost. We intend to contrast those values with both environmental benefits and the cost of protecting the land. To estimate the value of the land we have acquired a state tax parcel database with nearly statewide coverage for parcels, and coverage for approximately half of the state for land values. We are in the process of estimating values for missing areas so that the cost of protection in each sourcewater protection areas can be included in our report.

Activity 2 Status as of August 1, 2020:
We further expanded and refined the environmental benefit metrics used for assessing co-benefits of sourcewater protection. There are now 21 metrics which, in general, are applicable for both restoration and protection. This is the final set of variables for assessing co-benefits of sourcewater protection:

Metric	Category	Description
Forest Bird Species in Greatest Conservation Need (SGCN) Habitat	Biodiversity and Wildlife	Breeding habitat quality for Species in Greatest Conservation Need (SGCN), derived from observations and modeling by the Minnesota Breeding Bird Atlas. (https://mnbirdatlas.org/)

Grassland and Prairie Bird SGCN Habitat	Biodiversity and Wildlife	Breeding habitat quality for grassland SGCN, derived from observations and modeling by the Minnesota Breeding Bird Atlas.
Wetland Bird SGCN Habitat	Biodiversity and Wildlife	Breeding habitat quality for wetland SGCN, derived from observations and modeling by the Minnesota Breeding Bird Atlas.
Bird Species Richness	Biodiversity and Wildlife	Measure of the number of different bird species observed within a township.
Mammal SGCN Habitat	Biodiversity and Wildlife	Climate envelop modeling of SGCN mammals in the state.
Lakes of Biological Significance	Biodiversity and Wildlife	Department of Natural Resources dataset combining data from biological sampling efforts and lakes throughout the state.
Pollinator Habitat	Biodiversity and Wildlife	InVEST[2] Pollination model output of habitat quality for pollinator species.
Upland Game Bird Habitat	Hunting and Fishing	Breeding habitat quality for American Woodcock, Wild Turkey, and Ruffed Grouse from observations and modeling by MNBBA.
Pheasant Habitat	Hunting and Fishing	Pheasant habitat suitability based on local land cover.
Waterfowl Habitat	Hunting and Fishing	Breeding habitat quality for all waterfowl species from observations and modeling by MNBBA.
Mammal Game Species and Furbearers	Hunting and Fishing	Climate envelop modeling of mammal game species and furbearers.
Deer Abundance	Hunting and Fishing	Climate envelop modeling supplemented by deer hunting permit data.
Trout Streams	Hunting and Fishing	Catchments and 66-foot buffers of legally designated trout streams.
Birdwatching	Other Benefits	Bird watching activity concentration derived from eBird reports.
Lake Recreation	Other Benefits	Lake catchments weighted by phosphorus sensitivity and recreation activity.
Wellhead Protection	Other Benefits	Land within a Drinking Water Supply Management Area, weighted by groundwater sensitivity.
Trail Proximity	Other Benefits	Within a 500-foot buffer of state and regional trails.
Wild Rice Sites	Other Benefits	Within the catchment of a current wild rice site.
Nearby Population	Access and Risk	Proportion of the state's population within 50 miles.
Risk of Development	Access and Risk	Risk of land use change to developed (built) uses.
Risk of Ag Conversion	Access and Risk	Risk of land use change to agriculture.

We have also refined the cost of land acquisition layer by merging data from multiple sources, including county tax records and the Minnesota Land Economics database.

Activity 2 Status as of February 12, 2021:
We created all of the environmental benefit metrics we intend to draw on in our last reporting period, so there was not further development under this activity this period. Depending on feedback from MDH stakeholders, we may refine these (e.g., by aggregating some related metrics) before packaging the data for MDH. We are also aware of recent research improving land value estimation methodologies[3] and intend to review these data to determine if they would offer improved estimates over the data we have already collected.

Final Report Summary:
The outcomes of Activity 2 are documented in section 2 of our synthesis report. They are summarized here as follows:

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[2] https://naturalcapitalproject.stanford.edu/software/invest

[3] High-resolution land value maps reveal underestimation of conservation costs in the United States Christoph Nolte. Proceedings of the National Academy of Sciences Nov 2020, 117 (47) 29577-29583; DOI: 10.1073/pnas.2012865117

1.) Estimated treatment costs avoided with sourcewater protection.

Outcomes: We assembled a dataset on avoided treatment costs for nitrate based on data provided by MDH and a literature review from national surveys and datasets to estimate avoided treatment costs through sourcewater. Treatment costs for elevated nitrate have been previously estimated in Jensen et al. (2012). We reviewed the literature to confirm these estimates were consistent with recent observed costs in Minnesota. We then applied it to MDH data on PWSs to create cost estimates specific to the population served by each PWS. These results are discussed in section 2.1 and Table 3 of our synthesis report and the data are available in Appendix A.

Executive summary: We assembled data on the public water suppliers in the state and used estimates from the literature on the costs that similarly sized suppliers have paid to install and operate treatment for elevated nitrate. We estimated that the capital, operation and maintenance costs of installing reverse osmosis filtration for the 8% of PWSs with elevated (> 3 mg/L) nitrate concentrations ranged from 9.8 million to 45.7 million annually. If distributed uniformly between households, these costs would increase annual water rates by $161 to $751. However, rate increases would likely fall disproportionately on systems serving small populations. Our analysis estimated average annual household costs for systems serving fewer than 500 people of $803, while systems serving greater than 500 people had an average annual household cost of $269.

2.) Estimated value of health damages avoided based on potential health impacts of exposure to elevated drinking water nitrate.

Outcomes: Epidemiological research suggests a link between drinking water nitrate and some adverse health outcomes at levels below the U.S. federal maximum of 10mg/L. While uncertainty about relative risk remains, accounting for cases of cancer, neural tube birth defects, and preterm births may be plausibly attributed to elevated nitrate levels with implications for social costs of sourcewater contamination. We developed spatially explicit health-cost damage functions for Minnesota's public water supplies mindful of statistical and scientific uncertainty to help quantify potential health costs of N pollution. We summarized these values for all PWSs in the state in section 2.2 and Table 4 of our synthesis report.

Executive summary: We compiled demographic data on the population served by public water supplies, drinking water nitrate concentrations, and the risk for disease associated with exposure to nitrates. We used these datasets to implement a method for estimating disease incidence and associated costs attributable to exposure to elevated drinking water nitrate. Of the five types of cancer in our analysis, we estimated that 71 cases, roughly 1% of cases of these cancer types annually, can plausibly be attributed to elevated drinking water nitrate. Using recently developed methods, we also estimated 50 cases of adverse birth outcomes. We applied three valuation techniques that capture medical costs and the cost of premature mortality. The differing approaches to valuation produced annual cost estimates ranging from $27.2 million to $256.6 million.

3.) Quantified 19 other co-benefits associated with sourcewater protection.

Outcomes: These benefits (listed in Aug 2021 status update) were summarized first at the DWSMA level and then at the parcel level allowing practitioners to use the finest possible resolution to visualize co-benefits, and to allow for a multiple benefits approach to prioritizing land protection or restoration activities. These results are discussed in sections 2.3 and 2.4 of our synthesis report and the data are available in Appendix C.

Executive summary: We estimated the co-benefits of protecting DWSMAs through an analysis of 19 environmental co-benefits. We found that benefits such as pheasant habitat, bird watching, and lake recreation are overrepresented in unprotected, unbuilt source water protection areas relative to unbuilt, unprotected areas in the rest of the state. We applied spatial models of land use change to estimate potential threats to DWSMAs. Due to the proximity of DWSMAs to population centers, DWSMAs face greater than average development risks.

ACTIVITY 3: Assessment of equity and community capacity

Description: The costs of water pollution disproportionately affect rural, low income, and traditionally underrepresented populations. We will combine census data on demographics, income, and immigrant populations with the data collected in Activities 1 & 2 to quantify and report the equity implications of alternative protection strategies for clean water. This activity will allow MDH and other end users of the results to understand how activities in sourcewater protection may affect different communities and subpopulations around the state.

We also will conduct a series of focus groups with community actors and surveys across a geographically and demographically diverse sample of households to examine how different subpopulations use and value water, perceive water risk, and engage in water and land protection. We will conduct up to two focus group sessions in three "at-risk" communities and a broader resident survey in the regions. Insight gained from the focus groups and surveys will be synthesized in a report identifying constraints to and opportunities for equitable sourcewater protection.

Focus groups will be conducted with community actors in rural, low income, and traditionally underrepresented populations to examine how varying subpopulations use and value water, perceive water risk and engage in water and land protection. We will identify opportunities and challenges to existing water protection programming with attention to issues of inclusion and equity. Comparative analysis will be conducted to examine convergent and divergent themes within and across study communities.

A resident survey will complement the focus groups to gain a broader understanding of water uses, values and risk perceptions. The survey instruments will be developed based on a review of relevant literature and previously tested instruments, as well as insights from project partners. Based on previous research, we hypothesize that sociodemographic characteristics (e.g., gender, age) will influence risk perception and ultimately civic engagement behaviors around sourcewater protection.

Summary Budget Information for Activity 3:	**ENRTF Budget:**	**$ 108,295**
	Amount Spent:	**$ 108,295**
	Balance:	**$ 0**

Outcome	**Completion Date**
1. Report of the equity implications of alternative water management strategies, including how different communities use and value clean water. The report will include maps and planning tools that can be used to inform future investments in sourcewater protection.	January 2019
2. Focus groups and surveys in communities identified as "at-risk" based on Activity 1 that reveal how different subgroups use and value water, perceive risk, and engage in protection. Results will be synthesized in a report identifying constraints to and opportunities for sourcewater protection based on community assessments.	June 2019

Activity 3 Status as of August 3, 2018:

We designed, piloted, and distributed a statewide resident survey to 6000 Minnesota households in order to gain a broader understanding of water uses, values and risk perceptions. The survey was designed to better understand how sociodemographic characteristics (e.g., gender, age) might influence risk perception and ultimately civic engagement behaviors around sourcewater protection. We have received over 1,300 responses to the survey and data analysis of survey results is in progress. A copy of the survey instrument is included with this project report.

We have not yet completed the focus groups that will serve as follow-ups to the survey, nor the report on equity implications of water management. The next phase of our work on Activity 3 will prioritize these activities.

Activity 3 Status as of February 28, 2019:
The results of preliminary analyses of survey responses were presented to MDH and the Clean Water Council including what values are most important to Minnesotans, most popular activities in lakes, rivers, and streams and the top water concerns across the state. The results also included showing how responses varied when demographic characteristics were considered (i.e. socio-economic status, age, and gender). Based on these results, we created an informative fact sheet "Minnesota Water Values: Resident Survey Report," which will be disseminated across key state agencies and the public. Moving forward, we will identify "at risk" communities using threat and vulnerability data identified in activity 1. We anticipate identifying those communities before the next status update. Following that, we will conduct a focus group exercise in each community.

Activity 3 Status as of August 1, 2019:
We have continued to analyze the results of our MN value of water survey (1480 total responses, 28%), with a focus on understanding how communities differ in the water issues they face, and the resources they have to address those issues. Dr. Davenport's graduate student, Amelia Kreiter, used this survey as a foundation for a thesis analyzing the factors that influence the level of civic engagement of residents. Findings indicate that personal experience with water and feeling like they have enough information are the strongest predictors for water protection efforts. These findings are useful for developing successful outreach and communication programs to target and expand civic engagement on water protection issues. The completed thesis is included as an attachment.

Future work will use statewide survey results, combined with physical and social drinking water vulnerability characteristics co-developed with MDH to identify at-risk communities for further focus group based research.

Activity 3 Status as of February 1, 2020:
At several venues throughout the state, we have conducted a 'Q-sort' exercise, where participants receive 18 cards representing different water quality goals (e.g. protecting drinking water, protecting lakes for fishing, maintaining irrigation), and are asked to prioritize the cards. Several cards can be in the middle of the priority spectrum, but only one can be top priority, and one must be lowest priority. Initial results show consistent with our previous research, protecting drinking water quality is the top priority. We have observed this trend whether we are talking to water quality advocates or the general public. We intend to integrate and contrast the cost and benefits identified in activities 1 and 2 with the values expressed and an analysis of equity under activity 3.

Activity 3 Status as of August 1, 2020:
We did not conduct any further focus groups of community engagement due to concerns about covid-19. We believe between previously completed Q-sort exercises, and a statewide survey on the value of water we have sufficient data on perceptions of water quality and risk to complement the biophysical and economic analyses in activities 1 and 2. The linkages between public water supplies, consecutive connections, communities, and ultimately demographic data completed in activity 1 ads an equity dimension to the data collected in our survey work. We began drafting a manuscript that explores how the methods used to quantify water values can lead to very different recommendations for investments, and subsequent inequity in distribution of benefits and harms. This manuscript will merge all of the components of this, and other projects, into a synthesis of water valuation in Minnesota.

Activity 3 Status as of February 12, 2021:

As mentioned in our previous update, we continued to draft a manuscript synthesizing the insights we have from both the modeling of drinking water protection costs and benefits and the results from the statewide value of water survey, with a particular focus on at-risk communities. We have also submitted an abstract for the paper to the social cost of water pollution workshop entitled “Exploring Equity-Weighted Health Costs in the Social Costs of Nitrogen”.

Final Report Summary:
The outcomes under Activity 3 are split into two areas; demographic data curation and survey work. Both areas are summarized below, and additional results and discussion of demographic data curation are available in section 3 of our synthesis report and associated appendices.

1.) Developed a methodology to join data on public water supplies to census demographic data for municipalities or counties.

Outcomes: Activity 3 called for the incorporation of social vulnerability factors in the biophysical and economic assessments performed in the other activities. We addressed this by creating a new mapping of DWSMA data to census demographic data. Prior to this work, there was little information beyond the number of people served by a public water supply. Naming irregularities and complex distribution mechanisms made it difficult to link a public water supply with the municipality it served and thus access the rich data associated with the census. We made manual corrections necessary to increase the number of successful joins, and joined county level data when that was not possible. We created a dataset (Appendix A) that provides public water supply level demographic data for the municipalities they serve, or the county they are in if they do not serve a municipality. It also includes historical average and maximum nitrate concentrations (Table 5). The combined dataset enables practitioners to assess where elevated drinking water nitrate and associated costs might fall on a small and/or vulnerable population that would be disproportionately burdened by increased drinking water costs. They are also useful for refining predictions of cases of disease correlated with elevated drinking water nitrate, or analyzing the distributional effects of sourcewater contamination.

Executive summary: Many DWSMAs supply small or low-income populations that would be disproportionately burdened by an increase in water treatment costs. We designed and implemented a workflow that allows for combining information on public water supplies with census demographic data for municipalities or counties. We found that most PWSs did not have elevated drinking water nitrate, but those that did tended to be in the lower quartile for median household income. These datasets enable practitioners to assess where elevated drinking water nitrate and associated costs might fall on a small and/or vulnerable population that would be disproportionately burdened by increased drinking water costs.

2.) Survey and stakeholder outreach around the value of clean water.

We completed a statewide survey of water values (see the included file ‘MN Water Values Survey FACT Sheet UMN 2019.pdf’). One of the insights from the survey was that clean drinking water was consistently ranked as the most important water value and the top priority for state funding for water resources. Results of the statewide survey have been shared broadly with agency staff and water resource managers. The work is currently being revised for publication and two additional follow-up instruments are targeting water values of underrepresented communities in the metro area (Davenport et al. in prep) and water values of ratepayers in the selected regions served by MetCouncil. We also conducted a series of workshops using a Q sort methodology to assess water values of water resource professionals and communities. Results of the Q sort are also in the process of submission to a peer-reviewed journal (Keeler et al. in prep). The surveys and stakeholder workshops have revealed new insights into how subpopulations use and value water, perceive water risk, and engage in water and land protection.

V. DISSEMINATION:
Description: All data, analyses, and methods will be documented by the project team and shared with LCCMR and project partners at MDH. Insights from the work will be communicated to the public and the research community via blog posts on the IonE Eye on Earth blog, through the Natural Capital Project website, and through peer-reviewed publications. Plans are also underway to launch a web-based water valuation to be hosted on the Institute on the Environment website targeting an audience of users in Minnesota and globally interested in quantifying the value of clean water and seeking data resources, methodologies, and economic tools relevant to their question and projects of interest.

Status as of August 3, 2018: To bring awareness to the project, we created and distributed an ArcGIS storymap that describes the project objectives and preliminary insights about the value of clean water, especially in rural communities. The storymap was highlighted in a blog posted on the IonE site and widely distributed throughout agency and advocacy channels: View the blog and associated story map here:
http://environment.umn.edu/discovery/natural-capital-project/integrative-approach-protecting-minnesotas-drinking-water/

Status as of February 28, 2019: We presented our preliminary analyses to MDH and the Clean Water Council and received feedback on the type of analyses and data that would be most useful in vulnerability assessments of sourcewater areas. Based on that input, we have defined the next research steps including expanding our dataset with jurisdictional authorities represented in sourcewater areas, zooming in the co-benefits of sourcewater area protection, and analyzing the public health costs of nitrate exposure. In addition, we have also created a first one-pager report of survey responses "Minnesota Water Values: Resident Survey Report" to disseminate across agencies and other research and advocacy groups.

Status as of August 1, 2019:
We met with MDH and Pheasants Forever to demonstrate how the data we are synthesizing for this project can be used to identify more projects with multiple benefits, such as the successful Worthington Wells WMA.

A master's thesis (attached) was completed using data collected and analyzed for this project.

Status as of February 1, 2020:
We have highlighted our work at various presentations to state organizations, including MDH, EQB, and LSOHC. We have also had discussions about making the datasets directly available to TNC and the Freshwater Society to aid in their decision making for sourcewater protection.

Status as of August 1, 2020:
Our usual dissemination channels were limited by the pandemic, however, we still presented on this work early in the year at the MN environmental congress and virtually to groups such as the Clean Water Council, and Board of Water and Soil Resources. Notably, our engagement with TNC and Freshwater mentioned above has led to collaboration on several grant proposals that seek to reduce barriers to using water valuation methods in planning processes such as One Watershed One Plan.

The manuscript we are drafting to synthesize this and other research on the topic of drinking water protection valuation methodologies will form the foundation for communication and dissemination going forward. The manuscript will be peer-reviewed for scientific audiences, but we will also use it to create blog posts, figures, and presentations that convey its key findings in a simple and clear manner.

Status as of February 12, 2021:

We did not engage in dissemination activities in this period, however, we continue to prepare materials for dissemination through academic conferences, peer-reviewed publications, public facing blog posts, and reports and data for state agencies.

Final Report Summary:
Outreach and dissemination of our findings is ongoing. We presented our work at multiple venues targeting both academic and state agency audiences. We presented to academic audiences at the Cornell social cost of water pollution workshop in April of 2021. We presented to a primarily state agency audience at the MPCA consortium "Issues in water resources: Identifying the research and regulatory needs for the next 20 years". We also held smaller meetings with practitioners at MDH and the Groundwater Restoration and Protection Strategies (GRAPS) sub-team composed of representatives from multiple state agencies. We shared findings with state agencies including MPCA, MDH, DNR, and BWSR, along with external stakeholders and advocacy groups such as Freshwater Society and the Environmental Working Group. The updated State Water Plan led by the Environmental Quality Board features our research on the interaction between climate change and water resources. Our work contributed to multiple student professional papers and master's theses and several peer-reviewed journal products are in preparation for submission. A synthesis report and appendices are available on our lab website.

VI. PROJECT BUDGET SUMMARY:
A. Preliminary ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel	$61,000	One Lead Scientist and PI to oversee Activities 1 and 2 and lead project and dissemination at 25% FTE each year for 2 years; 66.3% salary, 33.7% benefits
	$16,000	One Faculty and Co-PI to oversee Activity 3 and lead project and dissemination at 10% FTE for 1 year (one month in year two); 66.3% salary, 33.7% benefits
	$36,000	One Project Coordinator and Research Support Staff Person to support project management, analysis and reporting at 25% FTE each year for 2 years; 72.6% salary and 27.4% benefits
	$115,000	One Research Analyst to support data collection, spatial mapping, and biophysical and economic analysis at 100% FTE each year for 2 years; 72.6% salary and 27.4% benefits
	$43,000	One University of Minnesota Graduate Student Assistant to support survey development, focus groups and analysis during Activity 3 at 50% FTE for 1 year; 17% salary and 83% benefits which include academic year tuition, fiscal year health care, and social security and Medicare for 6.5 summer pay periods
	$15,000	Two Summer Undergraduate Student Interns to support various project activities at 29% FTE total each year for 2 years.

Survey costs and supplies	$18,000	Survey distribution costs including printing and mailing for 4,500 surveys with cover letters and postage-paid return envelopes; 3 waves of mailing. Based on estimated costs incurred in previous surveys administered by PI Davenport.
Focus Group Expenses	$6,000	Focus group room rentals and hospitality. Based on estimated expenses incurred in previous focus groups conducted by PI Davenport in Minnesota.
Publication and dissemination of results	$3,575	Publication fees for disseminating project results in peer-reviewed open access journal such as the Journal of Soil and Water Conservation or PLOS One. Page fees at JSWC are $190/page plus $750 for open access = $1890 for a seven page article or $1,495 for PLOS ONE. We anticipate this work resulting in two open access publications for an estimated total cost of $3,385.
Presentation of work at regional conference or meeting	$425	Registration and fees for presentation of results at regional conferences. An estimated $425 is requested to support registration fees, poster printing, and attendance and presentation at one meeting or conference.
Travel	$6,000	Travel within Minnesota for data collection, focus groups and researcher attendance at regional conference to present project findings. Funds used to pay University of Minnesota rental vehicle and mileage (75%) and meals (25%) for researchers, graduate student and interns. Assumes $300 per trip for 2 people to 2 locations for Activity 2 ($1,200) and $300 per trip for 2 people to 8 locations for Activity 3 ($4,800). Expenses reimbursed per travel guidelines as set by the University of Minnesota.
TOTAL ENRTF BUDGET:	**$320,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: N/A

Total Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 4.18 FTEs

Total Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: N/A

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds

The Natural Capital Project and Institute on the Environment, University of Minnesota. In kind support. The IonE has supported and will continue to support research and outreach activities conducted by the Natural Capital Project. Total funding for the research program to date is $1.0 million, with an additional $125,000 projected for FY17 and FY18.	N/A	N/A, Secured	Although IonE funding is not dedicated or committed specifically to this proposal, the organization can support research, software, data hosting and complementary activities.
University of Minnesota. In kind support. UMN Facilities and Administrative rate is 53% of modified total direct costs (total direct less graduate student fringe, capital equipment, subawards over $25,000 and on-site facilities rental). The amount here is the total estimated contribution, if F&A expenses would have been allowed on the project.	$169,600	N/A, Secured	Office space, IT services, and administrative / financial services in support of the project.
TOTAL OTHER FUNDS:	**$169,600**	**N/A**	

VII. PROJECT STRATEGY:

The project will be led by Dr. Keeler, Director and Lead Scientist of the Natural Capital Project at the University of Minnesota's Institute on the Environment and Dr. Davenport, Associate Professor in the Department of Forest Resources at the University of Minnesota. The project will support several new positions, including a project coordinator, research analyst, two summer interns recruited from local colleges or universities, and one graduate research assistant. The project was developed in partnership with the Minnesota Department of Health and will be conducted in close collaboration with agency partners.

A. Project Partners:

Partners receiving ENRTF funding: N/A

Partners NOT receiving ENRTF funding

- Tannie Eshenaur, Planning Director, Drinking Water Protection, Minnesota Department of Health, Collaborator and Advisor

B. Project Impact and Long-term Strategy: This project is a stand-alone effort and not part of a longer-term funding request, although it builds and expands on a current LCCMR project led by Keeler, Brauman, and Twine entitled "Assessing Water Scarcity and Threats". The project also leverages a 2015 statewide assessment of Soil and Water Conservation District capacity to protect groundwater conducted by Pradhananga, Davenport, and Perry and funded by the Minnesota Department of Natural Resources.

The project outcomes include detailed assessments of risks to clean water and the value of sourcewater protection in Minnesota. In addition, the project will highlight the importance of considering equity and understanding local capacity in key sourcewater areas for community-based land protection for clean water. All data generated as part of the project will be shared with agency partners and made publicly available through publication in a peer-reviewed open access journal.

The project team is currently seeking funding to expand the work beyond Minnesota and across scales. We hope that success in this project will allow the team to extend the analyses to city and watershed planning audiences and to regional basin-scale work in the Mississippi River.

C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	$ Amount
Environment and Natural Resources Trust Fund – **M.L. 2015, Chp. 76, Sec. 2, Subd. 04a**: "Understanding Water Scarcity, Threats, and Values to Improve Management." Appropriation of cash funds ($234,936, with $190,000 remaining from existing ENRTF Appropriation as of January 2016) awarded July 1, 2015 to PI's Keeler, Brauman, and Twine used to assess water scarcity and threats in MN. This project will generate statewide maps and data on future precipitation, temperature, and water scarcity that will inform the sourcewater risk assessments proposed in this study. This project has an end date of June 30, 2018.	July 1, 2015 – June 30, 2018	$234,936 ($190,000 remaining as of January 2016)
Minnesota Department of Natural Resources. **Groundwater management: Capacity assessment at the local level.** PI M. Davenport. Cash funds of $16,868 awarded to support Davenport, Pradhananga and Perry in analysis to identify threats to groundwater quality and quantity across the state as perceived by Soil and Water Conservation District staff. The study helps to prioritize threats, as well as identify areas for capacity building. Outcomes of the study have been a series of workshops for Soil and Water Conservation District staff and other water managers.	January 1, 2015 – September 30, 2015	$16,868 (project completed in 2015)

VIII. REPORTING REQUIREMENTS:

- **The project is for 2 years, will begin on 07/01/2017, and end on 06/30/2021.**
- **Periodic project status update reports will be submitted 02/01 and 07/01 of each year.**
- **A final report and associated products will be submitted between June 30 and August 15, 2021**.

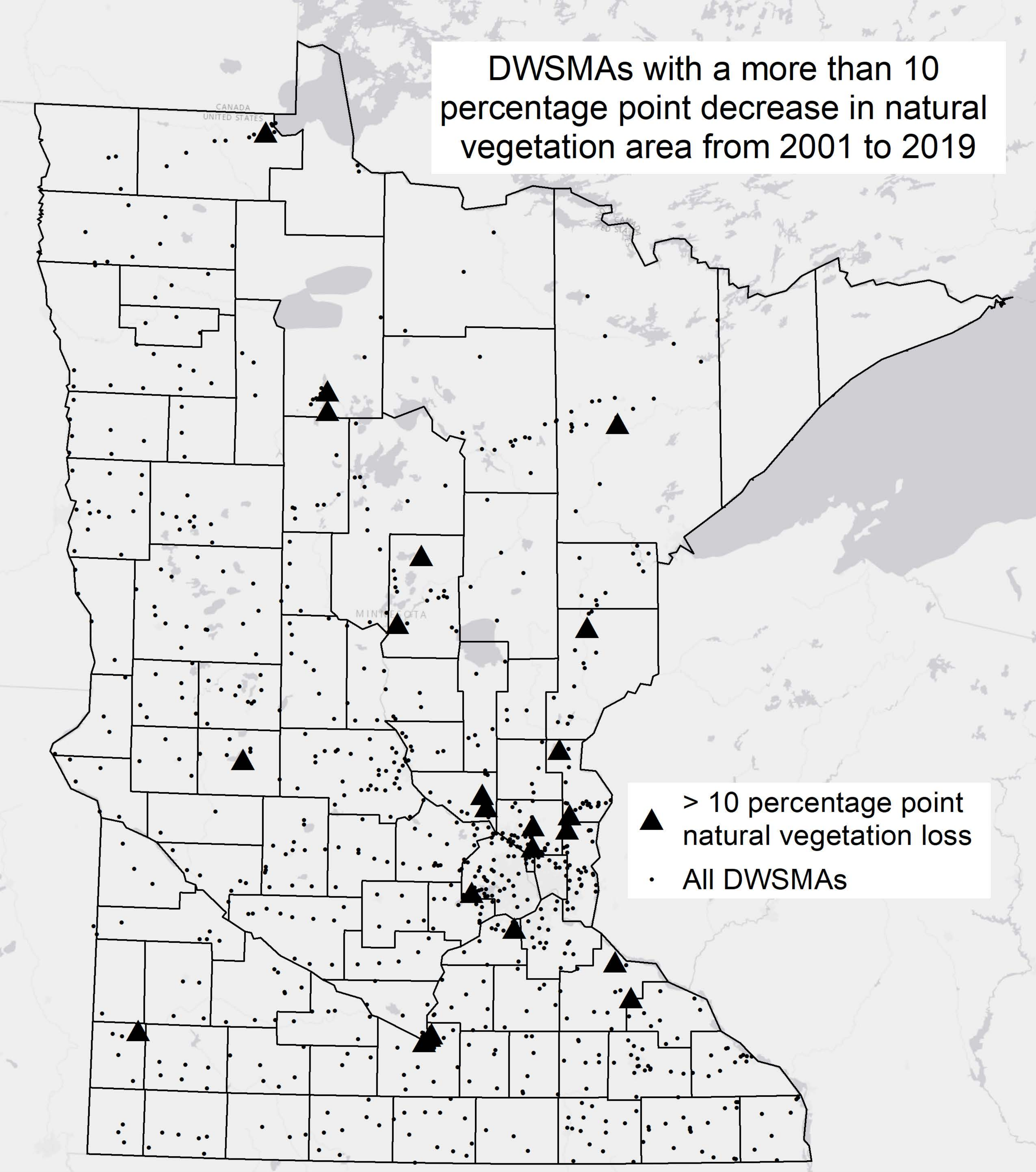
IX. VISUAL COMPONENT or MAP(S): See attached figure.

Environment and Natural Resources Trust Fund
M.L. 2017 Project Budget

Project Title: What are the public benefits of protecting sourcewater?
Legal Citation: M.L. 2017, Chp. 96, Sec.2, Subd. 03b
Project Manager: Bonnie Keeler
Organization: Humphrey School of Public Affairs, University of Minnesota
M.L. 2017 ENRTF Appropriation: $320,000
Project Length and Completion Date: 4 Years, June 30, 2021
Date of Report: Sep 15, 2021

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Activity 1 Budget	Amount Spent	Activity 1 Balance	Activity 2 Budget	Amount Spent	Activity 2 Balance	Activity 3 Budget	Amount Spent	Activity 3 Balance	TOTAL BUDGET
BUDGET ITEM	***Mapping land use change and risks to clean water***			***Valuation of the multiple public benefits of clean water***			***Assessment of equity and community capacity***			
Personnel (Wages and Benefits)	$104,000	$104,000	$0	$104,000	$104,000	$0	$91,400	$91,400	$0	$299,400
Bonnie Keeler, Lead Scientist and PI: $61,000 (66.3% salary, 33.7% benefits); 25% FTE each year for 2 years										
Mae Davenport, Faculty and Co-PI: $16,000 (66.3% faculty salary, 33.7% benefits); 10% FTE for 1 year (one month in year two)										
1 Project Coordinator and Research Support (support project management, analysis and reporting): $36,000 (72.6% salary and 27.4% benefits); 25% FTE each year for 2 years.										
1 Research Analyst (support data collection, spatial mapping, and biophysical and economic analysis): $115,000 (72.6% salary and 27.4% benefits); 100% FTE each year for 2 years										
1 University of Minnesota Graduate Student Assistant: $43,000 (17% salary and 83% benefits which include academic year tuition, fiscal year health care, and social security and Medicare for 6.5 summer pay periods); 50% FTE for 1 year										
2 Summer Undergraduate Student Interns: $15,000 (100% salary, part-time, hourly pay; $12.50/hr for 300 hours per student per year); 29% FTE each year for 2 years										
Supplies										
Survey distribution costs including printing and mailing for 4500 surveys with cover letters and postage-paid return envelopes; 3 waves of mailing							$10,000	$10,000	$0	$10,000
Other										
Focus group room rentals and hospitality. Based on estimated expenses incurred in previous focus groups conducted by PI Davenport in Minnesota.							$2,000	$2,000	$0	$2,000

Publication fees for disseminating project results in peer-reviewed open access journal such as the Journal of Soil and Water Conservation or PLOS One. Page fees at JSWC are $190/page plus $750 for open access = $1890 for a seven page article or $1,495 for PLOS ONE. We anticipate this work resulting in two open access publications for an estimated total cost of $3,385.				$2,080	$2,080	$0	$1,495	$1,495	$0	$3,575
Registration and fees for presentation of results at regional conferences. An estimated $425 is requested to support registration fees, poster printing, and attendance and presentation at one meeting or conference.				$425	$417	$8		$125		$425
Travel expenses in Minnesota										
Travel within Minnesota for data collection, focus groups and researcher attendance at regional conference to present project findings. Funds used to pay University of Minnesota rental vehicle and mileage (75%) and meals (25%) for researchers, graduate student and interns. Assumes $300 per trip for 2 people to 2 locations for Activity 2 ($1,200) and $300 per trip for 2 people to 8 locations for Activity 3 ($4,800). Expenses reimbursed per travel				$1,200	$1,200	$0	$3,400	$3,400	$0	$4,600
COLUMN TOTAL	**$104,000**	**$104,000**	**$0**	**$107,705**	**$107,697**	**$8**	**$108,295**	**$108,420**	**$0**	**$320,000**



Map of all 821 DWSMAs in the state, with those that experienced a 10-percentage point or greater decrease in natural vegetation area between 2001 and 2019 highlighted. Development pressure is a current issue for the protection of drinking water supplies. Development in DWSMAs is primarily urban or other built land covers, but agricultural expansion and intensification are issues as well. The distribution of DWSMAs with elevated natural vegetation loss indicates that source water protection is an issue affecting all regions of the state.

Source Water Protection Challenges and Co-benefits

November 2021

Version 1.0

Ryan Noe*, Bonnie Keeler, Terin Mayer

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Funding for this project was provided by the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR) under M.L. 2017, Chp. 96, Sec.2, Subd. 03b as extended by M.L. 2020, First Special Session, Chp. 4, Sec. 2

SCIENCE, TECHNOLOGY,
& ENVIRONMENTAL POLICY
Humphrey School of Public Affairs

ENVIRONMENT
AND NATURAL RESOURCES
TRUST FUND

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Executive Summary

Access to clean safe water is essential for promoting health, recreation, and economic development in Minnesota. However, many of our state's most pressing water quality problems remain unsolved. Over 40% of our lakes and rivers are rated as "impaired" and a growing number of households and communities face rising costs and health risks due to contaminated drinking water. If we hope to reverse current trends of water quality decline and preserve the valuable ecosystem services provided by clean water, we need to account for both the risks to water resources as well as the benefits of water quality protection.

Source water resources include both surface waters (lakes, rivers, and streams) and groundwater that supply households and communities with drinking water. Source waters are affected by land management, including agriculture, industry, and residential development. Pollution in the form of excess nutrients or other contaminants moves from land into surface waters and groundwater aquifers with consequences for households and communities. The majority of the land area that affects source water quality is under private ownership meaning it is not always possible for the state to protect water quality. Land use and management actions on these lands that increase nutrients and other contaminants can affect the health and welfare of millions of Minnesotans. There are successful examples of private and public partnerships that have worked together to protect source water and enhance valuable ecosystem services while supporting agricultural and rural economic development (e.g. Worthington Wells Wildlife Management Area). At the same time, other communities in Minnesota are facing known or unknown threats to their water supply with consequences for health and rising treatment costs.

Degraded source water can have important equity and distributional impacts. Rural households may face larger water bills when investments in expensive water treatment infrastructure are distributed among a small population of ratepayers. Due to decades of disinvestment in water infrastructure, some tribal communities and immigrant communities lack access to safe and affordable water supplies. Climate change may exacerbate these disparities as changes in precipitation and temperature affect the quality of surface water, the timing and intensity of floods, change demand for water resources, or place stress on existing water infrastructure.

Agency leaders, water resource managers, and communities have identified an urgent need to map and quantify the risks facing source water areas in Minnesota, better articulate the value of clean water, and develop practical approaches that enhance community capacity to protect source water and ensure safe and equitable access to clean water for all Minnesotans.

In this report, we focus on the 1.23 million acres designated by the Minnesota Department of Health (MDH) as the groundwater catchments for Public Water Supplies (PWSs). This land is divided among 821 Drinking Water Supply Management Areas (DWSMAs), which are themselves composed of individual private or publicly-owned parcels. Water from one or more DWSMAs is aggregated at a PWS before distribution to consumers. We summarize data on the costs and benefits of source water protection at the PWS, DWSMA, and parcel level (Appendices A, B, and C) as appropriate. Below we summarize key findings under our three research objectives:

1) Mapping land use change and land protection costs.

On average, land use in source water protection areas remained relatively stable from 2001 to 2019, with built area increasing by 12% while natural vegetation and agricultural land use areas declined by 5% and 8%, respectively. Although the area covered by agriculture declined, agriculture is still the dominant land cover, covering 49% of areas with high or very high vulnerability to contamination. Most DWSMAs had little change in land cover over the last two decades, but the overall trend was an increase in developed land covers. Some smaller DWSMAs, such as Willow River, Minnetrista Central, and Woodland MHP, had a more than 20 percentage point in built area in 18 years. DWSMAs experiencing increases of built and/or agricultural land covers face more potential threats to water quality within their water supply.

We used a novel dataset of land value to calculate the opportunity cost of protecting unbuilt land in source water areas. Our analysis demonstrates the high opportunity cost of acquiring land for protecting source water. The total area of unprotected and unbuilt land in source water protection areas is over 634,000 acres, with a value of $8.8 billion. Targeting a subset of the lowest value, highest vulnerability land reduces the cost substantially, but the opportunity cost remains high. Protecting 15% of this subset would cost over $100 million, and would produce inequitable protection that excludes high land value DWSMAs. Our addition of land value data at the DWSMA and parcel levels provides insights on the opportunity costs of protection that will help practitioners prioritize projects with a high return on investment.

2) Valuation of the multiple public benefits of land protection for clean water.

Protecting source waters via the adoption of best management practices or converting lands from row-crop agriculture to perennial cover can result in a stream of public benefits including reduced treatment costs for community water suppliers and reduced risk of diseases associated with exposure to contaminated drinking water. Source water protection can also lead to benefits beyond drinking water quality such as improved recreation or habitat for wildlife. We applied monetary and non-monetary valuation techniques to three areas of co-benefits associated with source water protection.

First, we assembled data on the public water suppliers in the state and used estimates from the literature on the costs that similarly sized suppliers have paid to install and operate treatment for elevated nitrate. We estimated that the capital, operation and maintenance costs of installing reverse osmosis filtration for the 8% of PWSs with elevated (> 3 mg/L) nitrate concentrations ranged from 9.8 million to 45.7 million annually. If distributed uniformly between households, these costs would increase annual water rates by $161 to $751. However, rate increases would likely fall disproportionately on systems serving small populations. Our analysis estimated average annual household costs for systems serving fewer than 500 people of $803, while systems serving greater than 500 people had an average annual household cost of $269.

Second, we compiled demographic data on the population served by public water supplies, drinking water nitrate concentrations, and the risk for disease associated with exposure to nitrates. We used these datasets to implement a method for estimating disease incidence and associated costs attributable to exposure to elevated drinking water nitrate. Of the five types of cancer in our analysis, we estimated that 71 cases, roughly 1% of cases of these cancer types annually, can plausibly be attributed to elevated drinking water nitrate. Using recently developed methods, we also estimated 50 cases of adverse birth outcomes. We applied three valuation techniques that capture medical costs and the cost of premature mortality. The differing approaches to valuation produced annual cost estimates ranging from $27.2 million to $256.6 million.

Finally, we estimated the co-benefits of protecting DWSMAs through an analysis of 19 environmental co-benefits. We found that benefits such as pheasant habitat, bird watching, and lake recreation are overrepresented in unprotected, unbuilt source water protection areas relative to unbuilt, unprotected areas in the rest of the state. We applied spatial models of land use change to estimate potential threats to DWSMAs. Due to the proximity of DWSMAs to population centers, DWSMAs face greater than average development risks.

3) Enabling assessment of equity in source water protection

Many DWSMAs supply small or low-income populations that would be disproportionately burdened by an increase in water treatment costs. We designed and implemented a workflow that allows for combining information on public water supplies with census demographic data for municipalities or counties. We found that most PWSs did not have elevated drinking water nitrate, but those that did tended to be in the lower quartile for median household income. These datasets enable practitioners to assess where elevated drinking water nitrate and associated costs might fall on a small and/or vulnerable population that would be disproportionately burdened by increased drinking water costs.

In summary, our work highlights potential risks and opportunities to protect water quality and provide multiple public benefits, helps to identify programs that protect the value of clean water, and builds capacity among citizens and decision-makers to take action in source water protection areas to improve water quality and realize additional public benefits from land protection.

1. Mapping land use change and land protection costs

1.1 Drinking Water Supply Management Areas (DWSMAs)

In Minnesota, source water protection areas for groundwater are referred to as Drinking Water Supply Management Areas, or DWSMAs. DWSMAs are delineated by the Minnesota Department of Health (MDH) as part of the source water protection planning process required of Public Water Suppliers (PWS). Although a PWS may use surface or groundwater, DWSMAs are only delineated for groundwater. MDH defines a DWSMA as "the area on the land covering the groundwater that could flow to the well within 10 years[1]." DWSMAs include all wells that serve a PWS that have an overlapping 10-year time of travel. If a PWS has multiple well fields that do not have an overlapping 10-year travel time, they are delineated as separate DWSMAs. The total area of all 821 currently delineated DWSMAs is 1.23 million acres, of which 634,000 acres are viable for protection activity because they are not already protected or in a built land cover (Table 1).

The geology within a DWSMA determines how quickly and easily water and contaminants from the surface makes its way to groundwater. MDH classifies land within DWSMAs as 'Very Low', 'Low', 'Moderate', 'High', or 'Very High' vulnerability. The classification is based on the connectivity of surface to groundwater, with higher connectivity more readily enabling contamination on the surface to reach groundwater, thus increasing the vulnerability of the water supply. Vulnerability is mapped within DWSMAs, it is common for a DWSMA to be composed of several regions with different vulnerability classifications (Figure 1). In this report we summarize results for all DWSMAs, and when appropriate also highlight results among the portions of DWSMAs categorized as 'High' or 'Very High' vulnerability. Appendices contain data aggregated at the individual PWS, DWSMA, or parcel level where appropriate.

Table 1. Drinking Water Supply Management Areas acreage summary statistics. The Minnesota Department of Health delineates DWSMAs and classifies the land within them into five vulnerability classes based on how vulnerable the water is to surface contamination based on geologic characteristics. We calculated the area of DWSMAs that is not yet a built land cover or already protected as this represents the subset of land that is viable for conservation activities.

Vulnerability class	Total acres	Unprotected and unbuilt acres
Very High	23,489	14,772
High	447,409	281,354
Moderate	334,024	125,233
Low	377,506	186,957
Very Low	48,648	26,037
Total Area	**1,231,077**	**634,353**

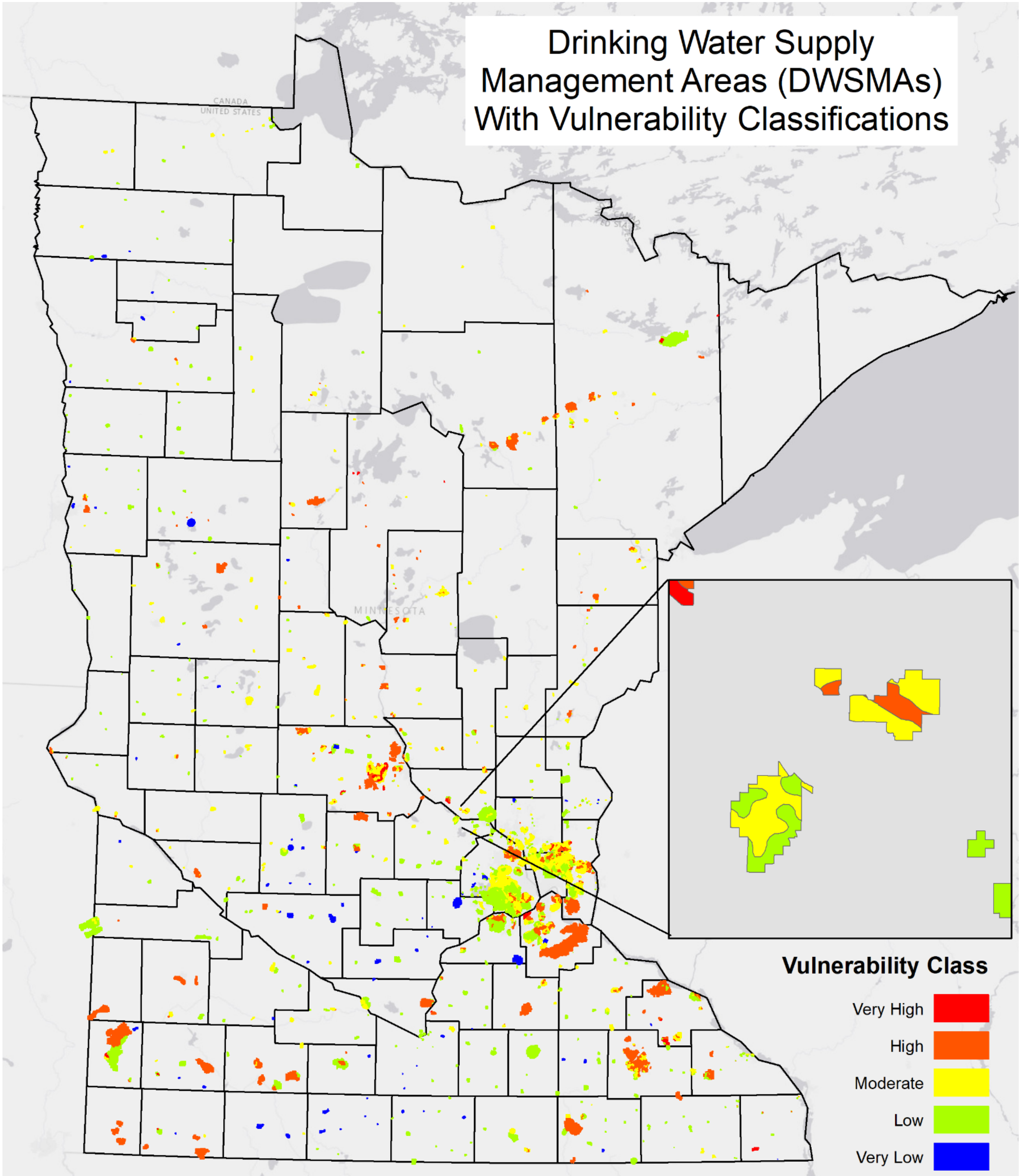

Figure 1. Overview map showing the location, size, and vulnerability classifications of all 821 Drinking Water Supply Management Areas (DWSMA) in Minnesota. Vulnerability classes are defined by the Minnesota Department of health and represent how susceptible groundwater is to surface contamination. The inset map shows a detailed view of how vulnerability classification can vary within a DWSMA depending on the geologic characteristics.

Source water faces risks from increasing urbanization and intensive agricultural practices, both of which can leach contaminants to groundwater. Nitrogen fertilizer used in agriculture and on lawns has led to elevated (>3 mg/L) drinking water nitrate concentrations in 8% of Minnesota's public water supplies[2]. Climate change has the potential to exacerbate sources of contamination like nitrate leaching with more frequent and more intense precipitation events in the spring[3] when fertilizer is typically applied.

Despite these threats, data on land use trends has been challenging to apply to source water protection. Inconsistent methods used to produce land cover maps confound actual changes, while the overlapping nature of DWSMAs is not compatible with the assumptions used in common spatial analysis tools. We address these challenges by applying newly available land cover data and custom spatial analysis tools to create a spreadsheet that allows users to measure and visualize trends in land use from 2001 to 2019 for any DWSMA. Additionally, we analyzed the value of land within DWSMAs to better understand the opportunity cost of mitigating risk through land protection. These datasets provide a comprehensive picture of the type and quantity of land use change and the cost of protection.

1.2 DWSMA land cover trends 2001-2019

To assess changes in land use and risks to sourcewater, we leveraged recent developments in longer term, methodologically consistent land cover datasets. We used the National Land Cover Dataset[4] (NLCD) analyzed using four aggregate land use classes; agriculture (NLCD classes 81, 82), built (21, 22, 23, 24, 31), natural vegetation (41, 42, 43, 52, 71, 90, 95), and water (11). Overlapping boundaries of some DWSMA's required us to develop a novel analysis technique for estimating land use trends. We used the Python packages geopandas and rasterstats to calculate land use trends for each DWSMA independently. From this analysis we created two outputs; statewide summary statistics and individual land use change statistics for each DWSMA.

Disaggregated results in Appendix A report land use change trends for each of the 821 DWSMAs. Using spreadsheet software, users can quantify changes in land cover and visualize trends from 2001 to 2019 for individual or groups of non-overlapping DWSMAs. Additionally, in the event a PWS is served by multiple DWSMAs, users can summarize land cover statistics for all of the land that contributes to it, giving a more accurate description of the aggregate influence of land use change.

Here we present aggregate trends in land use across all 1.23 million acres of land within the boundaries of Minnesota's DWSMAs. To prevent double counting, summary figures below merged overlapping DWSMAs, assigning the highest vulnerability class in the event overlapping DWMSAs had different vulnerability classes. In 2001, agriculture (including hay/pasture) was the most prevalent land cover in DWSMAs with 41% of the total area. However, over the next 18 years built land covers (e.g., roads, buildings, urban areas) increased by 53,118 acres, becoming greater in area than agriculture by 2019 (Figure 2). These gains were offset by a combination of losses of 40,529 acres of agricultural land and 11,516 acres of natural vegetation.

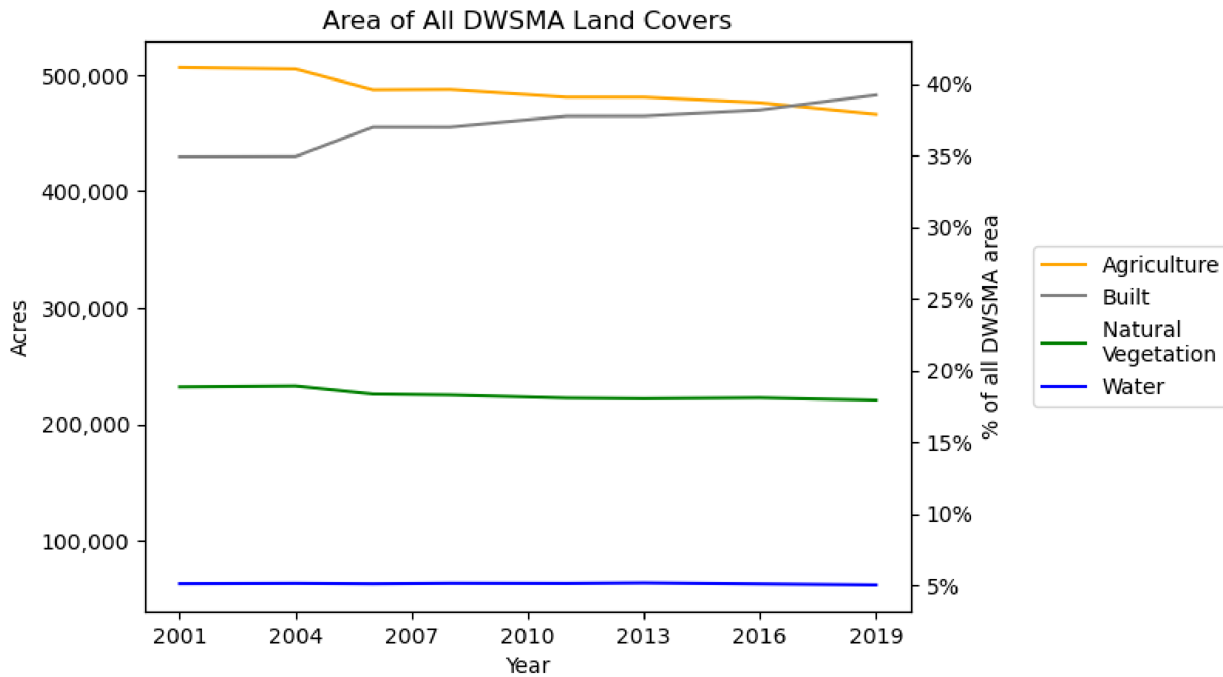

Figure 2. Land use change in all DWSMAs from 2001 to 2019. In 2001, agriculture was the most prevalent land cover in DWSMAs with 41% of the total area, however, over the next 18 years built land covers (e.g., roads, buildings, urban areas) gradually displaced agricultural land. By 2019 built land surpassed agriculture as the most prevalent land cover in DWSMAs. Natural vegetation experienced a decline of 1% of total DWSMA area.

We next analyzed land use trends in portions of DWSMAs ranked by the MN Department of Health as 'High' or 'Very High' vulnerability to surface contamination. We observed similar trends for this subset of vulnerable DSWMAs. Since 2001, built area in DWSMAs has expanded at the expense of agricultural and natural vegetation. High and Very High vulnerability DWSMAs have a higher proportion of agriculture, 49% in 2019 (Figure 3), compared to all DWSMAs which are 38% agriculture.

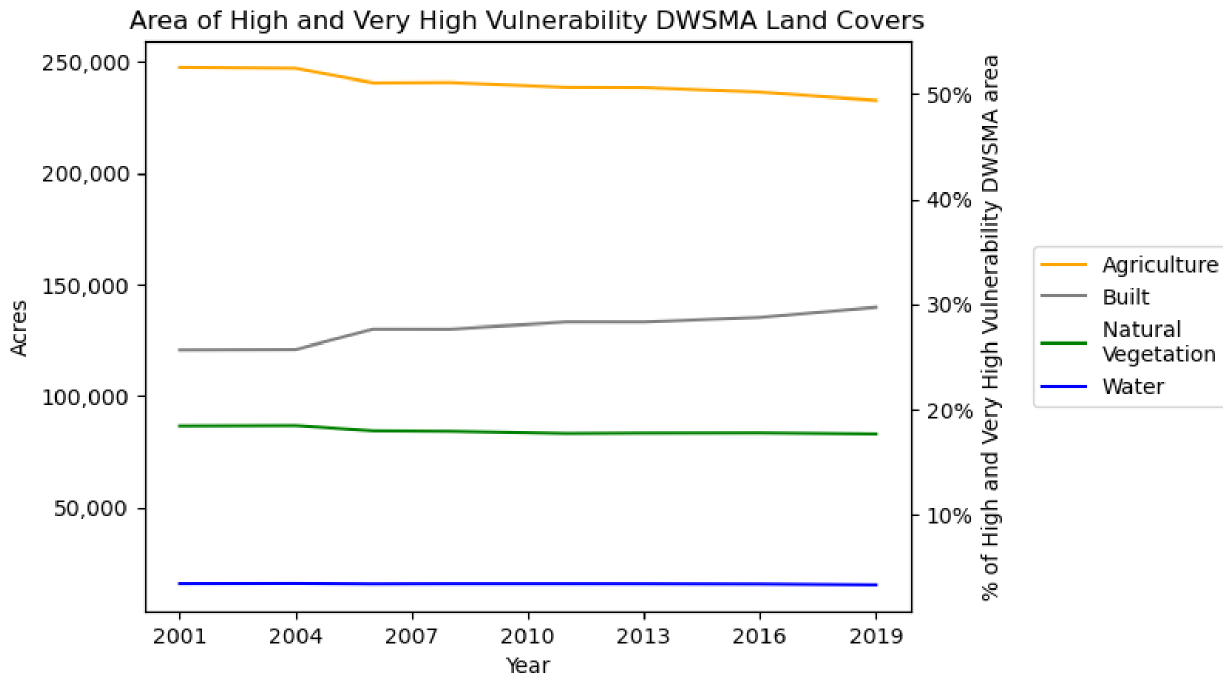

Figure 3. Land use change in the subset of High and Very High Vulnerability DWSMAs from 2001 to 2019. The trend of increased built area offset primarily by delines in agriculture and smaller declines in natural vegetation was also apparent in this subset of land. Despite similar declines in agricultural area, the higher initial proportion resulted in it remaining the dominant land cover in high vulnerability DWSMAs with 49% of the total area.

We were also interested in the spatial distribution of DWSMAs with elevated loss of natural land cover. Figure 4 highlights DWSMAs that experienced a greater than 10 percentage point decrease in natural vegetation (grassland, wetland, forest, and water) between 2001 and 2019. Change was concentrated in the metro area, however all regions of the state had at least one DWSMA with elevated loss in natural land cover.

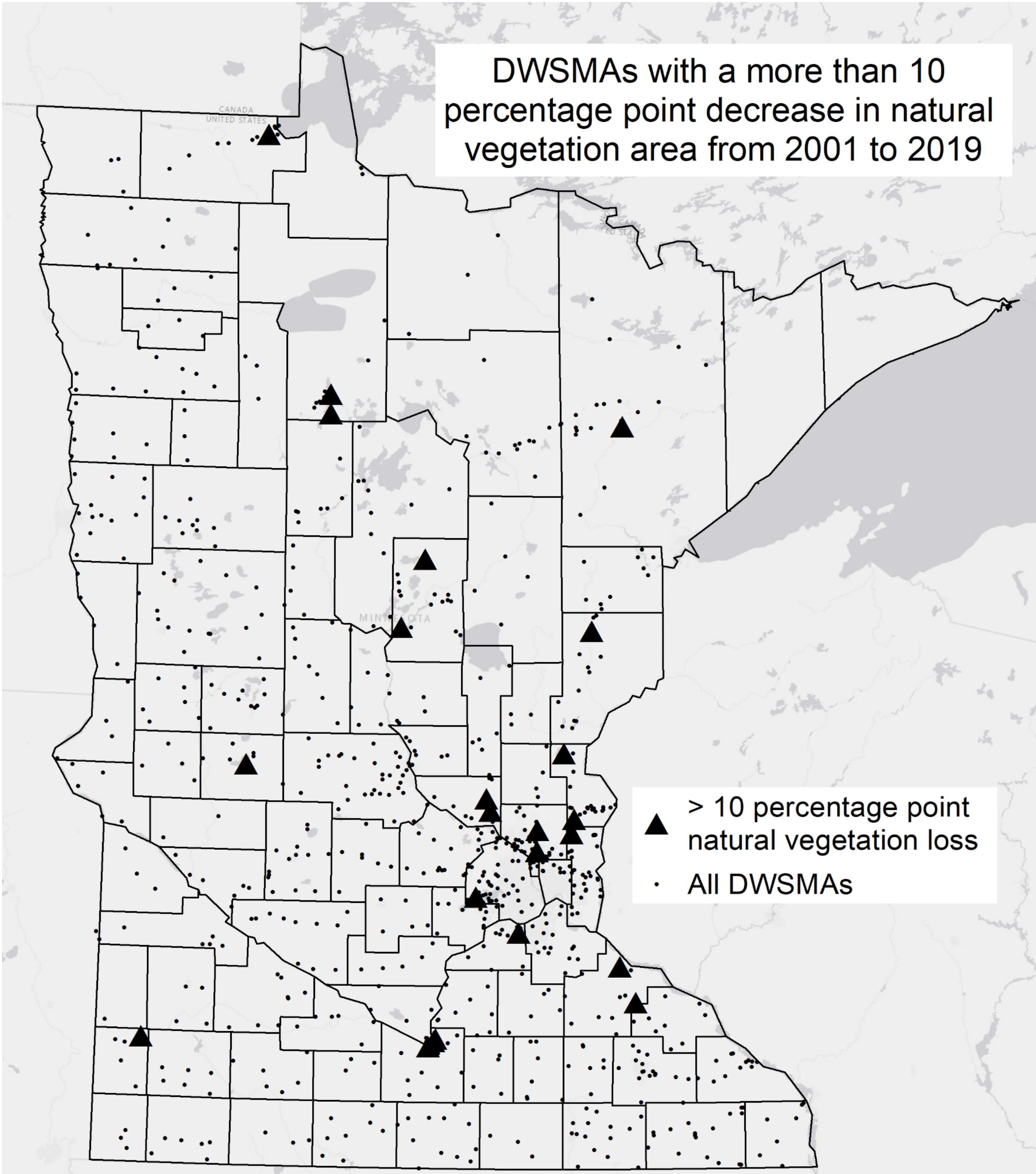

Figure 4. Map of Drinking Water Supply Management Areas in the state, highlighting those with a greater than 10 percentage point decrease in natural vegetation (grassland, wetland, forest, and water) area between 2001 and 2019.

Figure 5 presents a histogram of the change in developed (built, row crop agriculture, and hay/pasture) land covers between 2001 and 2019 in all DWSMAs. Most DWSMAs had little change, but the overall trend was an increase in developed land covers. Some smaller DWSMAs, such as Willow River, Minnetrista Central, and Woodland MHP, had a 20 percentage point or more increase in developed area in 18 years. DWSMAs experiencing increases of built and/or agricultural land covers face more potential threats to water quality within their water supply.

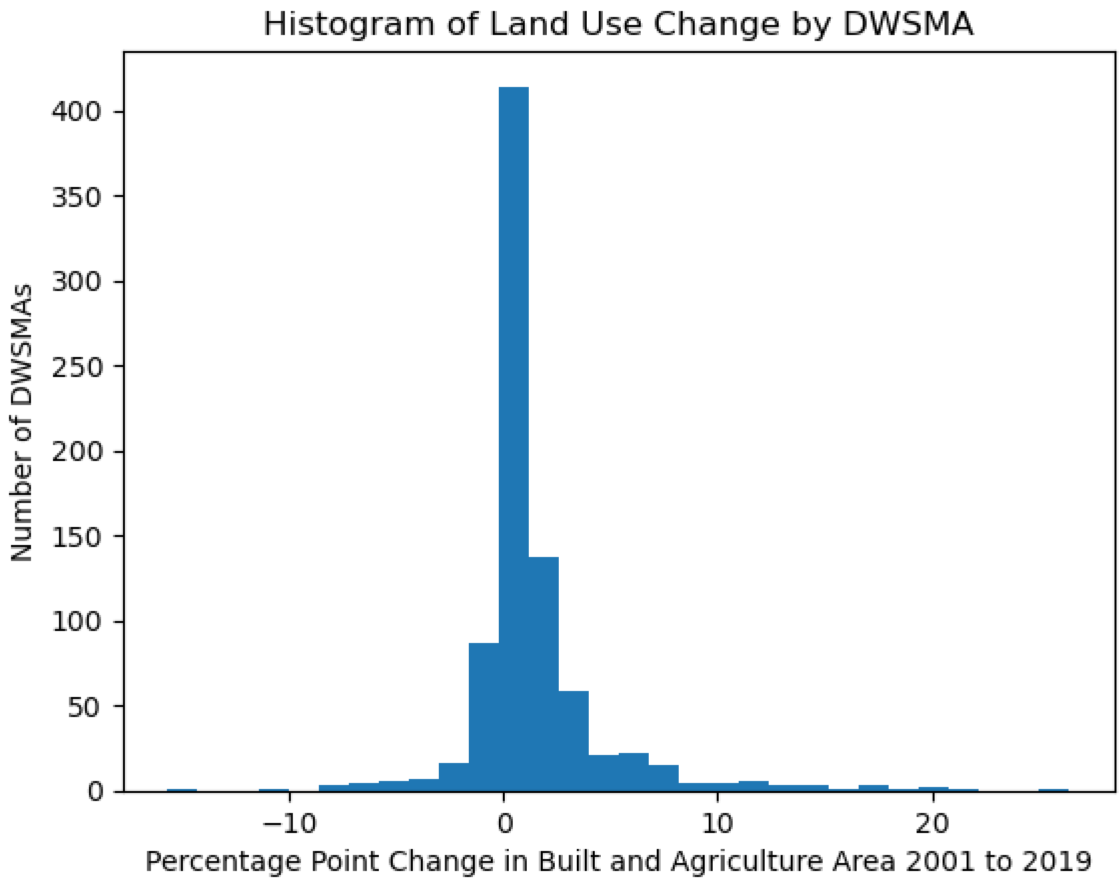

Figure 5. Histogram of change in build and agricultural area in each DWSMA between 2001 and 2019. Most DWSMAs had little to no change, but several had increases in developed land covers greater than 20% of their total area.

Despite record high corn and soy prices during the study period, agricultural area in DWSMAs declined by 3% of the total DWSMA area. Only built land covers showed a net increase in area between 2001 and 2019. Results aggregated to all DWSMAs can hide trends in the data. For example, although agricultural area also declined in High and Very High vulnerability DWSMAs, the proportion of agricultural area initially was higher than in all DWSMAs. Even after the growth in built area, agriculture remains the dominant land cover among the most vulnerable DWSMAs (Figure 3). Similarly, spatial disaggregation shows that although the loss of natural vegetation was 1% of the total DWSMA area, that loss occurred disproportionately in a subset of DWSMAs (Figure 4). Further disaggregation of these results at the DWSMA level is possible with the data provided in Appendix B.

1.3 Land value

Land protection or restoration to natural vegetation is one strategy to mitigate the development pressures and other risks to water quality within DWSMAs. However, preventing urban development and agriculture has an opportunity cost that must be considered when making water quality management prioritization decisions. To demonstrate the scale of the cost of drinking water protection using land acquisitions, we used newly available estimates of the fair market value of land statewide to quantify the amount of money required to purchase the unprotected, unbuilt land within DWSMAs.

Our analysis uses the Private-Land Conservation Evidence System (PLACES), a Boston University research effort led by Dr. Christopher Nolte to harmonize wide ranging spatial and tabular data on land ownership, development, and value (placeslab.org/places). While we explored using parcel and estimated market value of land directly from counties and the Minnesota Department of Revenue, we found that missing data and minor inconsistencies between counties limited the usefulness of the data in a statewide analysis. The PLACES data overcome these limitations by applying machine learning techniques to the same publicly available land value and parcel data, along with many other data sources, to consistently predict the cost of conservation acquisitions anywhere in the contiguous U.S., even when the underlying datasets are incomplete. In development of these data, Dr. Nolte compared his estimates to previously published estimates of the opportunity cost of conservation land, and found that his predictions were more accurate when compared to actual conservation land transactions, and that prior research tended to underestimate the value of land[5]. The sophisticated modeling techniques and validation with real-world transactions make this the ideal dataset to estimate opportunity costs of land acquisitions for source water protection.

Specifically, we used the PLACES Fair Market Value estimates trained on transactions of vacant land only. In this context, vacant means without buildings or structures, but includes agricultural land. Although land value estimates are modeled for the entire state, we only applied our analysis to land that could feasibly be protected or restored to protect water quality. To best match these assumptions, we used the NLCD to remove any estimates for water (i.e., lakes and rivers), roads, and urban development. We also removed estimates for land that was already protected by a state or federal conservation program. We adjusted the land values in the PLACES data for inflation (2017 to 2021 dollars), and aggregated the value of all of the land within DWSMAs.

While protecting all of this land is not feasible, the analysis and summary figures below serve two important purposes. First, they demonstrate the scale of the opportunity cost to protect all of the land in DWSMAs (Figure 6), or a subset of the land most vulnerable to contamination (Table 2, Figure 7). Second, in addition to statewide aggregations, we also provide the estimated value for every Public Land System quarter-quarter section parcel (approximately 40 acres) that intersects a DWSMA in Appendix C. The parcel level data provide decision support to practitioners seeking to balance the trade-offs between opportunity cost and source water protection.

To visualize the value of all unbuilt, unprotected land in DWSMAs we first sorted every hectare of land within a DWSMA from lowest to highest value. We then created a series of figures (Figures 6-7) that plots the total value on the Y-axis, and the proportion of all unprotected and unbuilt DWSMA land it represents on the X-axis. This shows the cumulative cost of the land that is viable for protection or restoration if you were to acquire land from least to most expensive.

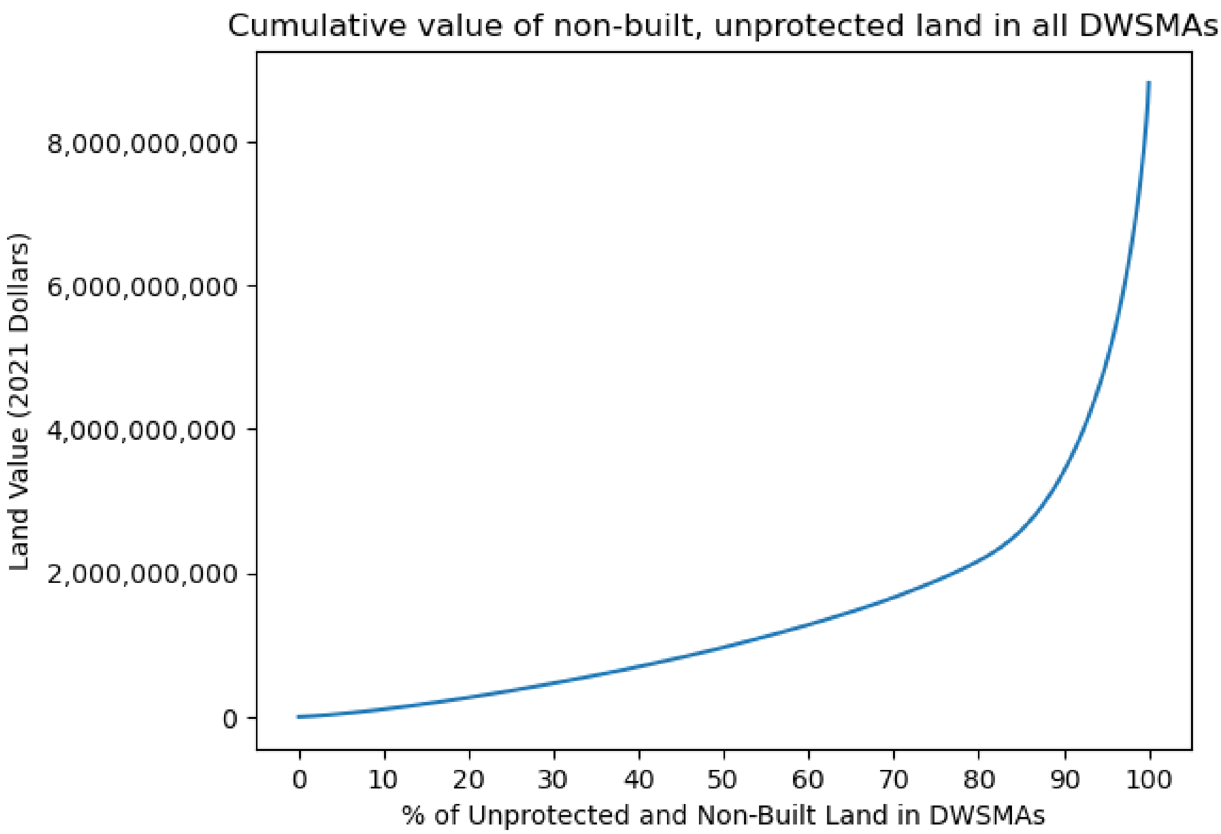

Figure 6. Cumulative value of unbuilt, unprotected land in all DWSMAs. Extremely high value land creates a skewed distribution where 15% of the land makes up over 75% of the total value. However, the value of the remainder of the land is still on the order of billions of dollars.

The total area of unprotected and unbuilt land covers is over 634,000 acres, an area larger than some counties, with a value of $8.8 billion. A point of rapid slope change at approximately the 85th percentile shows how just 15% of the land area makes up over 75% of the total value (Figure 6). Avoiding high value land is one strategy for maximizing the amount of protection for a given budget. However, it is impossible to avoid high cost land entirely without creating unequal protection of water quality between DWSMAs.

Table 2. Summary of value of unprotected and unbuilt land in DWSMAs by vulnerability class.

Vulnerability Class	Area (acres)	Total Value ($)	Average Value ($ / acre)	Median Value ($ / acre)
Very High	14,772	106,864,090	17,876	10,374

High	281,354	2,969,534,700	26,081	11,747
Moderate	125,233	2,982,303,700	58,846	12,627
Low	186,957	2,511,657,200	33,197	10,333
Very Low	26,037	244,283,940	23,183	11,315

Disaggregating land values by DWSMA vulnerability class shows that the highest average land value is Moderate vulnerability, likely due to large Moderate vulnerability DWSMAs in the metro area. The lowest average value was Very High vulnerability land. However, there are only 15,209 acres of Very High vulnerability land, compared to over 400,000 acres in the High and Moderate vulnerability classes (Table 2). Despite having the lowest average value and representing only 2.4% of the total area, the value of all High Vulnerability land still exceeds 100 million dollars.

Our analysis demonstrates the high opportunity cost of acquiring land for protecting source water. Even targeting the lowest cost and High or Very High vulnerability land, 100 million dollars would only be enough to acquire approximately 15% of that subset (Figure 7). Targeting strategies that produce more equal protection between DWSMAs are even more limited in the area they can protect as they must contend with high land values in urbanized DWSMAs. Despite these challenges, this analysis also reveals opportunities such as the lowest average land cost is found on the land with the highest vulnerability source water. This dataset informs the opportunity cost of potential activities and helps identify those with a high return on investment.

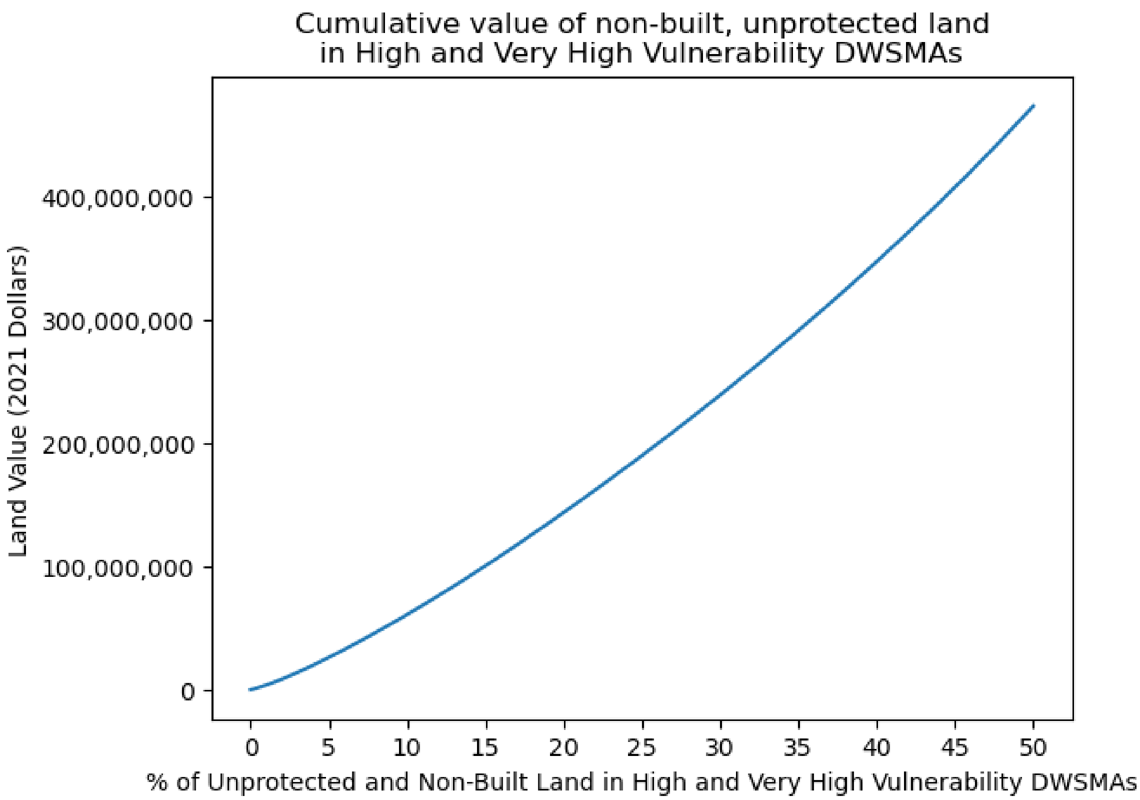

Figure 7. Cumulative value of unbuilt, unprotected land in DWSMAs with High or Very High vulnerability to surface contamination. This figure represents a subset of the land in all DWSMAs classified as High or Very High vulnerability and plots total value against the proportion of their total area. It only plots the lowest cost half of land to enable better visualization of the value of smaller subsets of land.

2. Valuation of the multiple public benefits of land protection for clean water

Source water protection can reduce water treatment costs, improve public health, and enhance recreation activities. These public goods or ecosystem services are important co-benefits of land protection or restoration but are often missing from planning and policy review because their values are difficult to quantify. We aimed to capture a comprehensive suite of potential benefits associated with source water protection in order to inform prioritization and planning decisions sensitive to the multiple values of public land protection for clean water. First, we assembled data on the public water suppliers in the state and used estimates from the literature on the costs that similarly sized suppliers have paid to install and operate treatment for elevated nitrate. Second, we compiled demographic data on the population served by public water supplies, drinking water nitrate concentrations, and the risk for disease associated with exposure to nitrates. We used these datasets to implement a method for estimating disease incidence and associated costs attributable to exposure to elevated drinking water nitrate. Finally, we include a non-monetary environmental benefit assessment technique to quantify how well 19 co-benefits are targeted when protecting DWSMAs as compared to other areas of the state. These activities will help to illuminate the true value of clean water and identify how this information can inform decisions ranging from payment programs or incentive schemes to evaluating the return on investment in land protection.

2.1 Avoided costs of drinking water treatment for elevated nitrate

One way to quantify the value of source water protection is to estimate the costs that public water supplies have to pay to install treatment to mitigate elevated drinking water nitrate. This approach is also applicable to other contaminants, but nitrate is well-studied and reflects a treatment need on the horizon of many PWSs in Minnesota. Common techniques for treating elevated nitrate include reverse osmosis, ion exchange, and blending with new or deeper wells. Of these methods, blending with new wells is often the cheapest, but it is contingent upon the availability of an uncontaminated water source. Because it cannot be used in all cases and its costs are dependent on local geology, blending is not included in this analysis. We limit our analysis to reverse osmosis because it is the most common approach used by PWSs that have had to install new water treatment in Minnesota. It is also effective against contaminants other than nitrate, such as chloride.

Previous research in California analyzed the total (capital, operation and maintenance) annual costs of reverse osmosis for PWSs of varying capacities. The researchers found total annualized costs of treatment systems ranging from $0.58 to $19.16 per 1,000 gallons. System size heavily influenced total costs, with average costs ranging from $6.64 per 1,000 gallons for very small systems to $2.38 for large systems[6]. We cross-referenced these estimates with more recent and local studies to ensure the estimates were relevant for Minnesota. A 2015 Minnesota Environmental Quality Board study described per household total costs ranging from $1,600 to $7,600 for new treatment plants for three communities with elevated drinking water nitrate[7]. Although the report does not specify what assumptions are used for amortization or household size, if we apply the assumptions described in Table 3, we find that the annual cost estimates range from $169 to $805 and are consistent with the estimates derived from Jensen et al.[6]

We applied the estimates found in table 24 of Jensen et al.[6] to Minnesota PWSs by using the MDH's population served value to estimate the annual amount of water treated. Using the typical average flow range reported by Jensen et al., we prorated the flow volume according to population. We then multiplied the estimated annual volume by the low, average, and high total combined cost estimates, and adjusted for inflation to 2021 dollars.

In Table 3 we report estimated treatment costs aggregated for all PWSs and just those with elevated nitrate. Appendix A provides the estimates specific to every PWS. If every PWS in Minnesota needed to install reverse osmosis treatment at the high end of the cost spectrum, the total would be over 1.3 billion dollars annually, exceeding the value of all of the unprotected and unbuilt land in DWSMAs within a decade (Tables 2, 7). A more plausible treatment cost scenario examining the 8% of PWSs with current elevated (>3 mg/L) drinking water nitrate shows the total cost for reverse osmosis ranges from 9.8 million to 45.7 million, or $161 to $751 per household annually if costs are uniformly distributed among all ratepayers. Summary treatment costs obscure the variability in costs associated with differing system sizes. Smaller systems with shallow wells are more at risk for nitrate contamination and are unable to take advantage of the economies of scale in treatment found in larger systems. Using our estimated average cost for PWSs with elevated nitrate, we found that annual costs for systems serving fewer than

500 people had a projected annual average household cost of $803, while systems serving greater than 500 people had an average annual household cost of $269.

Table 3. Estimated annual cost range for installing reverse osmosis filtration on all public water supplies, or a subset with a 2010-2020 average N concentration > 3 mg/L. Cost estimates include operation and maintenance and capital costs amortized over 20 years with an 7% interest rate. All estimates adjusted for inflation to 2021 dollars. Household costs use MDH population served estimate and assume 2.2 people per household. Household costs presented in this table assume costs are distributed uniformly across all households, in reality smaller systems have higher household costs because they lack economies of scale in treatment.

	Total Annual Cost			**Per Household Annual Cost**		
	Low	**Average**	**High**	**Low**	**Average**	**High**
All PWSs	298,712,303	884,487,145	1,375,188,492	150	444	691
PWSs with > 3 mg/L N	9,834,363	27,955,216	45,749,935	162	459	752

While new treatment system costs are influenced by many factors outside the scope of this analysis (e.g., construction costs, technology advances, existing infrastructure), the estimates shown here demonstrate that under some high cost scenarios, treatment costs can rival the costs of land acquisition. Even in low and average cost scenarios, additional treatment can increase costs to individual households by hundreds of dollars per year, with very small systems facing the highest costs.

2.2 Avoided health costs from exposure to elevated drinking water nitrate

Cost-benefit analyses of water pollution have typically assumed that drinking water treatment standards in the U.S. are sufficiently stringent to eliminate health risks [8], but a growing body of epidemiological evidence shows that nitrate exposure may be harmful even at levels below the threshold set by the Clean Water Act [9–11]. This emerging research links low-level nitrate exposure to a number of cancers and birth defects whose mortality and morbidity outcomes can be valued in dollar terms. While still tentative, as these links become substantiated by further epidemiological research they may dramatically increase the social cost of water pollution by incorporating yet uncounted health damages.

We replicated and expanded upon an approach from the environmental public health literature [11,12]. This method, first applied to drinking water nitrate in a European cost-benefit assessment [13], uses disease-specific estimates of relative risk due to nitrate exposure and observed cases of the disease to infer the portion of observed cases that can be attributed to nitrate. We combine disease incidences from the Minnesota Department of Health[14], the National Institutes of Health[15], and the March of Dimes Peristats database[16] with the demographics and population estimates of each public water supply to estimate counts of adverse health outcomes at each water provider. We then use measured nitrate levels in these supplies, as provided by MDH, and the relative risk values reported in table 1 of Mathewson et al.[11] to estimate counts of five different cancers and four adverse birth defects, including neural tube defects that are frequently fatal (Figure 8).

From case counts, we calculate a number of monetary figures that represent different approaches to valuing the social costs of these plausibly nitrate-caused diseases. Using estimates from the literature [12,17,18], we calculate direct medical costs for diagnosis and treatment. Following past research [12,19,20], we pursue two distinct approaches to valuing loss of life. The Value of a Statistical Life approach derives a value for mortality from observed trade-offs individuals make between job compensation and increased risk of fatality. The Quality Adjusted Life Years approach estimates a similar value for each year of lost life and for the diminution of quality of life during the course of the disease. The two approaches provide philosophically distinct, but complementary estimates to the health damages cleaner water could avoid.

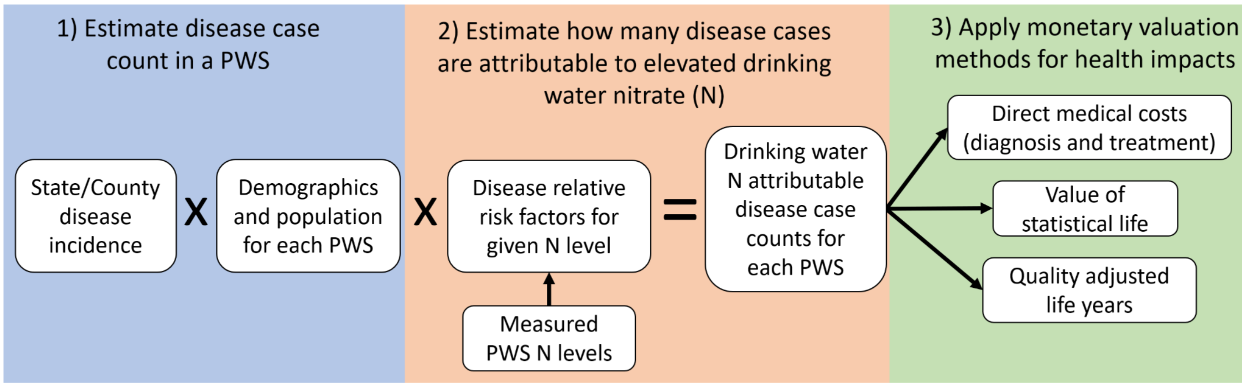

Figure 8. Conceptual diagram of avoided health costs calculations. Colored background boxes divide the process into three steps. First we estimate the number of disease cases that happen in each PWS based on local incidence rates and the population served by the PWS. Next we estimate how many of those are attributable to elevated drinking water nitrate using relative risk factors that correspond to the observed nitrate concentrations in the PWS. Finally, the disease cases attributable to elevated nitrate are monetarily valued using three techniques.

Our preliminary results show health impacts attributable to drinking water nitrate exposure include 51 adverse birth outcomes and 70 cases of cancer annually. Using the methods described in step 1 of this analysis (Figure 8), we estimated an annual average case count of all cancer types of 5,963. Despite being a small proportion of the total cancer cases, even the most conservative valuation methodology, direct medical costs, resulted in annual costs of $27.2 million. In contrast, the very commonly used value of a statistical life methodology produces estimates an order of magnitude higher, $256.6 million (Table 4). Of the diseases analyzed, colorectal cancer has the strongest link to elevated drinking water nitrate consumption in the epidemiological literature. Consequently, it is responsible for most cases, 39 annually, and highest annual costs, $137 million in our estimates (Table 4).

Table 4. Preliminary results of estimated annual disease and adverse birth case counts with three valuation techniques applied. Anencephaly is fatal at birth, resulting in no medical treatment costs. Thyroid cancer direct medical costs and data necessary for calculating adverse birth outcome quality adjusted life years were not available at the time of analysis. Further research is needed to better represent the underlying uncertainty and develop missing valuation techniques. All values adjusted for inflation to 2021 dollars. *Note the total excludes very preterm birth from total costs because these are highly correlated with low birth weight, however, both are included in the total case count.

Disease	Case count	Medical costs	Quality Adjusted Life Years	Value of a Statistical Life
Anencephaly	0.2			1,678,965
Spinabifida	0.5	322,606		601,741
Very low birth weight	30.1	8,663,286		21,169,152
Very preterm birth	20.7	7,457,095		13,119,672

Bladder cancer	0.2	27,464	66,173	579,012
Colorectal cancer	38.7	5,918,463	21,058,611	137,735,384
Kidney cancer	27.2	4,191,313	17,164,528	67,792,738
Ovarian cancer	2.7	628,387	2,510,934	13,824,115
Thyroid cancer	1.0		903,505	165,340
Total*	**121.2**	**27,208,614**	**41,703,752**	**256,666,119**

Our work also highlights the difficulty of attributing disease to exposure that can occur over decades. Rigorously estimating relative risk parameters, the key variable in the attribution method, is difficult to do in the face of numerous challenges: mobile populations whose lifetime nitrate exposure must be inferred, relatively rare maladies for which sufficiently large samples are not available, and mechanisms of nitrate metabolism that are sensitive to diet and other confounding factors. Our analysis used relative risk figures compiled in Mathewson et al.,[11] but our review of the epidemiological literature revealed that more research is needed to better characterize the uncertainty around the relative risks values that underpin this analysis. Future research will build on this work by incorporating simulations with a range of likely relative risk values informed by multiple studies weighted by their quality. Fully characterizing uncertainty would improve these results by representing them as a distribution of values weighted by likelihood, however, the health costs presented here are a useful starting estimate, and indicate that potential health damages may be significant if monetized.

2.3 Relative environmental benefit strengths of the DWSMA portfolio

Protecting source waters through adoption of best management practices, maintaining perennial cover, or protecting land from development has the potential to provide other environmental co-benefits, thus increasing the return on investment in protection activities. To assess the potential co-benefits of conservation or restoration activities within DWSMAs we mapped 19 unique spatial indicators representing a suite of environmental benefits. We applied the environmental benefit analysis at two scales; first analyzing all of the unbuilt land within DWSMAs as a single unit in comparison to unbuilt and unprotected land statewide, and second, by scoring all parcels within DWSMAs to facilitate comparisons between and within DWSMAs. We adapted methods developed over a decade of ecosystem services research in Minnesota and applied these methods for the first time to the context of source water protection.

Metrics were based on best-available ecological and social data and reflect the potential of land to deliver co-benefits. The metrics were designed to be applicable for either protection or restoration activities, so this analysis was applied to all unprotected and unbuilt land (i.e., it includes both natural vegetation and agriculture land covers). Environmental benefit scores range from 0 to 1. For binary metrics (trails, trout streams, and wild rice), 0 indicates a benefit is not provided by that land and 1 indicates it is. The remainder of the metrics are continuous, 0 indicates a benefit is not provided, low scores indicate lower potential to provide the benefit while scores near 1 indicate it is the best land in the state for that benefit. For example, land scoring higher on the co-benefit of lake recreation are those located within the catchment of lakes that also have public access and high visitation. Detailed explanations of co-benefits metrics are described in the 2021 report “Measuring what matters: Assessing the full suite of benefits of OHF investments”[21].

For the DWSMA level analysis, we reclassified the continuous metrics into binary maps where land received a score of 1 if it fell within the top quartile of land scores for that metric and a 0 if it was in a low-medium quality class, or outside of the area where the benefit is provided (e.g., lake recreation scores are 0 outside of the catchment of public lakes). Next, we calculated the proportion of highest quality class land for each metric within all DWSMAs and compared that to the proportion of high quality land found elsewhere in the state. If DWSMAs were no different than a random selection of land in the state then we assume that land protection or restoration in that DWSMA was no better than average (see Figures 9 and 10). However, if for example 22.5% of land within DWSMAs was in the highest quality class for pheasant habitat, but only 10% of the land statewide was in that class, the proportion for DWSMAs would be 125% that of the expected proportion in the state.

We found that unprotected and unbuilt land within DWSMAs scores higher than average on metrics of bird watching, pheasant habitat, and trail proximity relative to non-DWSMA land statewide. DWSMA lands scored lower for breeding habitat for forest, grassland, and wetland bird Species of Greatest Conservation Need (SGCN) (Figure 9). We also assessed metrics for risk of development, risk of conversion to agriculture, and nearby population. Methods for these metrics are documented in the aforementioned report[21]. The risk metrics are useful for targeting land with the greatest likelihood of conversion. The nearby population metric is important because it is an indicator of how accessible the environmental benefits land provides are to the public. DWSMAs are near more people, and the proportion of DWSMA area at high risk of development is nearly triple the proportion found statewide, likely due to their spatial correlation with population centers.

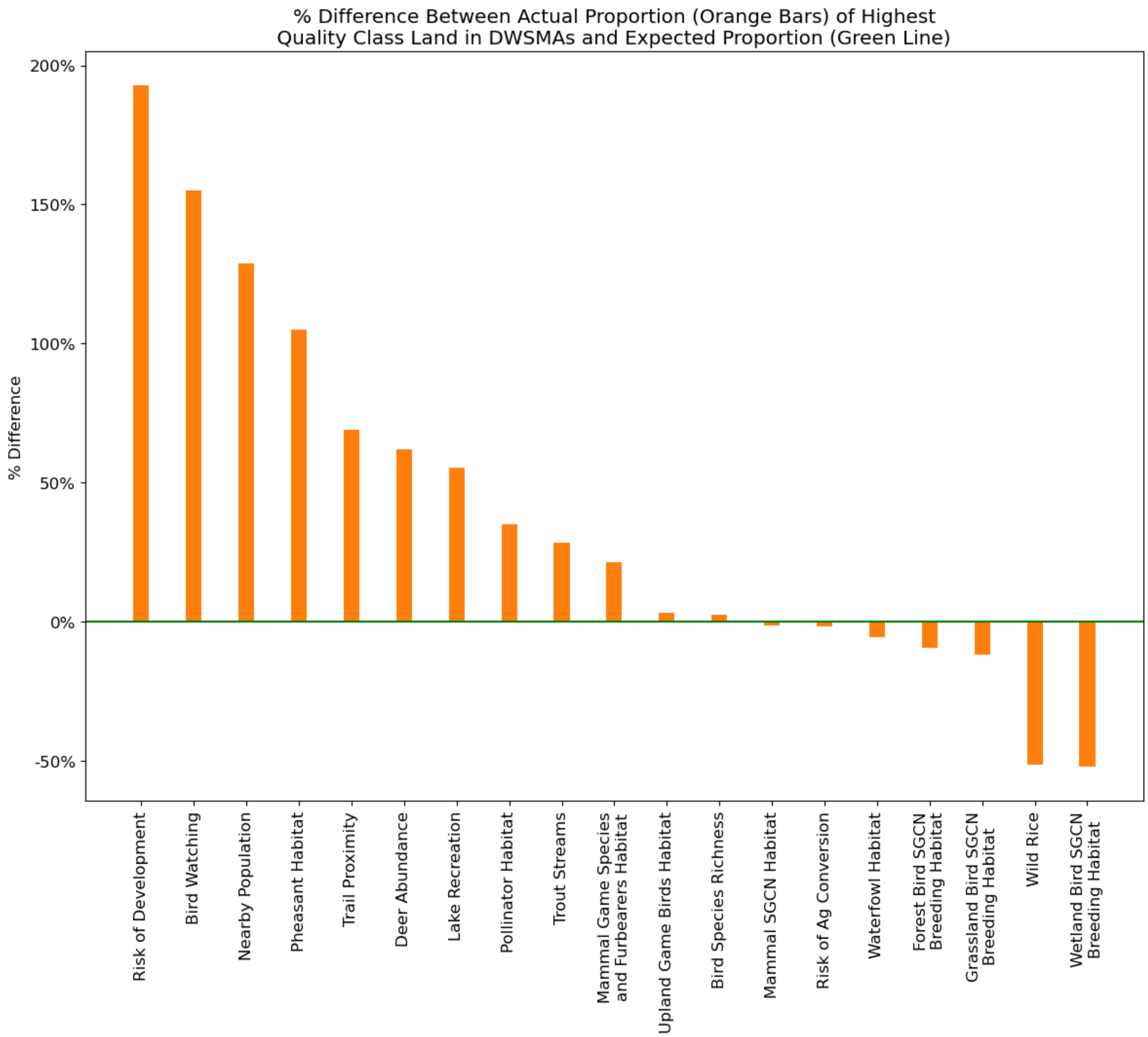

Figure 9. Comparison of the relative environmental benefit strengths of land in DWSMAs to the state. Analysis only applies to unprotected and unbuilt land. If the land in DWSMAs had the same proportions of highest quality class environmental benefits as are found in the rest of the state, the orange bars would be on the green 0% line. However, some benefits are more prevalent in DWSMAs (when the orange bars are positive) and some are less prevalent (when the orange bars are negative). The proportion of DWSMA area at high risk of development is nearly triple the proportion found statewide, and high quality pheasant habitat and bird watching are more prevalent than expected.

We applied the same analysis to the subset of High and Very High Vulnerability DWSMAs to identify co-benefits on the land most important for source water protection. Risk of development and nearby population were again the metrics that were disproportionately high in relative to the rest of the state (Figure 10). We found similar strengths of pheasant habitat and bird watching, and also found that metrics for lake recreation and trout streams were higher among High and Very High vulnerability DWSMAs than all DWSMAs and the state as a whole.

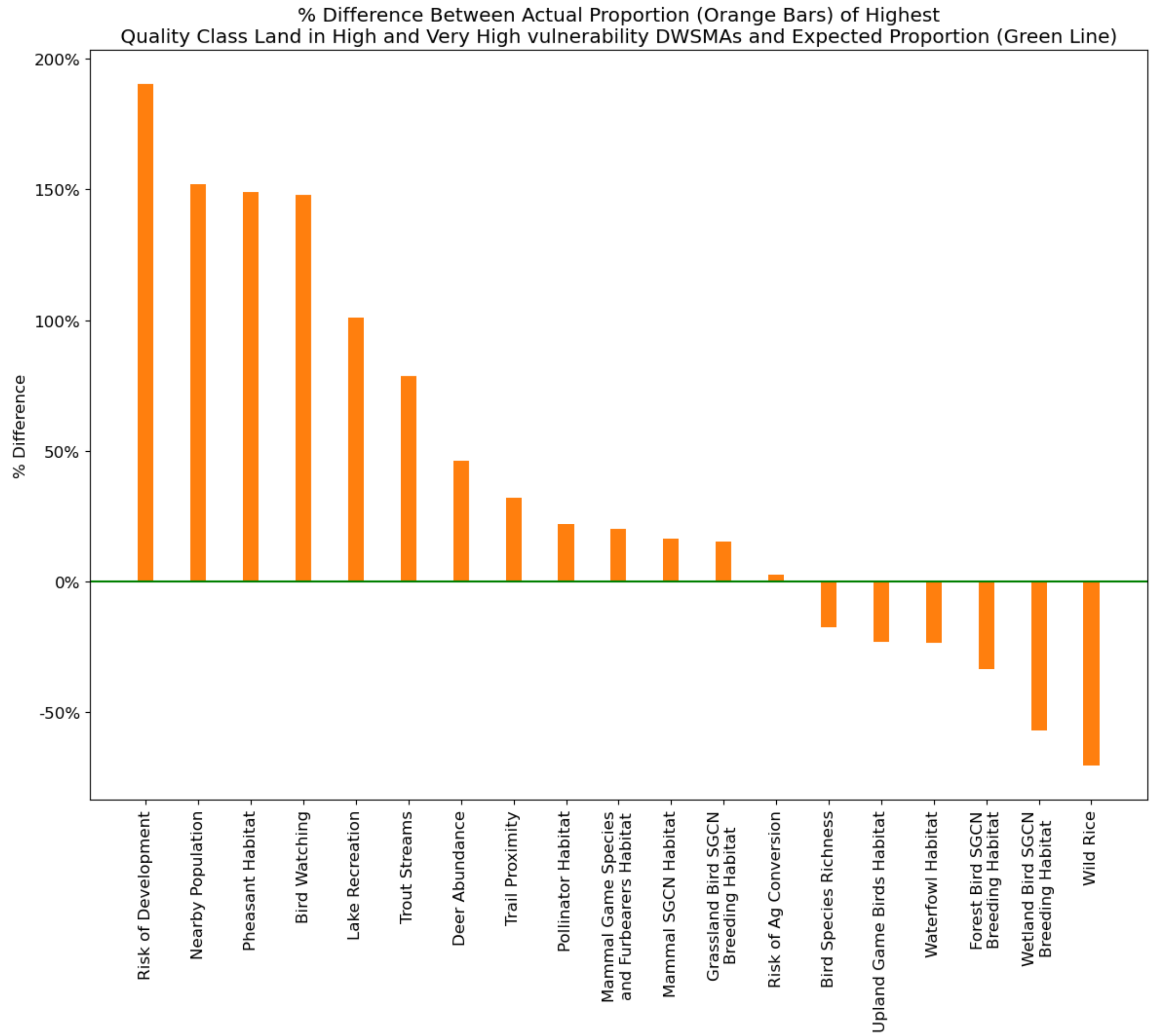

Figure 10. Comparison of the relative environmental benefit strengths of land in high and very high vulnerability DWSMAs to the state. See Figure 9 for detailed description of figure interpretation. The most disproportionately represented benefits are similar between DWSMAs and High and Very High vulnerability DWSMAs, however, note that the benefits are sorted in order from most represented to least represented, and the order is slightly different between the two figures.

Of the metrics in this analysis 12 of 19 were disproportionately found in DWSMAs compared to statewide. Four of those metrics (risk of development, nearby population, pheasant habitat, and bird watching) were more than twice as prevalent. High and Very High vulnerability DWSMAs performed similarly or slightly better than all DWSMAs with regards to number of benefits and magnitude of benefits represented. Metrics for wild rice, and breeding habitat for wetland bird species of greatest conservation need were under-represented in both of our DWSMA analyses. These benefits are still found within DWSMAs, just at a lower frequency than statewide. Given the high opportunity cost of protecting land, this analysis of co-benefit prevalence within DWSMAs is valuable for identifying partners to pursue multiple-benefit based source water protection strategies.

2.4 Parcel level attributes for screening and prioritization

The above figures and tables provide an overview of the costs and benefits associated with source water protection for all of the DWSMAs in the state. However, costs and benefits vary between and even within DWSMAs. Prioritizing areas with multiple benefits and a high return on investment requires higher resolution analysis. We scored over 30,000 Public Land Survey quarter-quarter section parcels (approximately 40 acres each) that overlap DWSMAs on the land cover, land value, and environmental co-benefits described above. The resulting table (Appendix C) can be sorted and filtered to identify parcels that score highly on any combination of our 19 environmental benefit metrics in addition to attributes such as land cover, land value, protection status, and DWSMA geologic vulnerability (Table 5). The table can also be joined to the included shapefile (Appendix D) for mapping and spatial analysis.

While all of the environmental benefit metrics are on a 0 to 1 scale, the scores are not comparable between metrics. Only comparisons between parcels for the same metric are appropriate. Because the underlying metrics are statewide maps, the highest scoring land may be located outside of the subset parcels that intersect with DWSMAs. This dataset is designed to facilitate comparison of relative environmental benefits of parcels within and between DWSMAs only.

Table 5. Definition of attributes and their source for parcel scores in Appendix C.

Column Name	Description	Source
forty_id	Unique identifier that corresponds to Appendix_D_parcel_shapefile.zip	Calculated
gis_acres	GIS calculated area of parcel in acres	Calculated
bird_sgcn_forest	Forest bird species of greatest conservation need habitat quality potential	Measuring what matters: Assessing the Full Suite of OHF investments (Appendix A)[21]
bird_sgcn_grassland	Grassland bird species of greatest conservation need habitat quality potential	
bird_sgcn_wetland	Wetland bird species of greatest conservation need habitat quality potential	
bird_species_richness	Bird species richness	
mammal_sgcn	Mammal species of greatest conservation need habitat quality potential	
pollination	Pollinator habitat quality	
bird_upland_game	Upland game bird species habitat quality potential	
pheasant	Pheasant habitat quality	
bird_waterfowl_game	Waterfowl species habitat quality potential	
mammal_fur+game	Mammal game and furbearer species habitat quality potential	

deer	Deer habitat quality potential	
bird_watching	Bird watching activity	
lake_rec	Lake recreation	
trails	Proportion of parcel within a 500m buffer of state trails	
wild_rice	Proportion of parcel within the catchment of a wild rice site	
population	Minnesotan population within 50 miles	
risk_of_dev	Risk of development (built land cover)	
risk_of_ag	Risk of conversion to agriculture	
trout_streams_bin	Proportion of parcel within catchment of a state designated trout stream	
dev-19	Proportion of parcel in developed (built and agriculture) land cover in 2019	National Land Cover Dataset[4]
undev-19	Proportion of parcel in undeveloped (natural vegetation and water) land cover in 2019	
ag-19	Proportion of parcel in agriculture (row crop and pasture/hay) in 2019	
built-19	Proportion of parcel in built (any intensity) land covers in 2019	
natveg-19	Proportion of parcel in natural vegetation (wetland, grassland, forest) in 2019	
water-19	Proportion of parcel with open water in 2019	
Very Low	Proportion of parcel with very low geologic vulnerability to contamination	Drinking Water Supply Management Areas[22]
Low	Proportion of parcel with low geologic vulnerability to contamination	
Moderate	Proportion of parcel with moderate geologic vulnerability to contamination	
High	Proportion of parcel with high geologic vulnerability to contamination	
Very High	Proportion of parcel with very high geologic vulnerability to contamination	
DWS_ID	The DWSMA ID of the highest vulnerability DWSMA the majority of the parcel falls within	
Avg Land Value per ha	Average value per hectare of parcel as modeled in Nolte 2020 (2021 USD)	Nolte (2020)[5]
Total Land Value	Total value of parcel as modeled in Nolte 2020 (2021 USD)	
Protected %	Proportion of parcel protected by a conservation program	Parcel Environmental Benefit Assessment Tool Expanded Documentation (Pages 5-7)[23]

In Table 6, a hypothetical example demonstrates how filters can be used to identify a small subset of parcels that meet the requirements of the user. This approach is useful if several interest groups are collaborating on a protection project that would be too large or expensive for any one of them individually. For example, in the Worthington Wells Wildlife Management Area, a partnership between Pheasants Forever, Worthington public utilities, and other local stakeholders resulted in the protection of high geologic vulnerability land within a DWSMA and high quality pheasant habitat[24]. By targeting parcels with multiple benefits, conservation practices can achieve a higher return of environmental benefits for their investment.

Table 6. Example of how filters can be used to screen for parcels that meet the users requirements. Each filter is applied to the output of the filter above it until the priorities of the user are satisfied and the number of parcels is reduced to a more manageable number for individual investigation. Parcels in all DWSMAs can be analyzed for statewide screening, or a subset from specific DWSMAs for targeted prioritization.

Filter	Number of parcels
Initial dataset	33,186
< 50% developed (built or ag)	6,051
Above average lake recreation score	1,488
Above average pheasant habitat score	233
Above average bird species richness score	118
Above average risk of development score	46
100% High or Very High geologic vulnerability	10
Average land value < $15,000 per hectare	5

3. Enabling assessment of equity in source water protection

Elevated costs for water treatment, higher incidence of disease, and reduced access to recreation amenities have the potential to disproportionately affect rural, low income, and traditionally underrepresented populations. We were interested in the distribution of source water contamination threats to different communities in Minnesota. Our work was also motivated by a need to include demographic and income data in prioritization exercises enabled by the co-benefits and land value analysis described above. If agencies and resource managers seek to target source water protection or restoration investments in DWSMAs that address water quality, environmental co-benefits, and environmental justice concerns, then new datasets would be needed to facilitate this analysis.

At the beginning of our work, there was no easy way to link census-based demographic data to DWSMAs or PWSs. Multiple DWSMAs may serve a single PWS, and census data at the block or tract-level cannot be joined to DWSMAs or PWSs using spatial intersection. Data for DWSMAs and PWSs were limited to estimates of population served and geologic vulnerability. Policy makers, practitioners, and the public are unable to assess if the benefits of protecting source water are equitably distributed if the data only represent the biophysical aspects of land and water protection.

We addressed this gap by manually correcting for mismatches between municipalities and PWSs and joining demographic attributes of populations served to PWSs. With indicators of social vulnerability available at the same management unit as water quality, we are enabling the inclusion of equity in source water protection decisions.

3.1 Demographic characteristics of Public Water Supplies

Despite a wealth of data on drinking water quality and management in the state, the complexity of the data often poses a challenge to analyzing multiple datasets simultaneously. For example, demographic data useful for identifying vulnerable populations is linked to municipalities, whereas DWSMAs correspond to the 10-year travel time for well fields. Connecting these management units allows practitioners to visualize where threats to drinking water quality and vulnerable populations co-occur.

To bridge this gap, we manually reviewed PWSs to identify those that serve a municipality and renamed them to match census records (e.g., ‘Blue Earth Light and Water’ to ‘Blue Earth’). We joined the resulting table to both the Minnesota Department of Health’s (MDH) records on drinking water nitrate[2], and a subset of U.S. census American Community Survey 2015-2019[25] demographic characteristics (Table 7).

Not all PWSs serve municipalities, many serve manufactured housing parks, colleges, prisons, and large businesses. For these, we include the demographic characteristics for the county of the PWS, along with the population served according to MDH records. For some non-municipal PWSs, the demographic characteristics of the county will be of limited use (e.g., age distribution for a county is likely not representative of the population served by a college). PWSs may also serve multiple municipalities, or only serve a subset of the population of a municipality. Demographic data should be interpreted carefully in this context and cross-referenced with population served estimates from MDH.

Demographic characteristics that we joined to PWSs are described in Table 7, and the full dataset is included as Appendix A. Appendix A can be joined to the MDH DWSMA shapefile on the ‘pwsId’ field for spatial analysis or analyzed in tabular format. Note that if a one-to-one join is desired, the DWSMA layer should be dissolved on the 'pwsId' first. Entries with a 'join_type' of 'municipal' indicate a PWS that joined to census municipality data, while entries labeled as 'county' indicate a PWS that is either not a municipality or did not have a name that matched a census municipality and is joined to census county data.

Table 7. Definition of values in each column and their source for appendix of public water supply demographic characteristics. Light grey rows indicate the attribute is only available if the PWS has one or more associated DWSMAs. DWSMAs are continuously being delineated, so not all PWSs have had theirs delineated yet. Dark grey rows indicate the variable is only available when a PWS is joined to census municipality data.

Column Name	**Column description**	**Source**
pwsId	MDH Public Water Supply ID	Minnesota Department of Health[2]
pwsNameRecent	Most Recent PWS Name	
county	County of PWS	
waterSource	Surface or Groundwater	
max_2010to2020	All time highest N concentration 2010 to 2020	
mean_2010to2020	Average of all N concentration readings 2010 to 2020	
MDH_pop	MDH estimate of population served	
AreaName	Municipality name (in census)	U.S. Census American Community Survey 2015-2019 5-year average[25]
geoid	census geographic ID	
census_pop	Total population from census data	
pctAge0_4	% Age 0 to 4	
pctAge5_9	% Age 5 to 9	
pctAge10_14	% Age 10 to 14	
pctAge15_19	% Age 15 to 19	
pctAge20_24	% Age 20 to 24	
pctAge25_34	% Age 25 to 34	
pctAge35_44	% Age 35 to 44	
pctAge45_54	% Age 45 to 54	
pctAge55_59	% Age 55 to 59	
pctAge60_64	% Age 60 to 64	
pctAge65_74	% Age 65 to 74	
pctAge75_84	% Age 75 to 84	
pctOver85	% Over 85	
MedianAge	Median age in years	
pctWomenGivingBirth	% Women 15 to 50 years old who had a birth in the past 12 months	
pctWhite1	% White alone	
pctBlack1	% Black or African American	
pctIndian1	% American Indian and Alaska Native	
pctAsian1	% Asian	

pctHawnPI1	% Native Hawaiian and Other Pacific Islander	
pctOther1	% Some other race	
pctHispanicPop	% Hispanic or Latino of any race	
pctMultiRace	% Two or more races	
MedianHHInc	Median household income	
pctPoor	% Persons below poverty	
pctCashRenterOver30Pct	% Gross rent 30% or more of HH income	
pctHUsMortOver30Pct	% Owner costs 30% or more of HH income	
pctNoVehicles	% No vehicles available	
RO_low_cost	Estimated low total cost for reverse osmosis filtration based on population served	Calculated based on Jensen et al. (2012)[6]
RO_average_cost	Estimated average total cost for reverse osmosis filtration based on population served	
RO_high_cost	Estimated high total cost for reverse osmosis filtration based on population served	
join_type	Indicates if the PWS is joined to 'municipal' or 'county' census data. Exercise caution when interpreting demographic characteristics from the county as the PWS may serve a non-representative sample (e.g, prisons, schools, manufactured housing parks, or companies).	Calculated
dev-19	Proportion of PWS DWSMA area in developed (built and agriculture) land cover in 2019	National Land Cover Dataset[4]
undev-19	Proportion of PWS DWSMA area in undeveloped (natural vegetation and water) land cover in 2019	
ag-19	Proportion of PWS DWSMA area in agriculture (row crop and pasture/hay) in 2019	
built-19	Proportion of PWS DWSMA area in built (any intensity) land covers in 2019	
natveg-19	Proportion of PWS DWSMA area in natural vegetation (wetland, grassland, forest) in 2019	
water-19	Proportion of parcel with open water in 2019	
Very Low	Proportion of PWS DWSMA area very low geologic vulnerability	Drinking Water Supply Management Areas[22]
Low	Proportion of PWS DWSMA area geologic vulnerability	
Moderate	Proportion of PWS DWSMA area geologic vulnerability	
High	Proportion of PWS DWSMA area high geologic vulnerability	
Very High	Proportion of PWS DWSMA area with very high geologic vulnerability	

Avg Land Value per ha	Average value of PWS DWSMA land as modeled in Nolte 2020 (2021 USD)	High-resolution land value maps reveal underestimation of conservation costs in the United States (2020)[5]
Protected %	Proportion of PWS DWSMA area protected by a conservation program	Parcel Environmental Benefit Assessment Tool Expanded Documentation[23]

3.2 Public water supply nitrate concentrations and demographic characteristics

In Figure 11, we demonstrate the only social vulnerability analysis that can be performed with data directly from the MDH Public Health Data Access: Drinking Water Query tool[2]. We plotted the population served against the average of all nitrate concentration readings for a PWS, to show where a PWS that serves a small population has elevated drinking water N. That combination has the potential to create a disproportionate burden on rate-payers because the large capital costs of installing additional water treatment is distributed among a small group of people relative to a larger PWS.

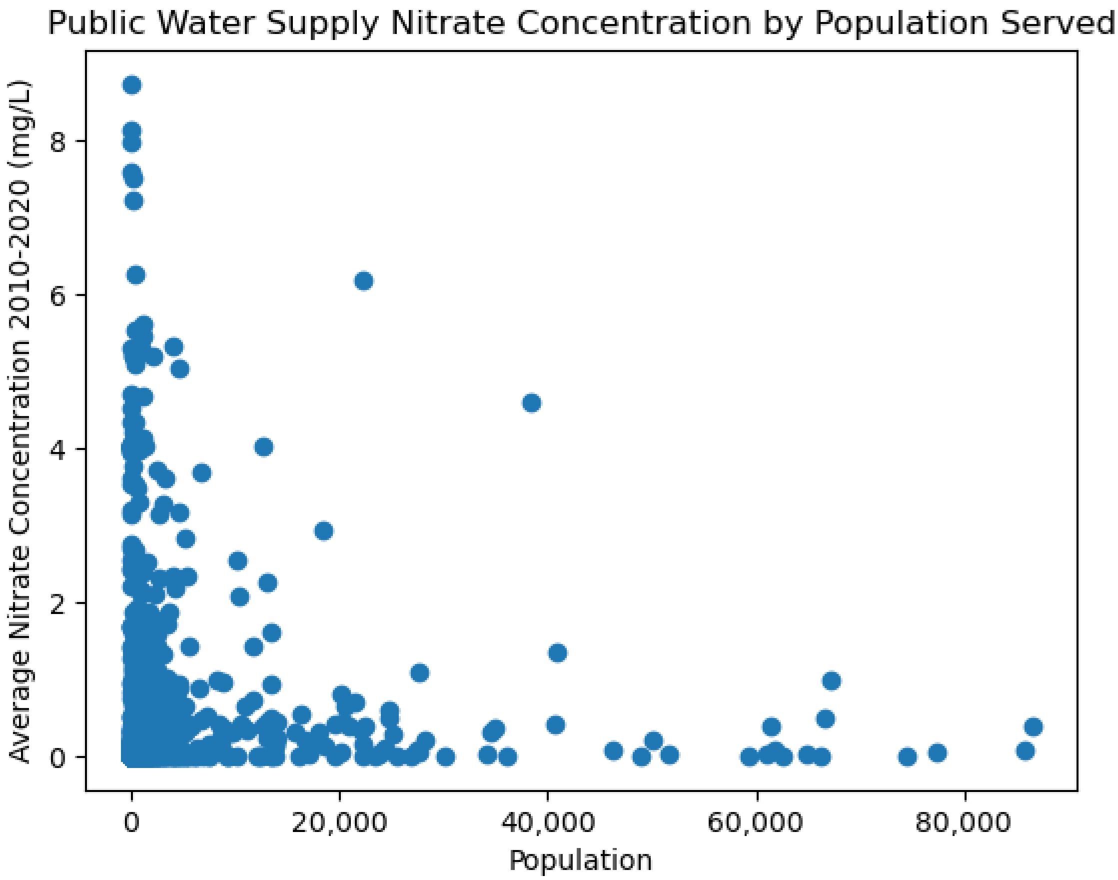

Figure 11. Plot of PWS average drinking water nitrate concentration and the size of the population it serves. The points in this figure represent all municipal and non-municipal public water supplies in the state, and use the MDH's estimate of population served. It shows that the public water supplies with the greatest nitrate contamination serve the fewest people, resulting in a higher individual cost for treatment upgrades.

With joins between water quality data from MDH and census demographic characteristics, it is possible to go beyond population size and analyze how the concentration of drinking water nitrate varied with other measures of social vulnerability. For example Figure 12 shows the relationship between drinking water nitrate concentration and median household income. Municipalities in the lower quartile for median household income had a higher proportion of elevated nitrate than higher income municipalities. Demographic characteristics or combinations of characteristics in Table 7 such as household income or percent of people whose rent is > 30% of their household income provide a more meaningful measure of the burden of increased drinking water treatment costs than population served alone. The attributes in Appendix A create the foundation to analyze and explore relationships between multiple indicators of social vulnerability in source water protection planning.

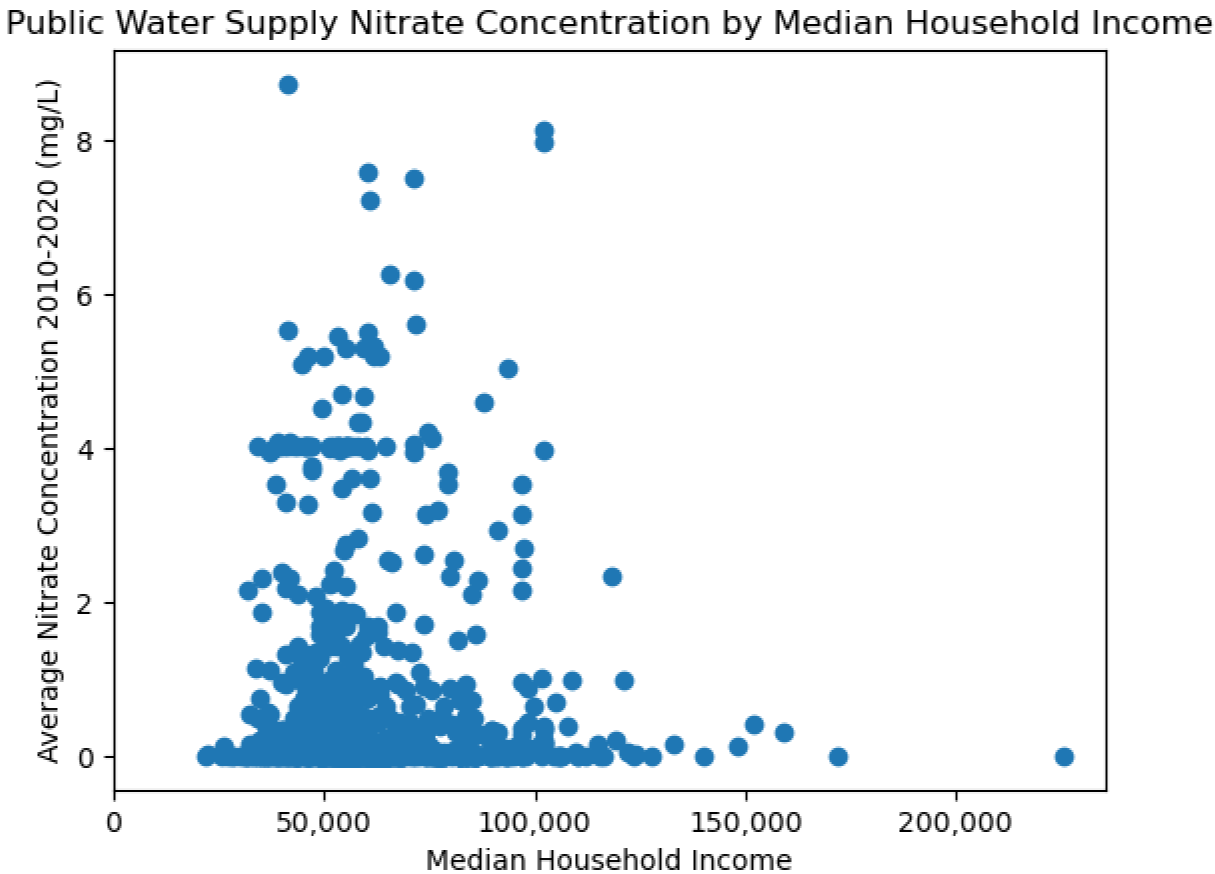

Figure 12. The points in this figure are limited to only municipal public water supplies that matched a municipality in census data, meaning that it excludes smaller public water supplies such as manufactured housing parks. While most PWS did not have elevated drinking water nitrate, those that did tended to be in the lower quartile for median household income.

4. Synthesis and future work

The analyses in this report describe the threats, costs, benefits, and distributional impacts that should be considered in source water protection activities. Our study is the first to combine data on these four topics for every DWSMA in Minnesota.

Threats

Our land use change analysis showed natural vegetation land covers that protect water quality are already less than 20% of total DWSMA area, and have declined slightly since 2001. Despite a period of record high crop prices, agricultural land area in DWMSAs declined over the last 20 years as built area expanded (Figure 2). However, agriculture remains the dominant land cover in High and Very High vulnerability DWSMAs (Figure 3). Mapping the distribution of DWSMAs with the elevated loss of natural vegetation shows this trend is occurring in all regions of the state, with a concentration in the metro area. In addition to observed land use change, we also modeled the risk of future development at the DWSMA level. We found that DWSMAs' proximity to population centers resulted in a proportion of land at high risk for development triple that of the statewide proportion.

Costs

The competition among land uses and proximity to population centers creates high opportunity costs for protection activities. We used a novel dataset to summarize the value of land at the parcel level in all DWSMAs. In total, the value of unprotected and unbuilt land is $8.8 billion (Figure 6). An investment of $100 million would be enough to acquire 15% of the least expensive, most vulnerable land (Figure 7). However, that strategy is unlikely to produce sufficient and equitable protection across all DWSMAs. The high cost of land requires consideration of the multiple benefits protection activities produce in order to prioritize investments with the highest return on investment.

Benefits

Preventing contamination of drinking water is associated with multiple benefits not in the form of avoided treatment costs or in avoided health damages associated with consumption of contaminated water. In this report, we applied previous research on monetary valuation techniques of topics to individual PWSs and the DWSMAs that supply them for the first time. Treatment costs for only PWSs with elevated nitrate ranged from $9.8 to $47.5 million annually (Table 3). Annual health costs from cancer and adverse birth outcomes ranged from $26.2 to $256.6 million depending on the valuation approach used (Table 4).

We also assessed potential co-benefits of source water protection in the form of habitat conservation, recreation, and other public goods using a non-monetary prioritization technique. This approach identifies the strength of DWSMAs for contributing to environmental benefits beyond drinking water quality, relative to the rest of the state. We found that DWSMAs have a disproportionate amount of high quality pheasant habitat, bird watching activity, proximity to trails, and deer abundance, among others (Figure 9). This analysis, which we also summarized at the parcel level, can be used to develop coalitions of interest groups to engage in source water protection targeting multiple benefits.

Distributional impacts

The benefits of source water protection have the potential to be inequitably distributed, resulting in high costs for vulnerable populations served by some PWSs. We addressed a limitation of PWS level data by creating a workflow to join census demographic data to PWSs. This analysis enabled us to visualize the relationship between drinking water nitrate concentrations and indicators of vulnerability such as median household income. We found that although most PWSs don't have elevated drinking water nitrate, those that do tend to be smaller and in the lower quartile for median household income. These variables can be used to both identify where PWSs serve vulnerable populations and ensure investments are equitably distributed between PWSs.

Contributions to future work

Our analysis integrated across several ongoing research efforts, and highlighted areas where future work was most needed to address remaining challenges. We anticipate building on the work presented here and pursuing new research in the following areas:

Characterizing uncertainty in drinking water nitrate health damages functions:
Our demographic join enabled us to create estimates of drinking water nitrate-related health damages at local scales. However, further work is required to represent the uncertainty in exposure and relative risk parameters.

Land use change prediction:
We improved on quantifying changes in land use change in DWSMAs using recent advances in the NLCD, and implemented a risk of development indicator at the parcel level. While these techniques are useful for quantifying threats from changing land use, we intend to improve on their respective strengths to better estimate both the quantity and location of land use change.

Integration of quantitative and qualitative methods for valuing water resources:
We are exploring the integration of the quantitative data on costs and benefits presented here with new research using deliberative and participatory methods of value elicitation, governance and institutional assessments related to groundwater, case studies in specific DWSMAs, and evaluation of alternative scenarios to protect water quality and multiple ecosystem services given budgetary constraints.

Coordination and data-sharing with state agencies:
While carrying out this research we observed numerous opportunities for collaboration with state agencies on the intersection between source water protection and topics such as climate change, watershed planning, nutrient modeling and the integration of source water protection benefits into policy. We will continue to engage with state agencies to ensure future research efforts complement and enhance their work.

Our work demonstrated that opportunity costs of protection of source water protection are high, but not insurmountable when compared to the value of its multiple benefit streams. Analysis at multiple scales, from statewide prioritization to parcel level comparisons are needed to identify where source water protection has a positive and equitable return on investment. The datasets included with this report on PWS level demographic characteristics and treatment costs, DWSMA level land use change trends, and parcel level environmental co-benefits and land value, provide foundational decision support data for weighing the threats to source water, costs and benefits of interventions, and the equity of outcomes.

5. Acknowledgements

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We are grateful to Humphrey School of Public Affairs Graduate Research Assistants; Sean Cullen, Conor Mckenzie, John Seng, and Maddie Hansen-Connell, along with Senior Scientist Christina Locke for their research contributions to this report. We thank MDH Drinking Water Protection Planning Director Tannie Eshenaur for her guidance and feedback throughout the research process.

6. References

1. Minnesota Department of Health. Requirements and Recommendations for Public Water Suppliers. https://www.health.state.mn.us/communities/environment/water/swp/reqrec.html#Wellhead (2021).

2. Minnesota Department of Health. Minnesota Public Health Data Access: Drinking Water Query. https://data.web.health.state.mn.us/web/mndata/drinkingwater_query (2021).

3. Liess, S. *et al. High-resolution Climate Projections over Minnesota for the 21st Century*. http://www.essoar.org/doi/10.1002/essoar.10507340.2 (2021) doi:10.1002/essoar.10507340.2.

4. Jin, S. *et al.* Overall Methodology Design for the United States National Land Cover Database 2016 Products. *Remote Sensing* **11**, 2971 (2019).

5. Nolte, C. High-resolution land value maps reveal underestimation of conservation costs in the United States. *Proc Natl Acad Sci USA* **117**, 29577–29583 (2020).

6. Jensen, V. B., Darby, J. L. & Seidel, C. *Technical Report 6: Drinking Water Treatment for Nitrate*. 198 https://groundwaternitrate.ucdavis.edu/files/139107.pdf (2012).

7. Environmental Quality Board. *Beyond the Status Quo: 2015 EQB Water Policy Report*. https://www.eqb.state.mn.us/sites/default/files/documents/WaterReport_091515_v2_0.pdf (2015).

8. Keiser, D. A., Kling, C. L. & Shapiro, J. S. The low but uncertain measured benefits of US water quality policy. *Proc Natl Acad Sci USA* **116**, 5262–5269 (2019).

9. Ward, M. H. *et al.* Workgroup Report: Drinking-Water Nitrate and Health—Recent Findings and Research Needs. *Environ Health Perspect* **113**, 1607–1614 (2005).

10. Ward, M. *et al.* Drinking Water Nitrate and Human Health: An Updated Review. *IJERPH* **15**, 1557 (2018).

11. Mathewson, P. D., Evans, S., Byrnes, T., Joos, A. & Naidenko, O. V. Health and economic impact of nitrate pollution in drinking water: a Wisconsin case study. *Environ Monit Assess* **192**, 724 (2020).

12. Temkin, A., Evans, S., Manidis, T., Campbell, C. & Naidenko, O. V. Exposure-based assessment and economic valuation of adverse birth outcomes and cancer risk due to nitrate in United States drinking water. *Environmental Research* **176**, 108442 (2019).

13. van Grinsven, H. J., Rabl, A. & de Kok, T. M. Estimation of incidence and social cost of colon cancer due to nitrate in drinking water in the EU: a tentative cost-benefit assessment. *Environ Health* **9**, 58 (2010).

14. Minnesota Department of Health. Cancer query - MN Data. https://data.web.health.state.mn.us/cancer_query.

15. United States Department of Health and Human Services, Centers for Disease Control and Prevention, & National Cancer Institute. National Program of Cancer Registries and Surveillance,

Epidemiology, and End Results SEER*Stat Database (2001-2018). (2020).

16. Peristats. National Center for Health Statistics, final natality data. www.marchofdimes.org/peristats.

17. Mariotto, A. B., Robin Yabroff, K., Shao, Y., Feuer, E. J. & Brown, M. L. Projections of the Cost of Cancer Care in the United States: 2010–2020. *JNCI: Journal of the National Cancer Institute* **103**, 117–128 (2011).

18. Grosse, S. D., Berry, R. J., Mick Tilford, J., Kucik, J. E. & Waitzman, N. J. Retrospective Assessment of Cost Savings From Prevention: Folic Acid Fortification and Spina Bifida in the U.S. *American Journal of Preventive Medicine* **50**, S74–S80 (2016).

19. Gourevitch, J. D., Keeler, B. L. & Ricketts, T. H. Determining socially optimal rates of nitrogen fertilizer application. *Agriculture, Ecosystems & Environment* **254**, 292–299 (2018).

20. Desaigues, B. *et al.* Economic valuation of air pollution mortality: A 9-country contingent valuation survey of value of a life year (VOLY). *Ecological Indicators* **11**, 902–910 (2011).

21. Noe, R. *et al. Measuring what matters: Assessing the full suite of benefits of OHF investments*. https://hdl.handle.net/11299/220181 (2021).

22. Minnesota Department of Health. Drinking Water Supply Management Areas. (2021).

23. Noe, R. *et al. Parcel Environmental Benefit Assessment Tool Expanded Documentation*. https://z.umn.edu/pebat-documentation (2018).

24. Wiklund, J. New Worthington Wells Wildlife Management Area Highlighted at Minn. Governor's Pheasant Opener. https://www.pheasantsforever.org/Newsroom/2014-October/New-Worthington-Wells-Wildlife-Management-Area-Hig.aspx (2014).

25. U.S. Census Bureau. Dexter: Data Extracter Tool - Missouri Census Data Center. *American Community Survey 5-year Estimates 2015-2019* https://mcdc.missouri.edu/cgi-bin/broker?_PROGRAM=utils.uex2dex.sas&path=/pub/data/acs2019&dset=usplaces5yr&view=0 (2020).

7. Appendices index

Appendix A: PWS land use and demographics

File name: Appendix_A_PWS_attributes.csv

Description: This .csv file contains data that can be analyzed independently or joined to a DWSMA shapefile (typically the user will want to dissolve the DWSMA shapefile on the 'pwsId' field prior to joining). This file contains attributes on the demographics of populations served by PWS, nitrate concentrations, estimated treatment costs of reverse osmosis, and aggregated geologic vulnerability, land value, land cover, and protected area of the DWSMAs that serve a PWS. See Table 7 for descriptions of all attributes.

Appendix B: DWSMA land use trends

File name: Appendix_B_land_use_trends.xlsx

Description: This .xlsx spreadsheet file contains data on land cover for every DWSMA disaggregated by vulnerability class for 2001 to 2019. The data are stored in a pivot table, so the user can select subsets of DWSMAs and automatically create a visualization and summary statistics of land use trends.

Appendix C: Parcel environmental benefits and land use table

File name: Appendix_C_parcel_scores.csv

Description: This .csv file contains data that can be analyzed independently or joined to Appendix D. This file contains attributes on the environmental benefits, geologic vulnerability, land value, land cover, and protected area of the parcels within DWSMAs. See Table 5 for descriptions of all attributes.

Appendix D: Parcel environmental benefits and land use shapefile

File name: Appendix_D_parcel_shapefile.zip

Description: This .shp shapefile contains a subset of Public Land Survey quarter-quarter section parcels (commonly referred to as forties because they are approximately 40 acres each) that intersect with DWSMAs. Users that want to map the data found in Appendix C should join it to this file on 'forty_id'.

COMMUNICATING RISK AND INCREASING CIVIC ENGAGEMENT IN WATER PROTECTION IN MINNESOTA

A Thesis
SUBMITTED TO THE FACULTY OF
THE UNIVERSITY OF MINNESOTA
BY

Amelia Laura Kreiter

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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MASTER OF SCIENCE

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ABSTRACT

Forty percent of Minnesota lakes and rivers are classified as "impaired bodies." The extent of water problems is far-reaching; each of Minnesota's 87 counties has an impaired river, lake, or stream. Despite the magnitude of Minnesota's water problems, water protection and restoration initiatives primarily have been agency-driven and technology-centered. Though new programs are touting a more collaborative watershed management approach, true civic engagement is needed to identify and solve water issues that span multiple jurisdictions and land uses. Engaging residents in water protection increases the success of a project, builds trust between residents and local agencies, and sets future projects up for greater public support. Despite all these benefits, the question of how to get residents involved in water management persists. Minnesotans value clean water and water provides multiple cultural services on which residents depend. Given these water values and benefits, how do residents perceive water in the state? Do perceptions of water quality and beliefs about water problems influence civic engagement in water? Using an integrated model of the Risk Information Seeking and Processing framework and Norm Activation Theory, I analyze data collected through a statewide survey of Minnesota residents to determine the influence of perceptions of water risk, experience with water, perceived information sufficiency, self-efficacy, socio-demographics, and social and personal norms on civic engagement in water. The integrated model explained 24% of variance in civic engagement in Minnesota residents, with information sufficiency and relevant water experience being the strongest predictors. This suggests that residents may need a stronger personal connection to water issues to get involved in protection efforts. Study findings will help to inform future outreach and risk communication strategies to develop pro-environmental behaviors in Minnesota residents.

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CHAPTER 1

INTRODUCTION

Water quality has long been a challenge for policy makers, resource managers, and agricultural producers across the United States. Traditional top-down agency approaches have come under increasing scrutiny as the complexity of water problems has become clearer. Collaborative watershed management was developed in response to the widespread, far-reaching problem of water issues in the United States. In the past, remediation efforts have been directed towards point-source discharges into water bodies, resulting in legislation such as the Clean Water Act (1972). However, water quality issues in the United States have since revealed themselves to be much more complex. An agricultural pollutant in the northern United States can be picked up in surface runoff and carried hundreds of miles across the landscape to ultimately arrive in the Gulf of Mexico.

Minnesota, despite being the headwaters of three major watersheds (the Mississippi, Great Lakes, and Red River watersheds), is not immune to these water problems. Forty percent of assessed Minnesota lakes and rivers are classified by the Minnesota Pollution Control Agency as “impaired bodies,” and an estimated 86% of the state’s water pollution stems from widely dispersed sources (MPCA, 2018a, 2018b). The extent of Minnesota’s water problems is far-reaching; each of Minnesota’s 87 counties has an impaired river, lake, or stream (MPCA, 2018a).

Assuming it were possible to identify all sources of a lake’s impairments, remediation is still complicated. Seventy-five percent of Minnesota’s land area is privately owned and jurisdiction over land uses is complex. An impaired lake in

Minneapolis, for example, could be under the jurisdiction of the City of Minneapolis, Hennepin County, the Department of Natural Resources, a local Soil and Water Conservation District, a local watershed district or the Minnesota Pollution Control Agency. While all state and local agencies have the common goal of clean water, their priorities for clean water vary, they often lack coordination and attempts to inspire meaningful community engagement have fell short. . In addition, current management efforts are likely to be focused on a solution for a particular water body, rather than broadly looking at the watershed-level stressors.

Collaborative watershed management examines all sources and solutions within a watershed. Collaborative watershed management and its key tenet, civic engagement, allows for a bottom-up approach that includes residents throughout the process, rather than solely asking for their opinions after all policies and rules have been drafted. In this process, residents are treated not only as consumers of water resources, but also as environmental managers whose decisions have significant direct or indirect impacts on the environment (Morton & Brown, 2011; Sabatier et al., 2005). Engaging residents in water protection has proven to increase the success of a project and build trust between residents and agencies to set up future projects for greater support (Prokopy & Floress, 2011).

This study examines how perceptions of water problems in Minnesota and experiences with water influence residents' engagement in water protection. Many past studies have examined who gets involved in environmental and water protection, but fewer have examined why they get involved. By integrating Griffin, Dunwoody, and Neuwirth's Risk Information Seeking and Processing model (RISP) and Schwartz's Norm Activation Theory (NAT), this study examines how information about water issues, experience with water, perceptions of threats to water, social and personal norms, self-efficacy, and sociodemographics impact civic engagement in water.

Study data were gathered using a statewide resident survey. The survey was administered via an 8-page, 25-item mail survey, and was sent to a geographically stratified random sample of 6000 Minnesota residents. The questionnaire included a variety of fixed-choice and scale questions that asked about residents' community, concerns about water, water protection, and sociodemographic information.

The overarching goal of this study was to answer the following questions:

1. What drives perceptions of water and water problems?
    a. Where do people get water information?
    b. Who or what influences them?
    c. Do sociodemographics matter?
2. How do perceptions of water quality and beliefs about problems affect civic engagement in water?

The survey instrument was developed with the goals of two broader research projects in mind. The first, funded by the Minnesota Clean Water Council, seeks to understand the true value of clean water to better account for the benefits of Clean Water Fund investments. The second, funded through the Environment and Natural Resources Trust Fund, asks the question "what are the public benefits of protecting sourcewater?" and similarly seeks to understand the value of clean water and community capacity to protect sourcewater in Minnesota.

This study contributes broadly to the body of knowledge around environmental decision making and pro-environmental behavior, and specifically to emerging theory related to the drivers of civic engagement in conservation and water protection. Findings point to opportunities for agencies and resource managers to enhance communication and outreach programming in Minnesota communities. Understanding where Minnesotans get water information and how they are influenced by it, will inform and improve community engagement. This thesis is organized into three chapters. This, the first chapter, provides an overview of the study. The second chapter details study methodology and results. Chapter two is presented as a standalone manuscript intended for submission to peer-reviewed journal. The final chapter concludes with a discussion of study findings, practical implications, theoretical implications, and areas for further research.

CHAPTER 2

COMMUNICATING RISK AND INCREASING CIVIC ENGAGEMENT IN WATER PROTECTION IN MINNESOTA

Introduction

Forty percent of U.S. water bodies are impaired for human uses such as swimming or fishing (Environmental Protection Agency, 1996). Similarly, in the “Land of 10,00 Lakes”, forty percent of assessed Minnesota lakes and rivers are classified by the Minnesota Pollution Control Agency as “impaired bodies,” and an estimated 86% of the state’s water pollution stems from widely dispersed, or non-point sources (MPCA, 2018a, 2018b). The extent of Minnesota’s water problems is far-reaching; each of Minnesota’s 87 counties has an impaired river, lake, or stream (MPCA, 2018a).

The problem of water pollution in the United States is widespread. The United States has invested in reducing point source pollution from industrial and agricultural sources with much success. However, states report that nonpoint source pollution, from widely dispersed sources (Environmental Protection Agency, 2018)) is the leading cause of water body impairments (Environmental Protection Agency, 2017, 2018). These impairments have impacts on human health, wildlife, recreation, and aquatic life.

Water protection and restoration initiatives in Minnesota, like many states, primarily have been top-down or agency-driven and characterized by technical solutions that focus on water pollution in a particular stream segment or lake (Sabatier et al., 2005). Sabatier and colleagues’ text on collaborative watershed management provides insights and critiques on traditional water protection solutions, and argues that technical solutions for water protection and restoration often do not capture the full extent of water problems. Water problems or consequences typically do not align with jurisdictional boundaries, and the full scope of the state's water pollution is not captured in agency strategies that target one county or water body (MPCA, 2018b). Water problems affect Minnesota residents and visitors in multiple ways and identifying or isolating threats to human well-being and community health is complicated. While new programs exist that integrate a more collaborative approach, engagement with local communities is still needed to identify and solve all parts of the issue. Engaging residents in water protection has proven to increase the success of a project and build trust between residents and agencies to set up future projects for greater support.

The most comprehensive way to ensure that all sources and impacts are being addressed is collaborative watershed management, which examines all sources and solutions to an impairment within a watershed (Sabatier et al., 2005). Engaging with the community to identify and solve local water issues is key in this process. Residents are treated not only as a consumer of the resource, but also as a land manager whose decisions make an impact on the environment (Morton & Brown, 2011; Sabatier et al., 2005). The traditional approach involves agencies proposing and stakeholders voting on a rule or policy. The collaborative approach allows stakeholders to be involved in the proposal design and policy development process (Leach, 2006; Michaels, 2001; Sabatier et al., 2005). This approach also integrates civic engagement, or decision-making and collective action through citizen participation rather than authority or political weight (Fagotto & Fung, 2009).

Minnesota residents have proven that water quality and natural resources are important to their lifestyles. The Clean Water, Land, and Legacy Amendment passed by Minnesotans is used for water restoration and protection activities throughout the state

(Clean Water, Land, and Legacy Amendment, 2008). However, the role of civic engagement in this plan is limited. The Amendment includes the Social Measures Monitoring System (SMSS), with the goal of improving public participation and engagement, but there have been no sustained efforts to evaluate community outcomes and little social information has been gathered since the implementation of the SMSS (Clean Water Land & Legacy Amendment, 2018). Other strategies to get Minnesota residents engaged in water protection have been marginally more successful. For example, Governor Mark Dayton's "25 by 25" Water Quality Goal engaged residents throughout the state in a series of town halls to evaluate top concerns and improvement strategies related to water quality. Minnesotans proved again that clean water is important to them and impacts all parts of their lives, from business to recreation to human health. However, while residents' needs and priorities have been identified, there has been little initiative to engage them further (Dayton, 2017).

Many Minnesota residents are unaware of impairments or threats to water in their local communities, despite their overarching support for water resource protection (Davenport, Perry, Pradhananga, & Shepard, 2016). Moreover, research suggests that while residents may adopt certain water conservation behaviors individually, they are unlikely to talk to their neighbors or other members of the community about water issues (A. K. Pradhananga, Davenport, & Olson, 2015). In this study, I examine what drives and constrains civic engagement in Minnesota in collaborative watershed management. Studies have found that multiple cultural, institutional and physical barriers exist (A. K. Pradhananga, Davenport, & Green, 2019), as well as psychological barriers like motivations to engage (A. K. Pradhananga et al., 2019, 2015). Here I explore motivations to engage civically and in particular risk perceptions as a driver of civic engagement. Do perceptions of water or experiences with water affect water-related behaviors, including civic engagement in water? In this study, I examine Minnesota residents' perceptions of water and the influence of perceptions on their engagement in clean water actions. Specifically I ask, how do perceptions of water quality and beliefs about water problems affect a resident's engagement in civic water actions and initiatives? Data for this study were gathered through a statewide Minnesota resident survey.

Related Literature

What is civic engagement and how does it affect water management?

Fagotto and Fung (2009) define civic engagement as "making public decisions and taking collective actions through processes that involve discussion, reasoning, and citizen participation rather than through the exercise of authority, expertise, status, political weight, or other such forms of power." In collaborative watershed management, civic engagement takes the form of a face-to-face exchange of information and problem solving that includes community stakeholders and decision-makers to come up with creative, win-win solutions to this complex problem (Koontz & Newig, 2014; Sabatier et al., 2005). Engaging a community can be more time-consuming than the traditional approach of drafting and voting on a policy, there are countless benefits that may ultimately increase a project's likelihood of success (Michaels, 2001; Prokopy & Floress, 2011; Sabatier et al., 2005).

While it may challenging for local decision-makers to give up their power to citizen groups, studies have proven that engaging the community in this process can set up a project for success. Citizen engagement can be the difference in whether the goals of a project meet the needs of a community, whether a project will attract participants, and whether a project will succeed in the long-term (Prokopy & Floress, 2011). Civic engagement in social issues builds trust in the community, and builds the behavioral patterns needed to address future problems more successfully (Leach, 2006; Sabatier et al., 2005). Increased trust in the community also can increase support for regulations surrounding water protection initiatives, as well as increase social capital to help stakeholder groups accomplish a wide variety of tasks (Lubell et al., 2005).

Civic engagement can increase the effectiveness of water protection and restoration plans. A study of community-based environmental stewardship in Portland found that involving citizens throughout the stormwater remediation planning and implementation process enhanced the riparian canopy, and allowed community members to establish a connection between their own actions and the environment around them (Shandas & Messer, 2008). Similarly, a study conducted in Ohio and West Virginia found that when collaborative watershed groups are involved, there is an increased likelihood of implementation of total maximum daily loads (TMDLs). However, the study also found that the challenge is not only in implementing the TMDLs, but in developing collaborative watershed management efforts (Hoornbeek, Hansen, Ringquist, & Carlson, 2013). Of the watersheds with EPA-approved TMDLs, 43% had not pursued collaborative management approaches, despite them being the only effective mechanism at the federal level (Hoornbeek et al., 2013). While the benefits have been examined, the question of how to engage people in pro-environmental behavior and civic action still persists.

Who engages in water and why?

Studies find that income, education, gender, geographic location, and age often predict *who* is engaged in community issues (Larson & Lach, 2008; Manzo & Weinstein, 1987; Martinez & McMullin, 2004; Smith, 1994). However, *why* citizens participate is a growing area of study. Hines, Hungerford, and Tomera (1987) found that the variables most associated with responsible environmental behavior were knowledge of issues, knowledge of action strategies, locus of control, attitudes, verbal commitment, an individual's sense of responsibility, and situational factors. Norm activation theory (NAT) (Schwartz, 1973) integrates these similar variables, and proposes that since environmental and ecosystem services are a public good, personal moral norms must be activated to avert any harmful environmental consequences of one's behavior (Schwartz, 1973; Stern, 2000) (Appendix E). In civic engagement and environmental action, norms become activated when an individual becomes aware of the consequences of not acting, and believes that they have control over the action that will eventually make a difference (A. K. Pradhananga et al., 2015; Schwartz, 1973).

Personal experience with an environmental risk or hazard can also serve as a guide for an individual who is deciding how to think, behave, or communicate in a situation (Griffin, Dunwoody, & Neuwirth, 1999). The Risk Information Seeking and Processing model (RISP) proposed by Griffin, Dunwoody, & Neuwirth (1999), proposes that individual characteristics, perceptions, and external pressures all influence the extent to which an individual will seek out and critically analyze risk information (Appendix D). The information-seeking strategies that people apply make a difference in what messages they take away, and how those messages impact their future behaviors (Kahlor, 2011).

Griffin examines the variables that determine whether an individual undergoes deeper, systematic processing. Those who undergo systematic processing are more likely to develop stable attitudes towards the topic and are more resistant to change than those who only go through heuristic processing (Kahlor, Dunwoody, Griffin, & Neuwirth, 2006). Demographic and sociocultural characteristics, perceived hazard characteristics, relevant hazard experience, informational subjective norms, information sufficiency, and perceived information gathering capacity all determine whether an individual will pursue deeper processing effort about a risk.

The RISP model was originally developed to evaluate the development and maintenance of preventative health behaviors. However, several studies have successfully applied the model to environmental risk information (Kahlor, 2011; Yang, Rickard, Harrison, & Seo, 2014). Studies have successfully integrated other models such as Ajzen's Theory of Planned Behavior (Ajzen, 1991; Kahlor, 2011) in an effort to extend the TPB to information seeking as the variable or behavior of interest. Most RISP applications evaluate personal risk (e.g., public health issues such as contaminated food), rather than environmental risk, which for some may be a less immediate personal issue. In applications of impersonal risk, studies found that informational subjective norms (the knowledge a person believes they would be expected to hold about the risk) play a more powerful role, and are not only related to information insufficiency but also to information seeking and processing directly (Kahlor et al., 2006). Overall, the study found that the RISP model holds up when applied to impersonal risk. The results suggest that communicators of impersonal risk can use the RISP model as a guide in developing strategic communication (Kahlor, 2011; Kahlor et al., 2006).

Conceptual Model

Based on the literature outlined above, a conceptual model is proposed to determine the influence that multiple independent variables have on engagement with an issue. The conceptual model (Figure 1) draws on NAT, RISP and the model of responsible behavior (Griffin et al., 1999; Hines, Hungerford, & Tomera, 1987; Schwartz, 1973) to examine determinants of civic engagement: Information sufficiency, social and personal norms, perceived hazard characteristics, relevant water experience, self-efficacy and demographic information. In our conceptual framework, relevant water experience is used in place of RISP's relevant hazard experience. This was our best available measure from our survey instrument, and could be interpreted as a measure of likelihood of having encountered a water hazard or threat. In the proposed framework, I hypothesize that each of the psychological and social determinants will have a positive relationship with an individual's civic engagement in water. I hypothesize that residents are more likely to be engaged in water protection if they are frequent visitors to water bodies (and therefore potentially see water issues firsthand), they are highly knowledgeable about water issues, they feel socially and personally obligated to engage in water resource issues, and they believe that water resources are at risk.

In developing the final study model, we first used a baseline model with all hypothesized independent variables relating to RISP and NAT regressed on the dependent aggregated civic engagement variable. Then we used stepwise deletion of independent variables to develop the final study model. Variables in the baseline model that were not significant predictors of civic engagement were removed, with the exception of survey items needed to maintain the integrity of the model and to answer our research questions.

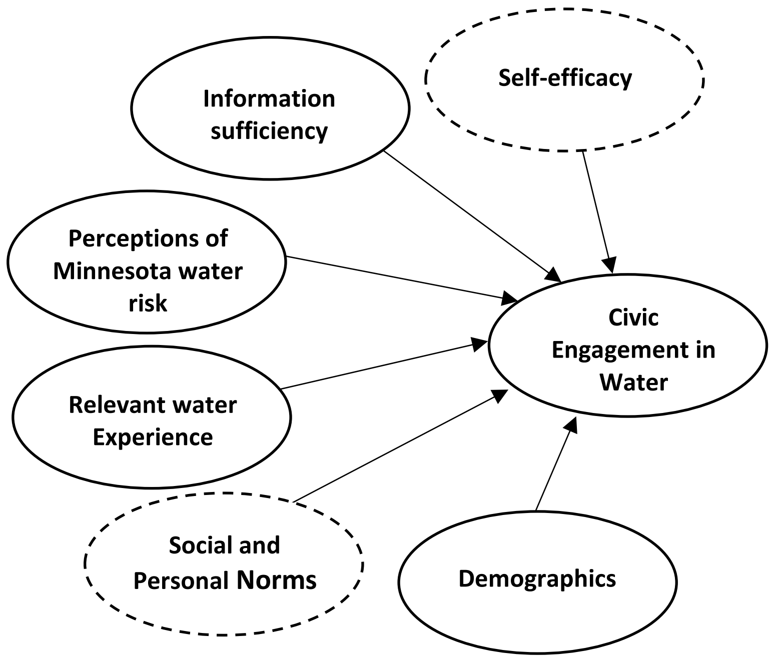


Figure 1. Study conceptual framework (RISP constructs outlined with solid lines, NAT constructs outlined with dashed lines).

Methods

The study was conducted to determine how Minnesota residents use and value water, perceive water risk, and engage in water-related behaviors. Data were collected using a self-administered mail survey, sent to a geographically stratified random sample of 6000 Minnesota residents. The sample was purchased from Survey Sampling International (SSI). The sampling strata are consistent with the Minnesota Soil and Water Conservation Districts. In each of the 8 districts, 750 residents were selected for participation to ensure that denser metropolitan areas are not overrepresented in our sample.

The questionnaire included a variety of fixed-choice and scale questions that asked about residents' community, concerns about water, water protection, and sociodemographic information. Several strategies were used in questionnaire design to ensure question validity and boost questionnaire completion. Care was taken to ensure that items were technically accurate, not double-barreled, succinct, and clear and understandable. Each item required an actionable response from the participant so that participants could answer quickly and accurately. The study included three waves of mailing, and used an adapted version of Dillman et al.'s (2014) tailored design method. Each mailing included a cover letter, questionnaire, and a self-addressed postage-paid return envelope. The survey introduction page and cover letter described sponsors and goals for the survey. After the first wave of mailing, subsequent waves were sent to non-respondents only. An option to take the survey online was included in the cover letter of the survey. Survey questions were piloted with relevant stakeholders to assess the effectiveness of the questionnaire. The study was reviewed by the University of Minnesota's Institutional Review Board. Returned and completed questionnaire responses were coded and entered into a database. Data were analyzed using R (R Core Team, 2017) and Statistical Package for Social Sciences (IBM Corp., 2016).

Measures

Perceptions of risk and threats to water.

Perceptions of risk to water were measured using two items adapted from previous research (Amberson, Biedenweg, James, & Christie, 2016; A. Pradhananga, Fellows, & Davenport, 2018). Respondents rated the statements "water resources in Minnesota are at risk," "I am concerned about the consequences of water problems or pollution for people in my community," and "I am concerned about the consequences of water problems or pollution for local economies" on a 5-point Likert scale from *strongly disagree* to *strongly agree.*

The baseline model also asked about concern for the consequences for recreation opportunities, human health, and future generations. The baseline model included a question about pollutants in Minnesota; pollutants and water issues were measured using four items, “agricultural runoff,” “sediment in water bodies,” “urban runoff,” and “road salt runoff.” The response format was in a 4-point scale from “not a problem” to “severe problem,” and included a “don’t know” option.

Relevant water experience.

Respondents were also asked, “In the last twelve months, about how many times did you visit a lake, river, or stream in Minnesota in which visiting the water body was one of the primary purposes of your trip?” Options were “0 (I did not visit a water body),” “1-3,” “4-12,” “13-24,” and “25 or more.” Responses were analyzed using the lower bounds of each range (0, 1, 4, 13, and 25). In our conceptual framework, relevant water experience is used in place of RISP’s relevant hazard experience. The survey did not include any items that asked specifically about experiences with hazards to water.

Information sufficiency.

Information sufficiency was measured using items adapted from Pradhananga et al (2018). Respondents answered “how familiar are you with water issues in your local area?” on a 5-point scale from “not at all familiar” to “very familiar." In addition respondents answered “where do you get information on water-related issues?” by selecting from a list of 15 sources of information. Responses were dummy-coded into science-related sources of information (federal agencies/government, tribal agencies/government, state agencies/government, county agencies/government, city or township government, and university researchers/academic community), community-related sources of information (family and friends, my neighbors), and a variable for residents that used both sources.

Social and personal norms.

Items used to measure social and personal norms were adapted from previous research (Davenport et al., 2016; A. Pradhananga et al., 2018) and measured personal and subjective norms in reference to water resource protection. Respondents rated the statements, “people in my community expect me to help protect water,” and “it is my responsibility to help protect water,” on a 5-point scale from “strongly disagree” to “strongly agree.” The baseline model also included the statement “residents in my area should be responsible for protecting water,” measured on the same 5-point scale.

Self-efficacy.

Self-efficacy was measured using the statement “residents in my community have the ability to work together to protect water resources,” adapted from Pradhananga et al (2015). Participants rated the statement on a 5-point scale from “strongly disagree” to “strongly agree.” The baseline model also included the question “how important are the following qualities of a community to you?” in regards to “opportunities to be involved in community projects.”

Sociodemographics.

The baseline model included education (“What is the highest level of formal education you have completed?”), age (“In what year were you born?”), gender (“How do you describe yourself?”), and income (“Which of the following best describes your total household income from all sources in 2017 before taxes?”). In the final study model, education was the only demographic included. Past studies have found that education is consistently the strongest demographic predictor of volunteer participation (Smith, 1994).

Engagement in civic water action.

Engagement in water action, the dependent variable, was measured using four items adapted from (Kahlor et al., 2006; A. K. Pradhananga et al., 2015). Respondents were asked “have you engaged in the following actions or initiatives in the past 12 months? If yes, how often did you engage in the action or initiative?” Respondents answered “yes” or “no” to the first question, and if they marked yes, picked one of four options: “every few months,” “once a month,” “every two weeks,” “weekly or more.” Items used for this construct were “heard about a water resource protection initiative,” “talked to others about conservation practices,” “attended a meeting or public hearing about water,” and “worked with other community members to protect water.” Responses were recoded so that “no” was recoded into “never,” and responses were analyzed on a 5-point scale from “never” to “weekly or more.” Participants’ response to each item were aggregated into a single dependent variable for analysis, or the grand mean of all engagement activities.

Analysis

The hypothesized relationships were analyzed using multiple regression. Multiple regression was chosen because of its flexibility in analyzing a quantitative dependent variable as a function of multiple independent variables of interest. The analysis yields a measure of the magnitude of the entire relationship of all independent variables to the dependent variable, as well as the partial relationships of each of the independent variables (Cohen & Cohen, 1975). In our study, we assessed the influence that each of the independent variables (Information sufficiency, social and personal norms, perceived hazard characteristics, relevant hazard experience, self-efficacy, and sociodemographic information) had on our dependent variable, civic engagement.

Listwise deletion of model variables, as well as deletion of case where the “don’t know” or “NA” option were selected, yielded an effective sample size of 1195. Listwise deletion is appropriate because multiple regression requires the same number of cases to be analyzed for each variable. While the data loss was fairly large, a sample size of 1195 is adequate for a multiple regression with six independent variables (Cohen & Cohen, 1975; Maxwell, 2000).

There are four key assumptions for multiple regression. First, the linearity assumption states that the mean of all y-values from the conditional distribution all fall on the same line. The independence assumption assumes that each y-value is independent from every other y-value in the distribution. The normality assumption indicates that the conditional y-values are normally distributed. Lastly, the homogeneity of variance, or homoscedasticity assumption, states that the variance of the conditional distributions is the same (Cohen & Cohen, 1975; Lewis-Beck & Lewis-Beck, 2016). The Central Limit Theorem states that if you have a sufficiently large sample size, the sampling distribution starts to approximate a normal distribution (Maxwell, 2000; Rouaud, 2017).

Our study variables were checked for multicollinearity between variables. Intercorrelations between variables were examined to see if any had coefficients of .8 or larger (Lewis-Beck & Lewis-Beck, 2016). Coefficient values ranged from <.001 to .664, indicating that our study variables were below the threshold for high multicollinearity.

Results

Of the 6,000 surveys mailed, 681 were returned undeliverable and 1480 completed surveys were received, resulting in a final response rate of 28%. A majority of respondents were male (64%) and white (93%). The median age of respondents was 62 years old, and median income was between $50,000 and $74,999 per year. About 18% of respondents completed high school, 21% had a bachelor's degree, and 14% had a graduate degree. While the sample size was large enough to conduct analysis, a limitation of the study was the sample demographic, which differs from Minnesota's population (see Table 1).

Table 1. Survey sample vs. Minnesota Census numbers

	Survey respondents	**Minnesota population[1]**
Male	64.1%	49.8%
White	93%	84.4%
Median income	$50,000 - $74,999	$65,699
Bachelor's degree or higher	42.9%	34.8%
Persons 65 years and over	43%	15.4%

[1]Minnesota Census 2018 estimates (United States Census Bureau, 2018)

Wave analyses were conducted to determine whether participants who responded early (wave 1) were different from those who responded late (wave 3), or not at all. Significant differences in means were found between wave 1 respondents and wave 3 respondents in the information sufficiency construct. Those who responded early were significantly more familiar with local water issues ($p<.001$) and used more scientific sources of information for their water-related issues ($p<.001$). Significant differences

Table 2. Descriptive statistics of survey items used in the study conceptual model

Theoretical construct	**Survey items**	**Mean***	**SD**
Information sufficiency	How familiar are you with water issues in your local area?[1]	2.48	.88
	Where do you get information on water-related issues? (science sources)[2]	.29	.45
	Where do you get information on water-related issues? (social sources)[2]	.15	.35
	Where do you get information on water-related issues? (both science and social sources)[2]	.38	.49
Social and personal norms	People in my community expect me to help protect water[3]	3.64	1.06
	It is my personal responsibility to help protect water[3]	4.39	.83
Perceptions of risk and threats to water	Water resources in Minnesota are at risk[3]	3.70	1.05
	I am concerned about the consequences of water problems or pollution for local economies[3]	3.95	.87
	I am concerned about the consequences of water problems or pollution for people in my community[3]	4.11	.86
Relevant water experience	In the last twelve months, about how many times did you visit a lake, river, or stream in Minnesota in which visiting the water body was one of the primary purposes of your trip?[4]	3.02	1.36
Self-efficacy	Residents in my community have the ability to work together to protect water resources[3]	3.54	.93
Civic engagement in water	*Have you engaged in the following actions or initiatives in the past 12 months? If yes, how often did you engage in the action or initiative?*		
	Heard about a water resource protection initiative[5]	1.44	.80
	Talked to others about conservation practices[5]	1.65	1.01
	Attended a meeting or public hearing about water[5]	1.16	.45
	Worked with other community member to protect water[5]	1.15	.54
	Aggregated civic engagement variable (dependent variable)[6]	1.35	.52

Notes: SD, standard deviation
**n* = 1480
[1]Items measured on a 4-point scale from “not at all familiar” (1) to “very familiar” (4)
[2]Items dummy-coded between did not use this type of source (0) and did use this type of source (1)
[3]Items measured on a 5-point scale from “strongly disagree” (1) to “strongly agree” (5)
[4]Items measured on a 5-point scale: “0 (I did not visit a water body)” (1), “1-3” (2), “4-12” (3), “13-24” (4), “25 or more” (5)
[5]Items measured on a 5-point scale from “Never” (0) to “Weekly or more” (5)
[6]Dependent variable created by taking a mean of all civic engagement activities

were also found in number of visits to water. Early respondents had visited a lake, river, or stream in Minnesota significantly more times in the last twelve months than late respondents ($p<.001$). Early respondents were also significantly more educated than late respondents ($p<.001$) and were also significantly more civically engaged (based on the four engagement activities used in the model), than those who responded late ($p<.001$).

Table 3. Conceptual model regression results

Theoretical construct	Survey Items (independent variables)	Baseline model	Final reduced model			
		B	*B*	SE	*P*	β (std. beta weight)
Information sufficiency	How familiar are you with water issues in your local area?	.2166**	.205**	.0162	.000	.346
	Where do you get information on water-related issues? (science sources)	.1996**	.104*	.0426	.0146	.0920
	Where do you get information on water-related issues? (social sources)	.1124	.0276	.0475	.562	.0191
	Where do you get information on water-related issues? (both science and social)	.2468**	.129**	.0408	.0016	.1218
Social and personal norms	People in my community expect me to help protect water	.0315	.0095	.0144	.511	.0193
	It is my personal responsibility to help protect water	.0254	.0068	.0185	.714	.0107
	Residents in my area should be responsible for protecting water	-.0483				
Perceptions of risk and threats to water	In your opinion, how much of a problem are the following water pollutants or issues to water in your local area? (Agricultural runoff, sediment in water bodies, urban runoff, road salt runoff)	.0590				
	Water resources in Minnesota are at risk	.0232	.0244	.0131	.0632	.0494
	I am concerned about the consequences of water problems or pollution for recreation opportunities	-.0198				
	I am concerned about the consequences of water problems or pollution for human health	-.0237				
	I am concerned about the consequences of water problems or pollution for future generations	.0072				
	I am concerned about the consequences of water problems or pollution for local economies	-.0721*	-.0532**	.0202	.0085	-.0887
	I am concerned about the consequences of water problems or pollution for people in my community	.0923**	.0483*	.0205	.0186	.0806
Relevant water experience	In the last twelve months, about how many times did you visit a lake, river, or stream in Minnesota in which visiting the water body was one of the primary purposes of your trip?	.0121**	.0096**	.0014	.000	.1796
Self-efficacy	Residents in my community have the ability to work together to protect water resources	-.0052	-.0106	.0148	.472	-.0190
	How important are the following qualities of a community to you? Opportunities to be involved in community projects	-.0089				
Demographics	Education	.0209	.0361**	.0079	.000	.1164
	Income	.0110				
	Gender	-.0351				
	Age	-.000006				
	Constant	.345	.420**			
	n	650	1205			
	F statistic	11.1	33.3			
$**p \le 0.01$, $*p \le 0.05$	**Adjusted R^2**	**.246**	**.243**			

Model results

The final regression model in this study explained 24.3% of variance in civic engagement. Although the full baseline model explained 24.6% of variance in civic engagement, removal of nine non-significant variables resulted in a loss of only 0.3% of variance. Variables used in the final study model were significant, or were included for theoretical consistency with RISP. Full results are outlined in Table 3.

Familiarity with water issues was the strongest predictor overall, followed by the science information source variable, both from the information sufficiency construct. A one-unit increase in familiarity with water issues (e.g. from "moderately familiar" to "very familiar") increases a resident's civic engagement score by .205. A resident who uses only scientific information for their water-related issues has a civic engagement score that is 0.1 unit higher than that of a resident who uses only social information.

Relevant water experience and education, respectively, were the next highest predictors of civic engagement. A one-unit increase in water experience (e.g. from 4-12 visits in the last 12 months to 13-24 visits in the last 12 months) led to a .01-point increase in civic engagement score.

The only negative predictor of significance was concern about the consequences of water problems for local economies. The more concerned a resident is about impacts of water to local economies, the less likely they are to get involved civically.

Discussion

This article began by examining the shortcomings of traditional top-down agency approaches to water protection in the United States, and collaborative watershed management and civic engagement as a solution to those shortcomings. This study examined Minnesota residents' perceptions of water quality and beliefs about water problems, and how those perceptions impact their engagement in civic water actions. By using an integrated RISP/NAT model, this study not only examined residents' information seeking about water issues, but also explored other information processing behaviors: talking to others about conservation practices, working with other community members to protect water, and hearing about a water resource protection initiative.

Results show that familiarity with water issues and sources of water information were the strongest predictors of civic engagement in water. Those who were familiar with water issues and used scientific sources of information for water-related issues were more likely to engage in civic water action. This supports past findings that science communication and environmental education are key in promoting pro-environmental behaviors in residents (Hines et al., 1987; Samuelson et al., 2005).

Civic engagement in water resource protection was also driven by experience with water, measured in this study through visits to water. Similar to previous applications of RISP (Griffin et al., 1999; Kahlor et al., 2006), relevant experience was a significant predictor of engagement in water resource protection. The more residents visit water bodies, the more likely they are to engage in civic actions and seek out more information about the issues. Though not a direct measure of "hazard" experience, those with fewer visits, and presumably less firsthand experience with water problems or threats, are far less likely to participate in protection initiatives.

Study findings suggest new strategies and approaches for getting residents and stakeholders involved in the collaborative watershed management process in Minnesota and beyond. This study found that environmental risk perception goes beyond scientific and technical knowledge and relies more on experiential processes. Results suggest that residents need a stronger connection to water issues to get engaged. This is consistent with past studies of environmental risk, where researchers found that global warming risk perception was greatly influenced by emotional factors and negative imagery, rather than political ideology (Leiserowitz, 2006).

Future research should examine what residents hope to gain from risk communication, and how to best characterize risk surrounding water resource issues. While many studies have explored science communication in relation to climate change, very few studies have examined communication specific to water problems. Characterizing water resource issues effectively and allowing for more experiential knowledge can lead to more effective participation and decision-making (Besley & McComas, 2014; Kahlor et al., 2006; Leiserowitz, 2006).

A future integrated RISP/NAT model could be expanded to include other variables such as ascription of responsibility, awareness of consequences, or barriers to engagement. In building a more comprehensive model, researchers could examine what factors specifically take residents beyond information seeking and processing into other engagement behaviors.

Moving forward, science communication efforts should focus on getting residents "out in the field," and integrate real-time reporting of issues at water bodies that are frequently visited. Agencies have found that getting residents out to the water and showing them what water problems look like can help the reality of the issues sink in and provide the experiential knowledge needed to motivate residents to take the next step (Comito & Helmers, 2011; Leiserowitz, 2006). For example, a visitor may see a sign that shows elevated nitrogen levels in the lake, and when they get to the lake, they will see algal blooms that makes their swimming or boating experience less pleasant. Since the connection between the two may not be obvious to the layperson, agencies and resource managers can build communication connecting those two experiences and send home a relatable message that a particular pollutant will create a particular experience for the visitor.

Beyond making residents aware of the problems in their area, resource managers can also build communication to show pollutant sources and how pollutants make their way to water bodies. An educational sign at a water body laden with litter could also include information about stormwater runoff or storm drain contamination in their neighborhood. Showing how a problem came to be can help residents to build connections between their actions and the physical world.

CHAPTER 3

DISCUSSION

Water pollution in the United States comes from widespread, dispersed sources across the landscape, and solutions must be equally as widespread to capture the full extent of the problem. Traditional top-down agency strategies to water remediation often fail to engage the residents and other key stakeholders in their approaches. By engaging the community, and examining all sources and solutions to a water problem, collaborative watershed management allows for residents to be involved throughout a remediation process. Many past studies have explored who gets involved in civic water action, but few have examined why they get involved.

This study sought to investigate decision making in pro-environmental behavior, specifically civic engagement in water. This study aimed to answer the following questions:

1. What drives perceptions of water and water problems?
    a. Where do people get water information?
    b. Who or what influences them?
    c. Do sociodemographics matter?
2. How do perceptions of water quality and beliefs about problems affect civic engagement in water?

In exploring why residents get involved in civic water action, we can increase participation in water protection initiatives, create more effective water policies, and eventually improve water conditions across the United States.

Key Lessons

This study revealed key lessons in understanding civic engagement in water. First, information sufficiency and the use of scientific sources of information were found to be significantly correlated with civic engagement behaviors. Second, relevant experience with water was associated with higher rates of civic engagement. Lastly, perceptions of risks to water and concern about the consequences of these risks for people in the community were positively associated with civic engagement in water, but concern for local economies were negatively associated.

Civic engagement in water resource protection was most strongly correlated with the information sufficiency construct. Those who were familiar with local water issues and used scientific information for water-related issues were more likely to engage in local water protection efforts. This supports past findings that science communication and education are the first barriers that must be crossed in developing pro-environmental behaviors in citizens (Hines et al., 1987; Samuelson et al., 2005).

Civic water action was also significantly correlated with relevant water experience. Consistent with previous applications of RISP (Griffin et al., 1999; Kahlor et al., 2006), relevant experience was a significant predictor of engagement in water resource protection. Citizens who frequently visit water were more likely to engage in civic actions and seek out more information about the issues. These results suggest that those without direct experience with water issues (and by extension, experience with water threats) are far less likely to participate in protection initiatives. This finding, in conjunction with the information sufficiency finding, suggests that residents need a more personal connection to water issues beyond just the scientific information.

Perceptions of risk and threats to water were also a significant predictor of community engagement. Concern about the consequences of water problems for people in my community had a significant, positive correlation with civic engagement, but concern about the consequences of water problems for local economies had a significant negative correlation. This may suggest a divide between “community-minded” and “business-minded” individuals; those who are concerned about their community will engage civically to protect it, but those more concerned with economic issues may seek other strategies. This also possibly represents a divide between residents with more altruistic, collective values versus those with more egoistic values, and how the two groups engage civically.

Social and personal norms were not a statistically significant predictor of community engagement. Previous NAT and responsible environmental behavior (Hines et al., 1987; Schwartz, 1973) studies that found that citizens are more likely to act if they feel that others expect them to protect water resources, or if they feel personally obligated to act. However, in past studies of impersonal risk (such as global warming), informational subjective norms were the most powerful predictor of deeper processing behaviors, and expectations of others have been found to be significant when making decisions in community engagement (Kahlor et al., 2006; A. K. Pradhananga et al., 2015). However, these past studies engaged rural landowners or urban residents, where a social norm surrounding water action may be much stronger than in the resident sample for this study. The perceived personal impacts of water risk are worth investigating in the future. For example, health concerns related to drinking water may be considered a personal risk, but aquatic invasive species may be an impersonal risk.

Theoretically, this study supports an integrated RISP/NAT model to examine the effect that perceptions of water quality have on civic engagement behaviors in water protection. While the information sufficiency construct by itself may suggest that residents just need more data about water issues, when interpreted in conjunction with other variable constructs such as relevant experience, findings suggest that residents need a stronger emotional connection to water issues to get engaged. This is consistent with past studies of environmental risk, where researchers found that global warming risk perception was greatly influenced by emotional factors and negative imagery, rather than political ideology (Leiserowitz, 2006). The study found that perception of water risk goes beyond scientific and technical knowledge, and relies more on experiential processes.

Practical Implications

Water is a human and societal issue, impacting human health, economic development, recreation, and fish and wildlife. Reframing water risk as a more personal and community-level issue, rather than a technical one, could offer opportunity for the public to engage in the effects (Besley & McComas, 2014; Kahlor et al., 2006). Past studies have shown that health and economy were top priority issues for Minnesotans, yet few acknowledged that Minnesota's clean, abundant waters were central to those issues (Devitt, 2018). Future communication surrounding key community or social issues could benefit from an environmental perspective, and integrate the role of ecosystem services into the health and economic fields. Water is currently less recognized as an issue in its own right, and integrating it into other top-of-mind issues could play a role in getting the community engaged.

Our findings show that familiarity with water issues is the top predictor for engaging in water protection. However, studies have found that water issues often feel abstract compared to visible issues; farmers can see soil erosion on their land, but can't see, feel, or taste differences in their water, and don't feel a direct connection to downstream impacts (Comito & Helmers, 2011). Agency specialists have found that getting residents "out in the field," and showing them test kit results of their individual impact can help the reality of the problem sink in, and provide the experiential knowledge needed to motivate residents to take the next step (Comito & Helmers, 2011; Leiserowitz, 2006). Other statewide studies focusing on perceptions of Minnesota's water quality have found that inconsistencies in how information is presented, and who is presenting it, have perpetuated doubt about the baseline facts of water quality in the state. Establishing the common base fact across agencies, constituencies, and information sources could serve to unify the public about what exactly the issues are and how to fix them (Devitt, 2018). Clearly articulating the uncertainty in water quality data, and integrating different interpretations of risk (technical information about nutrient loads versus visible algal blooms) could help to ground the issue for residents and motivate them to help out in their community.

These findings suggest that agencies and resource managers can work to improve water resource communication in community engagement efforts. This study found that increasing familiarity with water issues is associated with an increase in civic engagement in water, but residents also need a more personal connection. In applying this information, agencies could look to water bodies that are frequently visited, and post test kit information about what pollutants are found in that lake, and how those pollutants manifest themselves. At a lake with a high level of suspended solids for example, agencies could post real-time information about the amount of sediment in the lake, and help visitors make the connection between that information and the poor water clarity that makes their swimming or fishing experience less pleasant.

Water protection agencies may also be missing large swaths of the population in existing outreach methods. Our findings show that the more a resident visits water bodies, the more likely they are to become civically engaged. Outreach to communities that may not have ready access to recreational waters, and assisting them in visiting more water bodies may establish a familiarity with the water issues, as well as a desire to help protect those water bodies. Past studies have found that while recreational user fees are widely accepted, they significantly reduce participation in lower-income residents (More & Stevens, 2000). There are likely many other demographics that are missing from community efforts, which increases the potential for ineffective policies (Sabatier et al., 2005; Samuelson et al., 2005). Communications about water problems may fail to be dispersed broadly throughout communities, or may not give appropriate attention to threats impacting rural or culturally isolated populations.

The issue of representation is one that has been much discussed in collaborative watershed management (Sabatier et al., 2005). When all demographics are not represented in land-use planning decisions, there is potential for policies to only be representative of those residents with a large amount of time and resources that enable them to participate in the planning process, and can set policies up for failure. Recruitment efforts for past studies found that older, middle-class, white citizens were much more available and willing to participate in community efforts than other demographic groups (Samuelson et al., 2005). Much of this study was limited by the demographic of the respondent population. While some conclusions could be drawn regarding civic engagement, it should be recognized that the sample population may be those residents with more time and resources to be able to respond to a mailing survey.

Future Research

Future research should focus on building survey instruments and items around this model to more precisely formulate questions to fit within these variables, and expand the model to include other variables used in NAT, RISP, and the Model of Responsible Environmental Behavior (Griffin et al., 1999; Hines et al., 1987; Schwartz, 1973), such as awareness of consequences and ascription of responsibility. A future model could also be expanded to extend beyond just risk information seeking and processing, and examine what factors take residents beyond information seeking and processing into other engagement behaviors.

Barriers to civic engagement were not examined in this study. This study examined why people engage in water protection, but not why they don't engage. Taking barriers into account when examining reasons for civic engagement may account for more variance in engagement behaviors, and allow for more effective communication surrounding water resource issues. Examining barriers may also shed light on what allows residents to shift from more passive engagement (such as information seeking) to a more active role in water protection (such as conservation practices or volunteering for an organization).

A limitation of this study was that although survey research allows for the analysis of proposed relationships, causality cannot be determined without random assignment. In addition, while the sample size was adequate for this study, the low survey response rate that is typically found with mail surveys could potentially result in non-response error, where those who responded to the survey are different from those who didn’t (Dillman et al., 2014). Because our wave analysis found that early respondents were significantly more civically engaged than late respondents, our sample likely showed higher levels of engagement than what actually exists in the Minnesota population.

There is also a need to examine the definition of civic engagement, and to synthesize all engagement behaviors into one overarching definition. Many definitions of civic engagement include the phrase “collective action” (Checkoway & Aldana, 2013; Fagotto & Fung, 2009), but there is potential for a future definition to include individual actions that contribute to the collective good. In defining civic engagement, it is difficult to capture all the different forms of engagement; in this study, behaviors from information seeking to working with community members were all included, but were by no means a comprehensive list. Social media, changing consumption habits, volunteering, and donating money could all be considered a form of civic engagement, yet in the current literature there is no definition that supports all of them.

Despite the limitations of this study, findings show that residents’ engagement in water resource protection is driven by relevant hazard experience, social norms, and perceived threats. These findings have implications for community organizers and state agencies who are seeking to get more support in the community, and more participation in water initiatives. Civic engagement in water resource protection builds trust in the decision-making process and leads to behaviors that are needed for future initiatives to be more effective.

Conclusion

Findings from this study support current theory on pro-environmental behavior and civic engagement in natural resources and enhance current understanding of the impact of science communication on civic water action. Combined with results of the past studies, the overarching message is that residents need to be educated on water issues and need to feel that the issues are personal to their lives if they are going to get involved in water protection. Agencies also need to work to improve access to recreational waters for lower-income or culturally isolated communities. The more frequently someone visits a water body, the more likely they are to engage in its protection, yet some recreational water bodies may be inaccessible for lower-income communities.

Overall, residents will be more likely to engage in water protection efforts if they are educated about the issues and the issues feel personal. If water problems feel abstract and irrelevant to residents' lives, they are far less likely to work to fix the issues in their community. If water issues are visibly impacting a resident's lifestyle, the chances that they will engage in water protection increase.

Water issues are a unique problem. Water risk can be personal (human health) or impersonal (aquatic health). Water can have individual and collective benefits and impacts. Water problems impact every person, and while there many different initiatives in place to remedy water's myriad issues, collective action must be taken in order to solve upstream and downstream problems.

REFERENCES

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, *50*, 179–211. https://doi.org/10.1016/0749-5978(91)90020-T

Amberson, S., Biedenweg, K., James, J., & Christie, P. (2016). “The Heartbeat of Our People”: Identifying and Measuring How Salmon Influences Quinault Tribal Well-Being. *Society and Natural Resources*, *29*(12), 1389–1404. https://doi.org/10.1080/08941920.2016.1180727

Besley, J. C., & McComas, K. A. (2014). Fairness, public engagement, and risk communication. In *Effective Risk Communication* (p. 341).

Checkoway, B., & Aldana, A. (2013). Four forms of youth civic engagement for diverse democracy. *Children and Youth Services Review*, *35*(11), 1894–1899. https://doi.org/10.1016/j.childyouth.2013.09.005

Clean Water, Land, and Legacy Amendment (2008).

Clean Water Land & Legacy Amendment. (2018). *Clean Water Fund Performance Report*. Retrieved from www.legacy.leg.mn

Cohen, J., & Cohen, P. (1975). *Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences*. Hillsdale, New Jersey: Lawrence Erlbaum Associates, Inc.

Comito, J., & Helmers, M. (2011). The Language of Conservation. In L. W. Morton & S. S. Brown (Eds.), *Pathways for Getting to Better Water Quality: The Citizen Effect2* (pp. 67–82). New York, NY: Spring Science+Business Media, LLC.

Davenport, M., Perry, V., Pradhananga, A. K., & Shepard, J. (2016). *A Community Capacity Assessment for Stormwater Management in Three Twin Cities Metro Area Watersheds* (No. 1). University of Minnesota.

Dayton, M. (2017). *25 By 25: Public Input*. Retrieved from https://www.eqb.state.mn.us/sites/default/files/documents/25by25-report-draft-v12-websm.pdf

Devitt, S. (2018). *The State of Minnesota's Water: An Evaluation of Stakeholder Perspectives on Water Priorities*.

Dillman, D. A., Smyth, J. D., & Christian, L. M. (2014). *Internet, Phone, Mail, and Mixed-Mode Surveys: the Tailored Design Method* (4th ed.). Hoboken, New Jersey: John Wiley & Sons, Inc.

Environmental Protection Agency. (1996). Nonpoint source pollution: The nation's largest water quality problem. Retrieved from https://nepis.epa.gov/Exe/ZyPDF.cgi/20004PZG.PDF?Dockey=20004PZG.PDF

Environmental Protection Agency. (2017). National Water Quality Inventory : Report to Congress, (August).

Environmental Protection Agency. (2018). Basic Information about Nonpoint Source (NPS) Pollution. Retrieved from https://www.epa.gov/nps/basic-information-about-nonpoint-source-nps-pollution

Fagotto, E., & Fung, A. (2009). Sustaining Public Engagement: Embedded Deliberation in Local Communities. *Everyday Democracy and the Kettering Foundation*. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Sustaining+Public+Engagement:+Embedded+Deliberation+in+Local+Communities#0

Griffin, R., Dunwoody, S., & Neuwirth, K. (1999). Proposed Model of the Relationship of Risk Information Seeking and Processing to the Development of Preventive Behaviors. *Environmental Research*, *80*, 230–245.

Hines, J. M., Hungerford, H. R., & Tomera, A. N. (1987). Analysis and synthesis of research on responsible environmental behavior: A meta-analysis. *Journal of*

Environmental Education, *18*(2), 1–8. https://doi.org/10.1080/00958964.1987.9943482

Hoornbeek, J., Hansen, E., Ringquist, E., & Carlson, R. (2013). Implementing Water Pollution Policy in the United States : Total Maximum Daily Loads and Collaborative Watershed Management. *Society and Natural Resources*, *26*(4), 420–436. https://doi.org/10.1080/08941920.2012.700761

IBM Corp. (2016). IBM SPSS Statistics for Windows. Armonk, NY: IBM Corp.

Kahlor, L. A. (2011). An Augmented Risk Information Seeking Model: The Case of Global Warming. *Media Psychology*, *10*(3), 414–435. https://doi.org/10.1080/15213260701532971

Kahlor, L. A., Dunwoody, S., Griffin, R. J., & Neuwirth, K. (2006). Seeking and processing information about impersonal risk. *Science Communication*, *28*(2), 163–194. https://doi.org/10.1177/1075547006293916

Koontz, T. M., & Newig, J. (2014). From Planning to Implementation: Top-Down and Bottom-Up Approaches for Collaborative Watershed Management. *Policy Studies Journal*, *42*(3), 416–442. https://doi.org/10.1111/psj.12067

Larson, K. L., & Lach, D. (2008). Participants and non-participants of place-based groups: An assessment of attitudes and implications for public participation in water resource management. *Journal of Environmental Management*, *88*(4), 817–830. https://doi.org/10.1016/j.jenvman.2007.04.008

Leach, W. D. (2006). Collaborative Public Management and Democracy: Evidence from Western Watershed Partnerships. *Public Administration Review*, *66*, 100–110.

Leiserowitz, A. (2006). Climate Change Risk Perception and Policy Preferences: The Role of Affect, Imagery, and Values. *Climate Change*, *77*, 45–72. https://doi.org/10.1007/s10584-006-9059-9

Lewis-Beck, C., & Lewis-Beck, M. (2016). *Applied Regression: An Introduction*. (J. Fox, Ed.) (2nd ed.). Thousand Oaks, California: SAGE Publications, Inc.

Lubell, M., Sabatier, P. A., Vedlitz, A., Focht, W., Trachtenberg, Z., & Matlock, M. (2005). Conclusions and Recommendations. In P. A. Sabatier, W. Focht, M. Lubell, Z. Trachtenberg, A. Vedlitz, & M. Matlock (Eds.), *Swimming Upstream: Collaborative Approaches to Watershed Management* (pp. 261–296). Cambridge, MA: Massachusetts Institute of Technology.

Manzo, L. C., & Weinstein, N. D. (1987). Behavioral Commitment to Environmental Protection: A Study of Active and Nonactive Members of the Sierra Club. *Environment and Behavior*, *19*(6), 673–694.

Martinez, T. A., & McMullin, S. L. (2004). Factors affecting decisions to volunteer in nongovernmental organizations. *Environment and Behavior*, *36*(1), 112–126. https://doi.org/10.1177/0013916503256642

Maxwell, S. E. (2000). Sample Size and Multiple Regression Analysis. *Psychological Methods*, *5*(4), 434–458.

Michaels, S. (2001). Making collaborative watershed management work: The confluence of state and regional initiatives. *Environmental Management*, *27*(1), 27–35. https://doi.org/10.1007/s002670010131

More, T., & Stevens, T. (2000). Do User Fees Exclude Low-income People from Resource-based Recreation ? *Journal of Leisure Research*, *32*(3), 341–357.

Morton, L. W., & Brown, S. S. (2011). Pathways to Better Water Quality. In L. W. Morton & S. S. Brown (Eds.), *Pathways for Getting to Better Water Quality: The Citizen Effect* (pp. 3–14). New York, NY: Spring Science+Business Media, LLC.

MPCA. (2018a). Impaired waters viewer. Retrieved March 23, 2019, from https://www.pca.state.mn.us/water/impaired-waters-viewer-iwav

MPCA. (2018b). Nonpoint source issues. Retrieved April 3, 2019, from https://www.pca.state.mn.us/water/nonpoint-source-issues

Pradhananga, A., Fellows, S., & Davenport, M. (2018). *An Assessment of Landowner Conservation Action in the Lower Minnesota Watershed*.

Pradhananga, A. K., Davenport, M., & Green, E. (2019). Cultural Narratives on Constraints to Community Engagement in Urban Water Restoration. *Journal of Contemporary Water Research & Education*, (166), 79–94.

Pradhananga, A. K., Davenport, M., & Olson, B. (2015). Landowner Motivations for Civic Engagement in Water Resource Protection. *Journal of the American Water Resources Association*, *51*(6), 1600–1612. https://doi.org/10.1111/1752-1688.12346

Prokopy, L. S., & Floress, K. (2011). Measuring the Citizen Effect: What Does Good Citizen Involvement Look Like? In L. W. Morton & S. S. Brown (Eds.), *Pathways for Getting to Better Water Quality: The Citizen Effect* (pp. 83–94). New York, NY: Spring Science+Business Media, LLC.

R Core Team. (2017). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://www.r-project.org/

Rouaud, M. (2017). *Probability, statistics, and estimation: propagation of uncertainties in experimental measurement*.

Sabatier, P. A., Focht, W., Lubell, M., Trachtenberg, Z., Vedlitz, A., & Matlock, M. (2005). Collaborative Approaches to Watershed Management. In P. A. Sabatier, W. Focht, M. Lubell, Z. Trachtenberg, A. Vedlitz, & M. Matlock (Eds.), *Swimming Upstream: Collaborative Approaches to Watershed Management* (pp. 3–22). Cambridge, MA: Massachusetts Institute of Technology.

Samuelson, C. D., Vedlitz, A., Whitten, G. D., Matlock, M., Alston, L. T., Peterson, T. R., & Gilbertz, S. J. (2005). Citizen Participation and Representation in Collaborative Engagement Processes. In P. A. Sabatier, W. Focht, M. Lubell, Z. Trachtenberg, A. Vedlitz, & M. Matlock (Eds.), *Swimming Upstream: Collaborative Approaches to Watershed Management* (pp. 137–169). Cambridge, MA: Massachusetts Institute of Technology.

Schwartz, S. H. (1973). Normative Explanations A Critique , Proposal , of Helping Behavior : and Empirical Test ' Criticisms of Normative Explanations. *Sociology The Journal Of The British Sociological Association*, *9*, 349–364. Retrieved from http://www.sciencedirect.com/science/article/pii/0022103173900711

Shandas, V., & Messer, W. B. (2008). Fostering Green Communities Through Civic Engagement. *Journal of the American Planning Association*, *74*(4), 408–418. https://doi.org/10.1080/01944360802291265

Smith, D. H. (1994). Determinants of Voluntary Association Participation and Volunteering : A Literature Review. *Nonprofit and Voluntary Sector Quarterly*, *23*(3), 243–263.

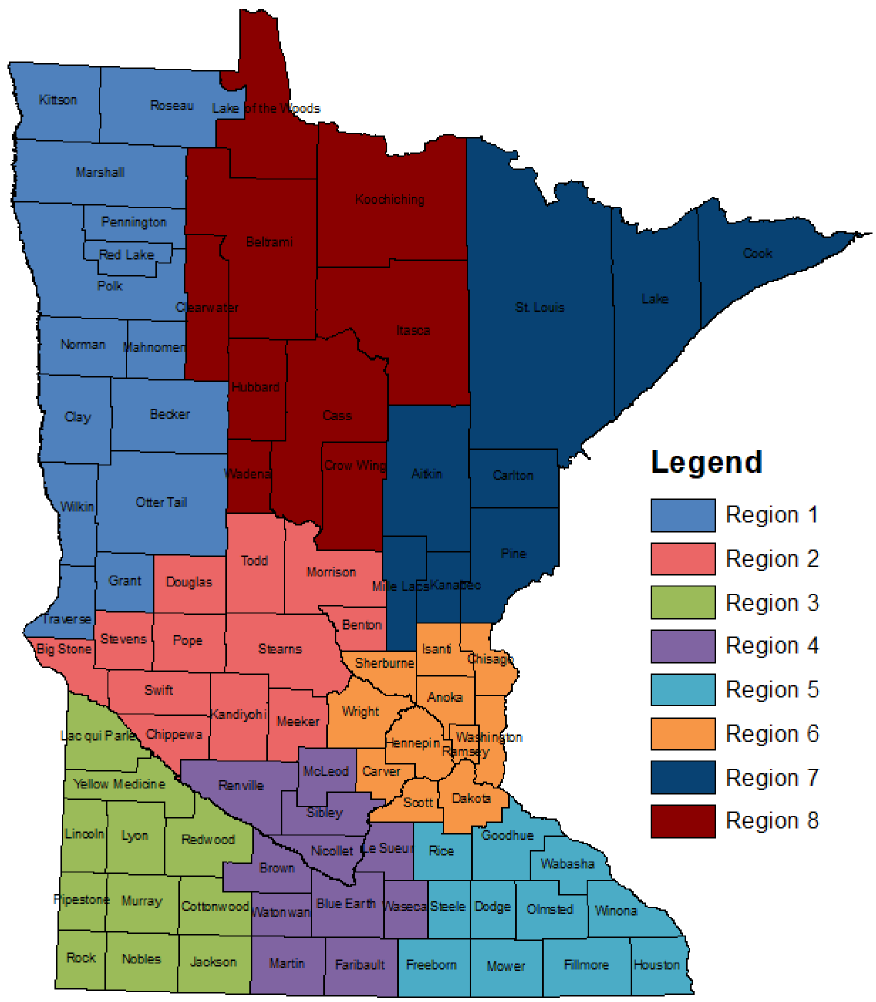
Stern, P. C. (2000). Toward a Coherent Theory of Environmentally Significant Behavior, *56*(3), 407–424.

United States Census Bureau. (2018). QuickFacts Minnesota. Retrieved April 4, 2019, from https://www.census.gov/quickfacts/mn

Yang, Z. J., Rickard, L. N., Harrison, T. M., & Seo, M. (2014). Applying the Risk Information Seeking and Processing Model to Examine Support for Climate Change Mitigation Policy. *Science Communication*, *36*(3), 296–324. https://doi.org/10.1177/1075547014525350

APPENDICES

APPENDIX A: MINNESOTA SOIL AND WATER CONSERVATION DISTRICT MAP



(Minnesota Association of Soil and Water Conservation Districts, 2010)

APPENDIX B: SURVEY COVER LETTER

UNIVERSITY OF MINNESOTA

Twin Cities Campus

Center for Changing Landscapes
College of Food, Agricultural and Natural Resource Sciences

115 Green Hall
1530 Cleveland Avenue North
St. Paul, MN 55108-6112
Office: 612-624-9321
www.changinglandscapes.umn.edu

ID#: _________

[First Name] [Last Name]
[Street Address]
[City] [State] [Zip code]

Minnesota Water Values Survey Information

May 7, 2018

Dear [First Name] [Last Name],

I am writing to ask for your help in a study about water values in Minnesota. The study is being conducted by Mae Davenport, Center for Changing Landscapes, and Bonnie Keeler, Humphrey School of Public Affairs, at the University of Minnesota and is supported by the Clean Water Council; Clean Water, Land and Legacy Amendment funds; Environment and Natural Resources Trust Fund; and the McKnight Foundation. **The goal of the study is to better understand how Minnesotans value and use water, and how they think water should be protected.** Findings from this study will help decision makers prioritize water programs and will support public engagement in water resource management across the state.

We understand that this may be a busy time of the year for you, so we really appreciate you taking the time to help us with this study. If you are willing, please complete the enclosed questionnaire. **It should take you only about 15 minutes.** We are only contacting a random sample of residents in Minnesota, so it is important that we hear from you! The survey is voluntary and completely confidential. The risks of participating in this study are minimal. You are free to withdraw at any time. Completion of this questionnaire indicates your voluntary consent to participate. Your decision to participate will not affect your current or future relationship with the University of Minnesota. The ID # on the front page of your survey is used to help us track mailings, ensuring that your name is never affiliated with your responses. Please answer the questions as completely as possible. Once you have completed the questionnaire, fold it in thirds and mail it back in the enclosed self-addressed, postage-paid envelope.

If you would prefer to complete an online version of the questionnaire, please send us a note with your email address to ccl@umn.edu.

We would be happy to answer any questions or listen to any comments you may have about this study.
Please feel free to contact me by phone at 612-624-9321, or by email at mdaven@umn.edu. If you have any questions or concerns regarding the study and would like to talk to someone other than the researcher(s), you are encouraged to contact the Research Subjects' Advocate Line, D-528 Mayo, 420 Delaware Street S.E., Minneapolis, Minnesota, 55455; telephone 612-625-1650.

I hope you enjoy completing the questionnaire and I look forward to receiving your response.

Sincerely,

Mae Davenport, Ph.D.
Director, Center for Changing Landscapes

APPENDIX C: SURVEY INSTRUMENT

ID#: _________

The Value of Minnesota Water:
A Resident Survey

Center for Changing Landscapes
University of Minnesota
Driven to Discover

Institute on the Environment
University of Minnesota
Driven to Discover

Environment and Natural Resources Trust Fund

Clean Water Land & Legacy Amendment

Before you begin:

We are conducting this survey to better understand Minnesota residents' opinions about the value of water and actions that protect water. This survey is voluntary and confidential. It should take about 15 minutes to complete this questionnaire. Please answer the questions as completely as possible.

Once you've completed the survey:

Please fold it in thirds and mail it back in the enclosed self-addressed stamped envelope.

Thank you for your help!

I. Your Community

First, we have a few questions about your community and the value of water resources.

1. When you think of your community, what comes to mind first? (*Choose one*)

[ ] My neighborhood
[ ] My county
[ ] My ethnic group
[ ] My city
[ ] My watershed
[ ] My close friends and family
[ ] My workplace
[ ] Organizations/groups
[ ] My school system
[ ] Other (please specify) ____________________

2. How important are the following qualities of a community to you? *(Please check one box in each row)*

	Not at all important	Slightly important	Moderately important	Extremely important
a. Good relationships among neighbors	☐	☐	☐	☐
b. Clean streams, rivers, and lakes	☐	☐	☐	☐
c. Strong family ties	☐	☐	☐	☐
d. Access to aesthetically pleasing landscapes/views	☐	☐	☐	☐
e. Opportunities to express my culture and traditions	☐	☐	☐	☐
f. Clean and safe drinking water	☐	☐	☐	☐
g. Opportunities to be involved in community projects	☐	☐	☐	☐
h. Opportunities for and access to outdoor recreation	☐	☐	☐	☐
i. A place with a climate that fits my lifestyle	☐	☐	☐	☐

3. To what extent do you agree or disagree with the following statements? *(Please check one box in each row)*

	Strongly disagree	Somewhat disagree	Neither disagree nor agree	Somewhat agree	Strongly agree
a. Water resources in my community are adequately protected	☐	☐	☐	☐	☐
b. Water resources in Minnesota need better protection	☐	☐	☐	☐	☐
c. Protecting water in my neighborhood is a lost cause	☐	☐	☐	☐	☐
d. Water resources in Minnesota are at risk	☐	☐	☐	☐	☐
e. Conservation practices contribute to quality of life in my community	☐	☐	☐	☐	☐
f. My community has the leadership it needs to protect water resources	☐	☐	☐	☐	☐
g. Residents in my community have the ability to work together to protect water resources	☐	☐	☐	☐	☐

4. How familiar are you with water issues in your local area?

[ ] Not at all familiar   [ ] Slightly familiar   [ ] Moderately familiar   [ ] Very familiar

5. How would you characterize the quality of water in the lake, stream, or river closest to you?

[ ] Very poor   [ ] Poor   [ ] Fair   [ ] Good   [ ] Very good   [ ] Don't know

6. How would you characterize the quality of water in Minnesota water bodies overall?

[ ] Very poor   [ ] Poor   [ ] Fair   [ ] Good   [ ] Very good   [ ] Don't know

7. How important is it to protect and restore Minnesota waters (lakes, streams, rivers, and groundwater) for the following values and uses? *(Please check one box in each row)*

	Not at all important	Slightly important	Moderately important	Extremely important
a. Drinking water that is safe and clean	☐	☐	☐	☐
b. Beaches and lakes that are safe for swimming and playing	☐	☐	☐	☐
c. Consistent water supply to water-dependent industries like energy production and agriculture	☐	☐	☐	☐
d. Equitable access to public waters for all Minnesotans	☐	☐	☐	☐
e. Anglers to be able to fish for preferred species	☐	☐	☐	☐
f. Future generations	☐	☐	☐	☐
g. High quality recreation opportunities for my or my family's use	☐	☐	☐	☐
h. Habitat for native fish and wildlife to survive	☐	☐	☐	☐
i. Recreation and tourism businesses across Minnesota to continue to thrive	☐	☐	☐	☐
j. Ricers to be able to harvest in historically abundant wild rice waters	☐	☐	☐	☐
k. The heritage and identity of Minnesota	☐	☐	☐	☐
l. Lakeshore landowners to maintain their property values	☐	☐	☐	☐
m. Healthful and natural foods for people	☐	☐	☐	☐
n. Consistent water supply for watering lawns and landscaping around my neighborhood	☐	☐	☐	☐
o. Towns and cities to avoid costly water treatment expenses	☐	☐	☐	☐
p. Natural systems and processes to be sustained	☐	☐	☐	☐
q. Minnesota <u>not</u> to send water pollution downstream to other states or nations	☐	☐	☐	☐

r. From the previous list (Question 7, a-q), what three water values or uses are <u>most important to you</u>? (*Please list in order of first, second, and third most important*)

1. ______ 2. ______ 3. ______

8. In the last twelve months, about <u>how many times</u> did you visit a lake, river, or stream in Minnesota in which visiting the water body <u>was one of the primary purposes of your trip</u>?

[ ] 0 (I did not visit a water body) [ ] 1-3 [ ] 4-12 [ ] 13-24 [ ] 25 or more

9. What lake, river, or stream do you visit most often in Minnesota? What city is it in or closest to?

Body of water ______________________ Closest city _________________

a. When you visit this water body, what activities do you engage in? *(Please check all that apply)*

[ ] Swimming
[ ] Hiking or walking near water
[ ] Observing water or wildlife
[ ] Picnicking near water
[ ] Wading or playing in the water
[ ] Motorized boating
[ ] Non-motorized boating (canoeing, kayaking, paddle-boarding, etc.)
[ ] Spiritual or cultural practices
[ ] Fishing (open water)
[ ] Ice fishing
[ ] Biking near water
[ ] Gathering plants (e.g., wild rice)
[ ] Getting together with others (e.g., friends, family)
[ ] Hunting waterfowl
[ ] Other (please specify) ______________________

b. Do you have a home or vacation property near this water body?

[ ] Yes [ ] No

c. To reach this body of water, about how long do you have to travel from your home?

[ ] 0-5 minutes (I don't have to travel)
[ ] 6-20 minutes (It's in my community)
[ ] 21-60 minutes (It's in a nearby community)
[ ] More than 1 hour to less than 4 hours
[ ] 4 or more hours

II. Concerns about Water

Next, we would like to know if you have concerns about water.

10. To what extent do you agree or disagree with the following statements? *(Please check one box in each row)*

I am concerned about the consequences of water problems or pollution for….	Strongly disagree	Somewhat disagree	Neither disagree nor agree	Somewhat agree	Strongly agree
a. Cultural heritage in Minnesota	☐	☐	☐	☐	☐
b. Recreation opportunities	☐	☐	☐	☐	☐
c. Human health	☐	☐	☐	☐	☐
d. Future generations	☐	☐	☐	☐	☐
e. Aquatic life	☐	☐	☐	☐	☐
f. Local economies	☐	☐	☐	☐	☐
g. People in my community	☐	☐	☐	☐	☐
h. Downstream communities outside of Minnesota	☐	☐	☐	☐	☐

11. In your opinion, how much of a problem are the following water pollutants or issues to water in your local area? *(Please check one box in each row)*

	Not a problem	Slight problem	Moderate problem	Severe problem	Don't know
a. Industrial discharge to streams, rivers, and lakes	☐	☐	☐	☐	☐
b. Agricultural drainage (e.g., drain tiles)	☐	☐	☐	☐	☐
c. Agricultural runoff (e.g., nutrients, fertilizers, pesticides)	☐	☐	☐	☐	☐
d. Sediment in water bodies	☐	☐	☐	☐	☐
e. Urban runoff (e.g., oil, grease, toxic chemicals)	☐	☐	☐	☐	☐
f. Contaminants of emerging concern (e.g., pharmaceuticals, personal care products)	☐	☐	☐	☐	☐
g. Increased frequency or intensity of floods	☐	☐	☐	☐	☐
h. Declining lake water levels	☐	☐	☐	☐	☐
i. Unsealed private wells	☐	☐	☐	☐	☐
j. Road salt runoff (chloride)	☐	☐	☐	☐	☐
k. Bacterial contamination	☐	☐	☐	☐	☐
l. Water scarcity	☐	☐	☐	☐	☐
m. Faulty septic and sewage systems	☐	☐	☐	☐	☐
n. Aquatic invasive species	☐	☐	☐	☐	☐

III. Protecting Water

Now, we would like to understand your perspectives on actions to protect water.

12. To what extent do you agree or disagree with the following statements? *(Please check one box in each row)*

	Strongly disagree	Somewhat disagree	Neither disagree nor agree	Somewhat agree	Strongly agree
a. It is my personal responsibility to help protect water.	☐	☐	☐	☐	☐
b. Local government should be responsible for protecting water.	☐	☐	☐	☐	☐
c. The state government should be responsible for protecting water.	☐	☐	☐	☐	☐
d. Residents in my area should be responsible for protecting water.	☐	☐	☐	☐	☐
e. The agricultural community in my area should be responsible for protecting water.	☐	☐	☐	☐	☐
f. The urban community in my area should be responsible for protecting water.	☐	☐	☐	☐	☐
g. People in my community expect me to help protect water.	☐	☐	☐	☐	☐

13. To what extent do you support or oppose the following water actions? *(Please check one box in each row)*

	Strongly oppose	Somewhat oppose	Neither oppose nor support	Somewhat support	Strongly support
a. Using conservation practices in my home or on my property	☐	☐	☐	☐	☐
b. Promoting voluntary conservation practices through increased education and outreach programs	☐	☐	☐	☐	☐
c. Expanding programs that offer financial incentives to residents/property owners for conservation practices	☐	☐	☐	☐	☐
d. Engaging more residents in local land use and water resource decision-making	☐	☐	☐	☐	☐
e. Coordinating land use and water planning and management across communities at a regional scale	☐	☐	☐	☐	☐
f. Conducting more water research	☐	☐	☐	☐	☐
g. Monitoring the status and trends of our water bodies	☐	☐	☐	☐	☐
h. Enforcing existing land use laws and regulations	☐	☐	☐	☐	☐
i. Expanding public and private partnerships in conservation	☐	☐	☐	☐	☐
j. Increasing land use laws and regulations	☐	☐	☐	☐	☐

14. Where do you get information on water-related issues? *(Please check all that apply)*

[ ] Family and friends
[ ] Federal agencies/government
[ ] Tribal agencies/government
[ ] State agencies/government
[ ] County agencies/government
[ ] City or township government
[ ] My neighbors
[ ] Community nonprofit organizations
[ ] Environmental organizations
[ ] University researchers/academic community
[ ] Local business owners/industry experts
[ ] Faith/religious leaders
[ ] Agricultural groups/producers
[ ] Elders in my community
[ ] News media
[ ] Other (please specify): ________________

15. Below are three potential funding scenarios (A-C) for distributing water program funds in Minnesota across four different water program areas (e.g., safe drinking water).

Water Program Areas	Scenario A	Scenario B	Scenario C
Safe drinking water	40%	40%	10%
High quality swimming and boating	40%	10%	10%
Healthy fish and wildlife populations	10%	40%	40%
Reduce MN's contribution to water problems outside state lines (e.g., Gulf of Mexico, Lake Winnipeg)	10%	10%	40%
Total	=100%	=100%	=100%

Of the three funding scenarios, which would you support the most? *(check one box below)*

[ ] Scenario A [ ] Scenario B [ ] Scenario C

16. Now, we would like you to freely assign the proportion of funding that you think should go to each of the four water program areas. *(Please write a percentage for each funding area. Your total should equal 100%.)*

	Safe drinking water	High quality swimming and boating	Healthy fish and wildlife populations	Reduce MN's contribution to water problems outside state lines (e.g., Gulf of Mexico, Lake Winnipeg)	
My own funding scenario	______	______	______	______	=100%

17. Have you engaged in the following actions or initiatives in the past 12 months? If yes, how often did you engage in the action or initiative?

	First, have you engaged in the following actions or initiatives in the past 12 months?		Second, if you marked "yes", how often did you engage in the action or initiative in the past 12 months?			
	Yes	No	Every few months	Once a month	Every two weeks	Weekly or more
a. Volunteered for a community organization or an event	☐	☐	☐	☐	☐	☐
b. Helped organize a community program	☐	☐	☐	☐	☐	☐
c. Heard about a water resource protection initiative	☐	☐	☐	☐	☐	☐
d. Talked to others about conservation practices	☐	☐	☐	☐	☐	☐
e. Attended a meeting or public hearing about water	☐	☐	☐	☐	☐	☐
f. Worked with other community members to protect water	☐	☐	☐	☐	☐	☐
g. Taken a leadership role around water resource conservation in the community	☐	☐	☐	☐	☐	☐

18. To what extent have you engaged in the following conservation actions in the past 12 months?

	Never	I have in some areas/occasionally	I have wherever and whenever possible
a. Maintained a vegetative buffer along streams, ditches or lakes on my property	☐	☐	☐
b. Used conservation agricultural practices (e.g., no till, cover crops)	☐	☐	☐
c. Donated money to a conservation organization	☐	☐	☐
d. Reduced or changed my personal household water consumption (e.g., turning off faucet while brushing teeth, etc.)	☐	☐	☐
e. Protected or restored wetlands on my land/property	☐	☐	☐
f. Used a rain barrel or cistern to store water	☐	☐	☐
g. Planted or maintained native plants or shrubs in my yard	☐	☐	☐
h. Minimized use of fertilizers/pesticides on lawns and gardens	☐	☐	☐
i. Other (please specify): ______________________	☐	☐	☐

IV. About you

Finally, we have a few questions about you. As a reminder, your responses to the survey are completely confidential and will only be used in aggregate—or in group form. No individual responses will be published.

19. In what year were you born? ________________ [ ] Prefer not to respond

20. How do you describe yourself? [ ] Female [ ] Male [ ] Transgender [ ] Non-binary/gender non-conforming [ ] Prefer not to respond

21. What is the highest level of formal education you have completed? (Please check one box)

[ ] Did not finish high school
[ ] Completed high school
[ ] Some college but no degree
[ ] Associate degree or vocational degree
[ ] College bachelor's degree
[ ] Some college graduate work
[ ] Completed graduate degree (Master's or PhD)
[ ] Prefer not to respond

22. What category best describes you? (Please check all that apply)

[ ] **White**
For example, German, Irish, English, Italian, Polish, French, Swedish, Norwegian, etc.

[ ] **Hispanic, Latino, or Spanish heritage**
For example, Mexican or Mexican American, Puerto Rican, Cuban, Salvadoran, Dominican, Colombian, etc.

[ ] **Black or African American**
For example, African American, Jamaican, Haitian, Nigerian, Ethiopian, Somalian, etc.

[ ] **Asian**
For example, Chinese, Filipino, Asian Indian, Vietnamese, Hmong, Korean, Japanese, etc.

[ ] **American Indian or Alaska Native**
For example, Anishinaabe, Dakota (Sioux), Navajo Nation, Mayan, Aztec, Nome Eskimo Community, etc.

[ ] **Middle Eastern or North African**
For example, Lebanese, Iranian, Egyptian, Syrian, Moroccan, Algerian etc.

[ ] **Native Hawaiian or other Pacific Islander**
For example, Native Hawaiian, Samoan, Chamorro, Tongan, Fijian, Marshallese, etc.

[ ] **Some other race, ethnicity or heritage (Please specify):**
____

[ ] Prefer not to respond

23. Which of the following best describes your total household income from all sources in 2017 before taxes?
(Please check one box)

[ ] Under $20,000
[ ] $20,000 - $49,999
[ ] $50,000 - $74,999
[ ] $75,000 - $99,999
[ ] $100,000 - $149,999
[ ] $150,000 - $199,999
[ ] $200,000 - $249,999
[ ] $250,000 - $299,999
[ ] $300,000 or more
[ ] Prefer not to respond

24. Approximately what percentage of your total household income is dependent on the following areas?

Agricultural production ____% Forest production ____% Nature-based tourism or recreation-related industry ____%

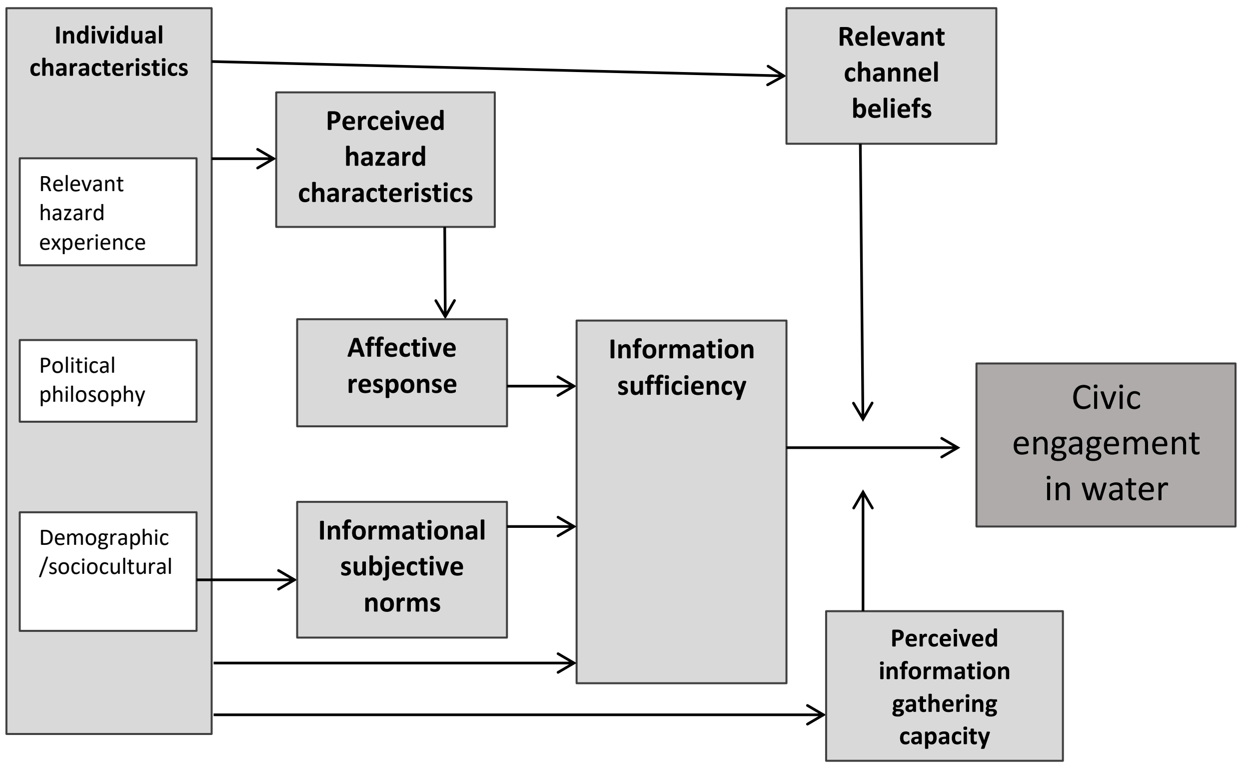
25. Do you have any other comments about water in Minnesota, or comments about this survey?

Thank you for your help!

Please complete the survey, fold it in thirds, and mail it back in the enclosed self-addressed stamped envelope.

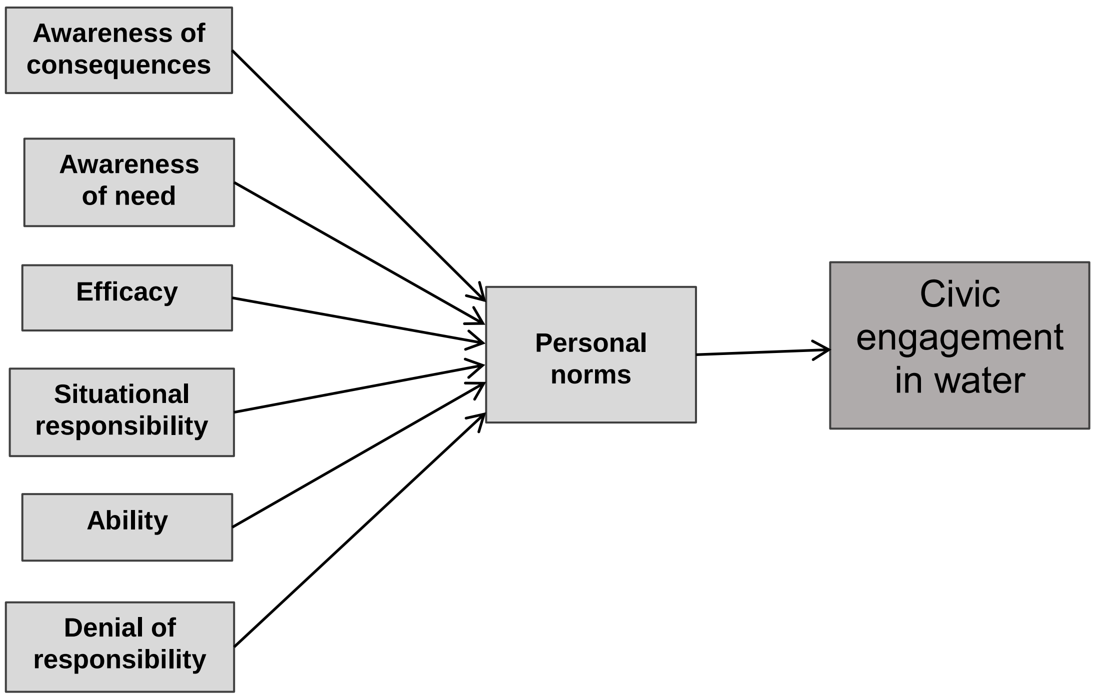
8

APPENDIX D: RISK INFORMATION SEEKING AND PROCESSING MODEL

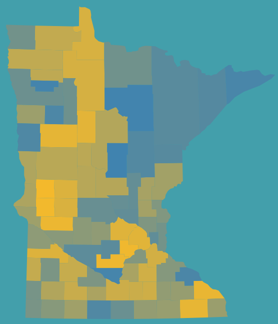


(Griffin, Dunwoody, and Neuwirth, 1999)

APPENDIX E: NORM ACTIVATION THEORY



(Schwartz, 1973)



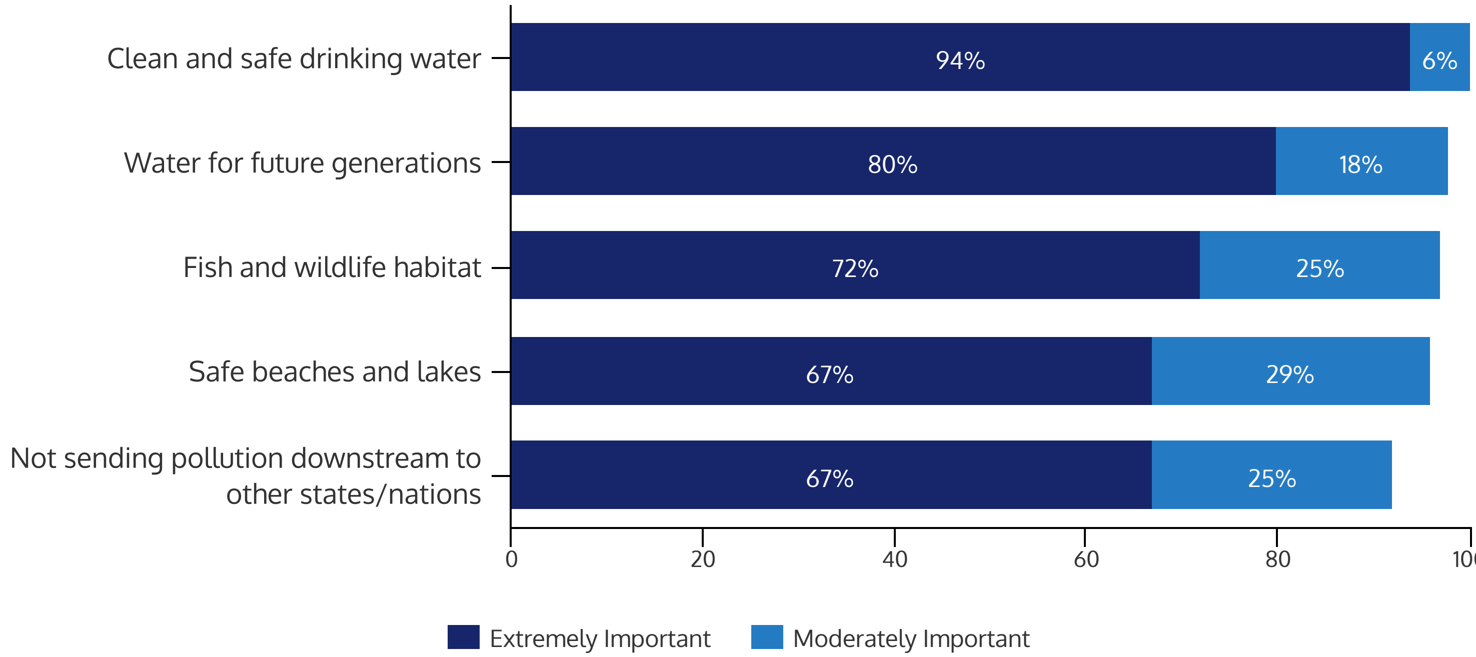
Minnesota Water Values

2019

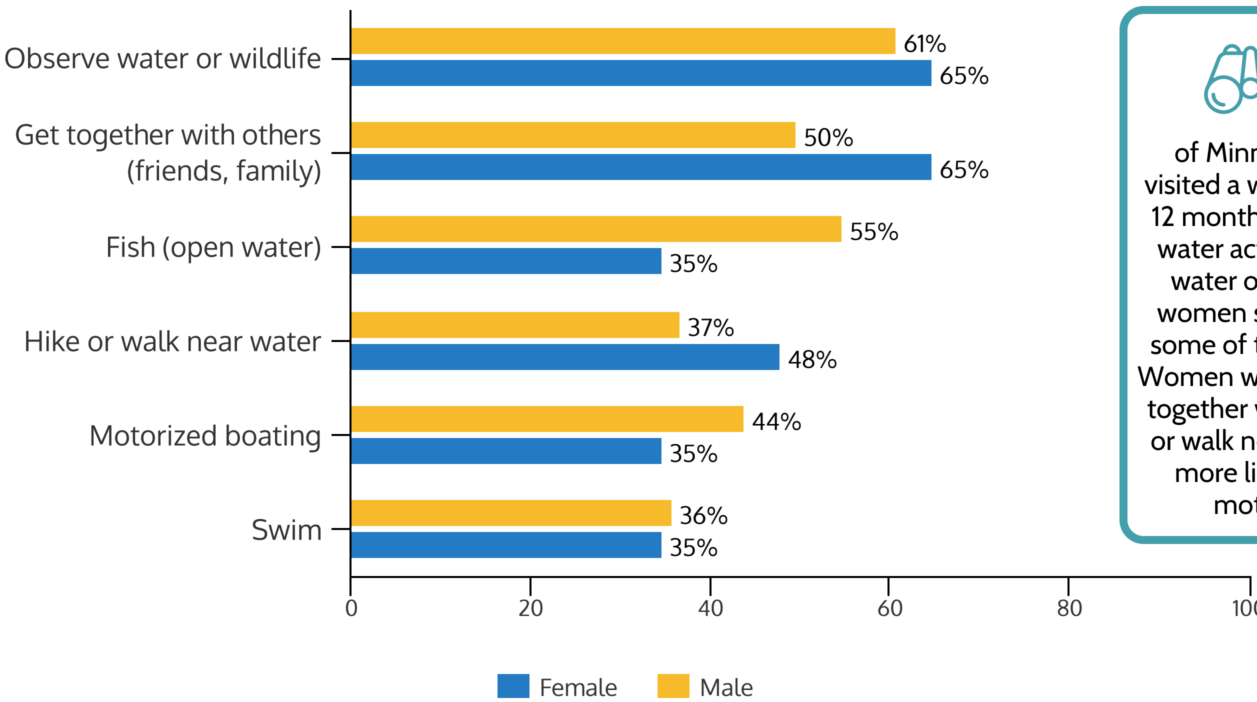
Statewide Resident Survey Report

Minnesota is the land of 11,842 lakes, home to the Mississippi River headwaters, and its residents are known for their love of water. But, *what* is it that Minnesotans value most about water? And, *how* should water be protected? In 2018 the University of Minnesota and partners* conducted the first-ever statewide survey of Minnesota residents on water values. The mail survey assessed residents' values, beliefs and behaviors associated with water. A total of 1,498 residents responded to the survey. The study findings will inform water policy making and programming across the state.

What water values are most important to Minnesotans?



What do Minnesotans do when they visit lakes, rivers or streams?



85%

of Minnesotans surveyed visited a water body in the last 12 months. The most popular water activity was observing water or wildlife. Men and women surveyed differed in some of their water activities. Women were more likely to get together with friends and hike or walk near water. Men were more likely to fish and go motorized boating.

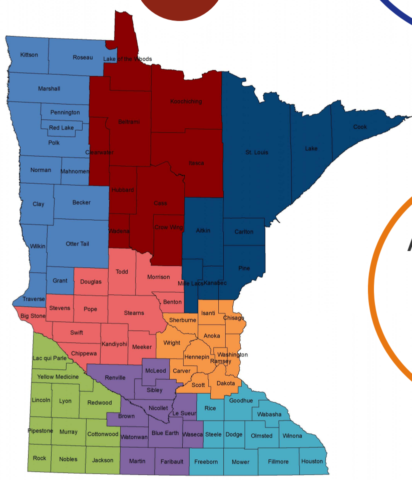
*This study was led by the Center for Changing Landscapes and Humphrey School of Public Affairs, University of Minnesota. Project partners include Minnesota Department of Health, Minnesota Clean Water Council and Legislative-Citizen Commission on Minnesota Resources. Project funding was provided by the Minnesota Clean Water Legacy Funds and Environment and Natural Resources Trust Fund. For more information about the study contact Mae Davenport at mdaven@umn.edu or 612-624-2721.

What are the top concerns about water across the state?

Aquatic invasive species
Ag runoff
Ag drainage

Aquatic invasive species
Ag runoff
Road salt runoff

Aquatic invasive species
Road salt runoff
Sediment



Aquatic invasive species
Ag runoff
Ag drainage

Aquatic invasive species
Urban runoff
Ag runoff

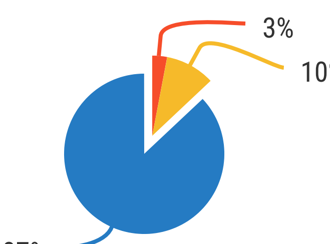
Ag runoff
Sediment
Ag drainage

Ag runoff
Ag drainage
Sediment

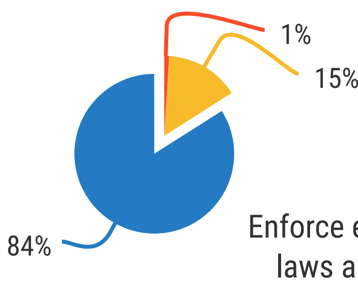
Ag runoff
Sediment
Aquatic invasive species

How should Minnesota water be protected?

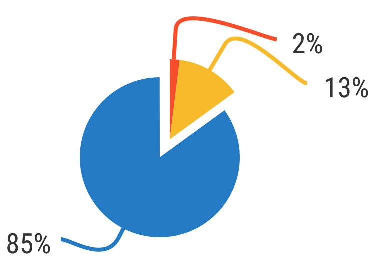
Conserve water at home



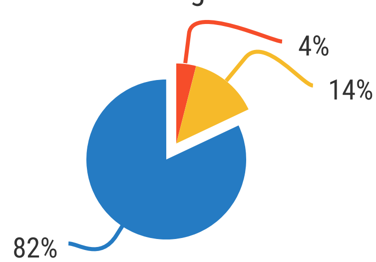
Increase education and outreach



Monitor the status and trends of water bodies



Enforce existing land use laws and regulations



- Support
- Neutral
- Oppose

74% of Minnesotans surveyed believe Minnesota water is at risk.

77% of survey respondents believe water resources in the state need better protection. Regional analysis revealed that central and northern Minnesota respondents are most concerned about aquatic invasive species, while southern residents are most concerned about agricultural runoff. Most respondents get their information on water-related issues from the news media, family and friends and county government.

Perceptions of community capacity to protect water vary. Slightly more than half (55%) of respondents think residents in their community can work together to protect water. Fewer than half (41%) think their community has the leadership it needs to protect water. When asked about their own civic engagement in water action, only 10% had worked with other community members and 4% had taken a leadership role in the community over the past 12 months.

Minnesotans surveyed expressed broad support (87%-73%) for a range of actions to protect and restore water. Most supported (82%) enforcing existing laws and regulations; respondents were more divided in their support (49%) for new laws and regulations to protect water.

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND
UNIVERSITY OF MINNESOTA
Driven to Discover®
CLEAN WATER LAND & LEGACY AMENDMENT

Assessment of Public Benefits of Protecting Source Water

Preliminary results – maps and visualization

February 28, 2019

Contents:

- Land use trends for DWSMAs
- Prioritization visualization with biophysical and socio-economic data
- Co-benefits visualization at the HUC8 level.
- Statewide resident survey

HUMPHREY SCHOOL OF PUBLIC AFFAIRS
UNIVERSITY OF MINNESOTA

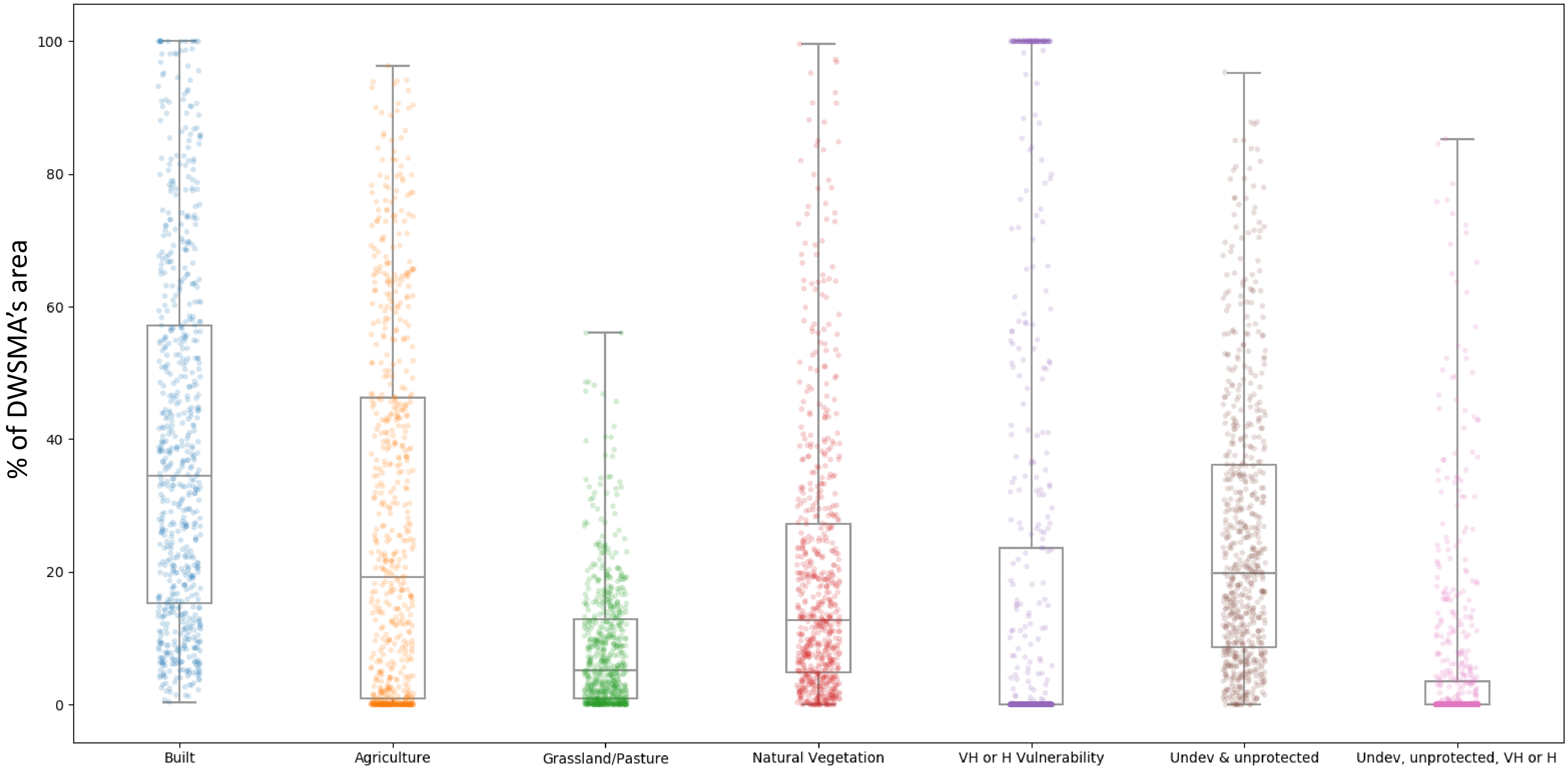
natural capital PROJECT

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND

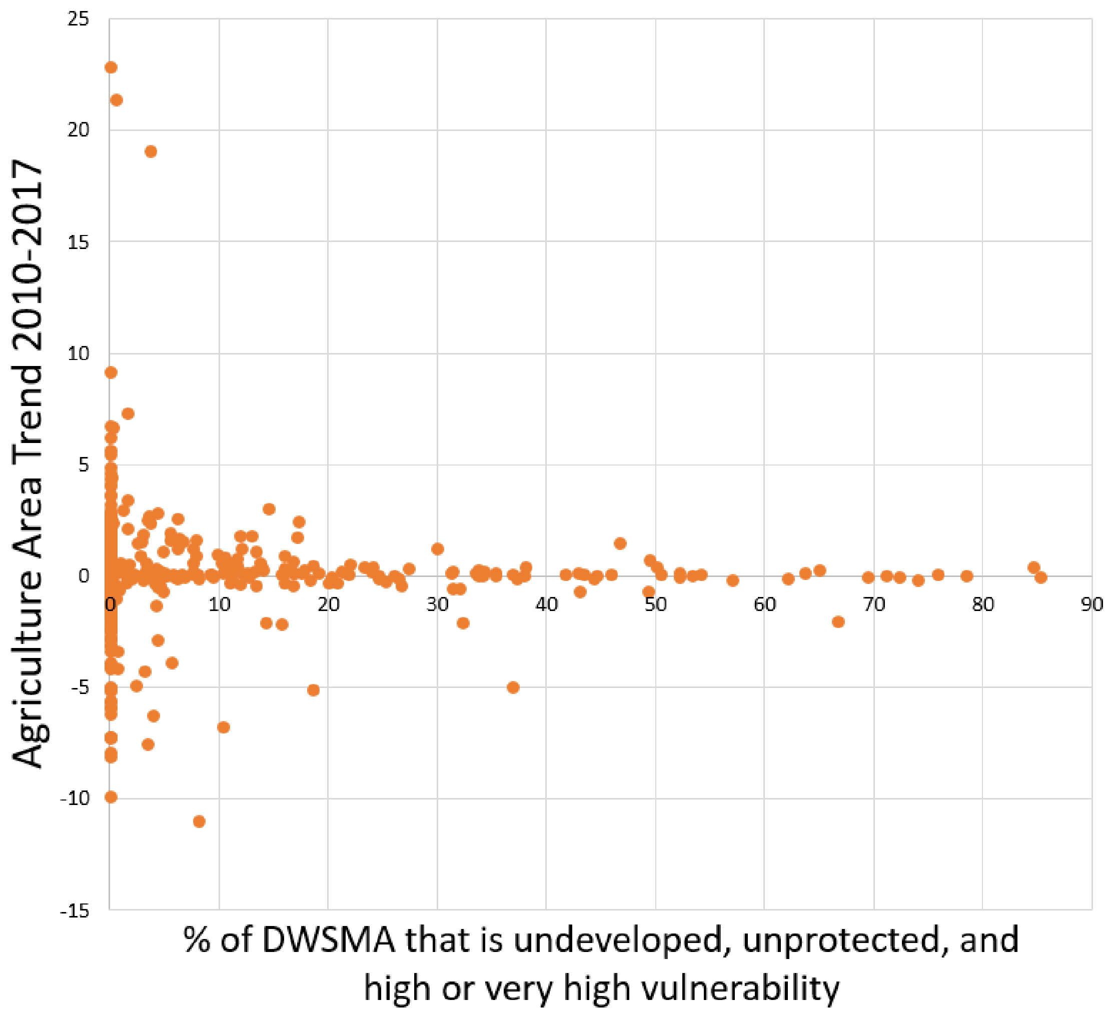
CLEAN WATER LAND & LEGACY AMENDMENT

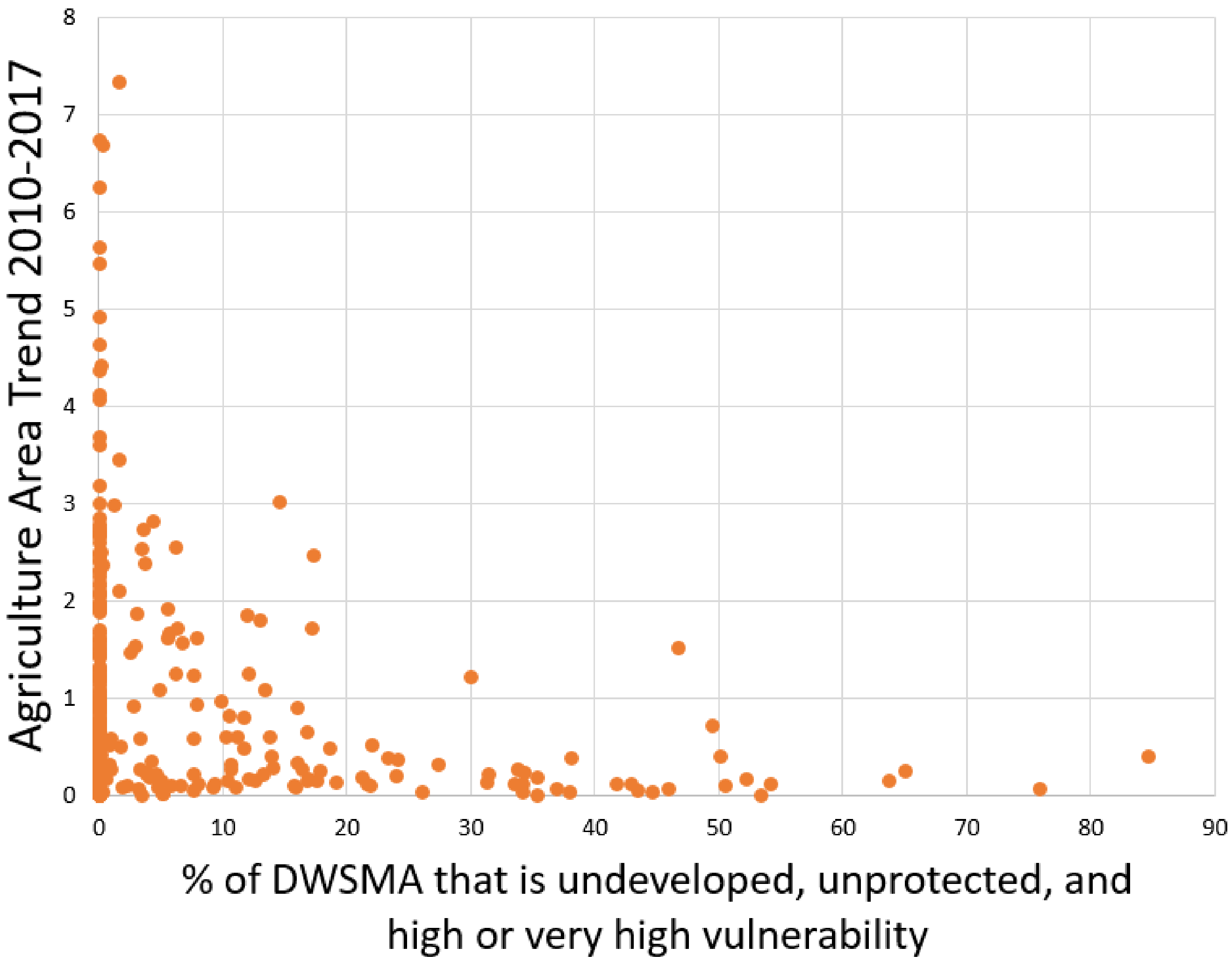
Land use trends for DWSMAs

DWSMA Land Use



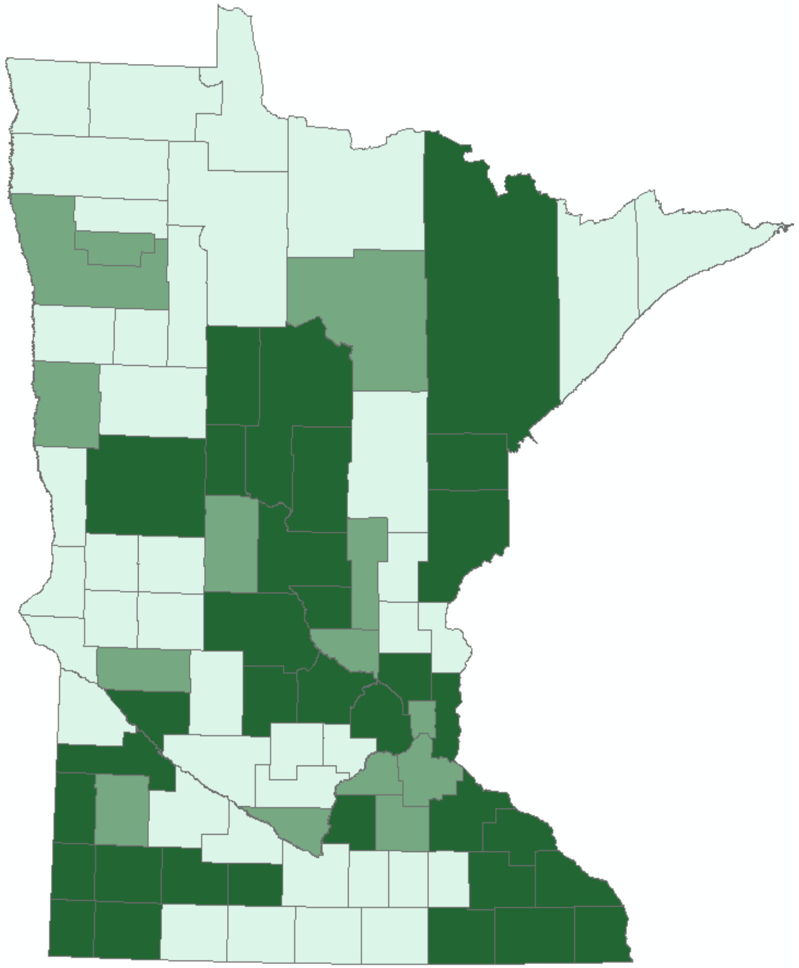
Slope of trend line for % ag 2010-2017 and groundwater vulnerability



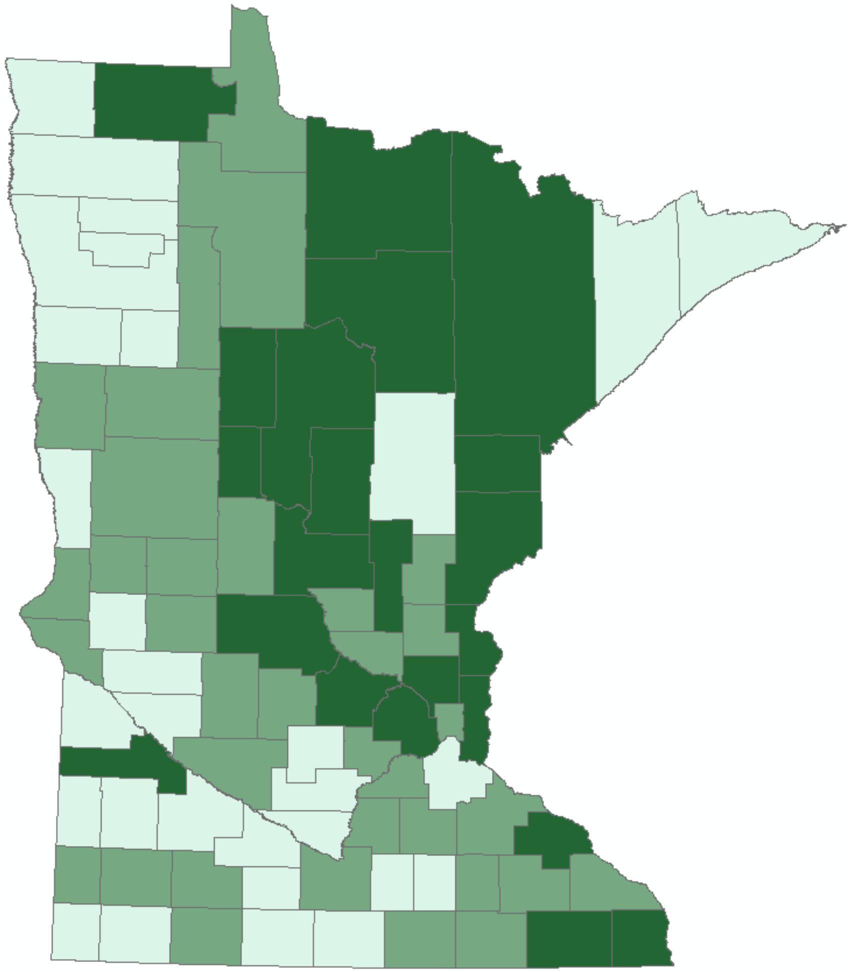


Prioritization visualization with biophysical and socio-economic data

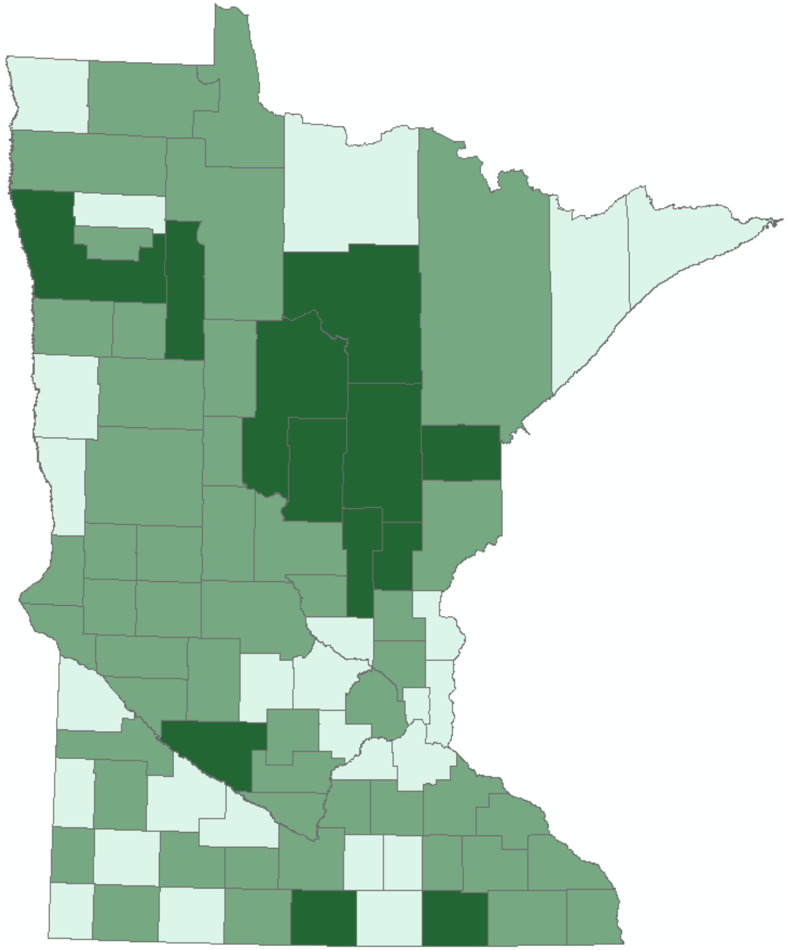
Counties with sourcewater areas high in …



Geologic Vulnerability



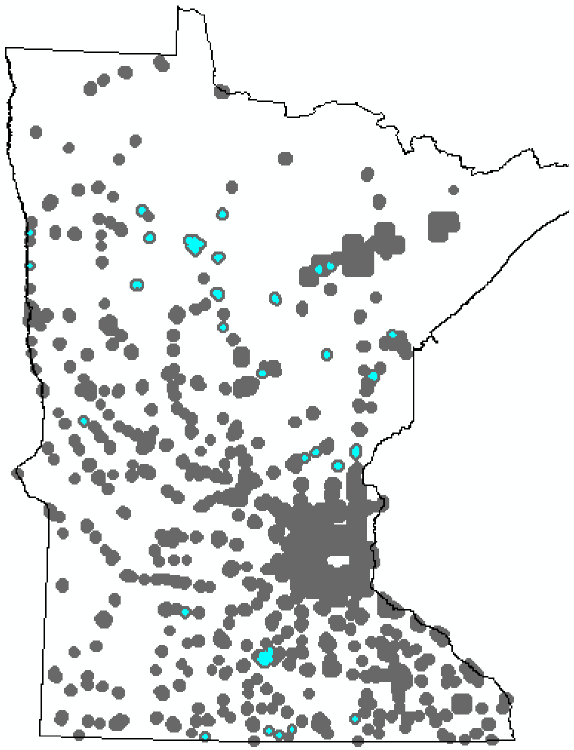
Unprotected & Undeveloped land



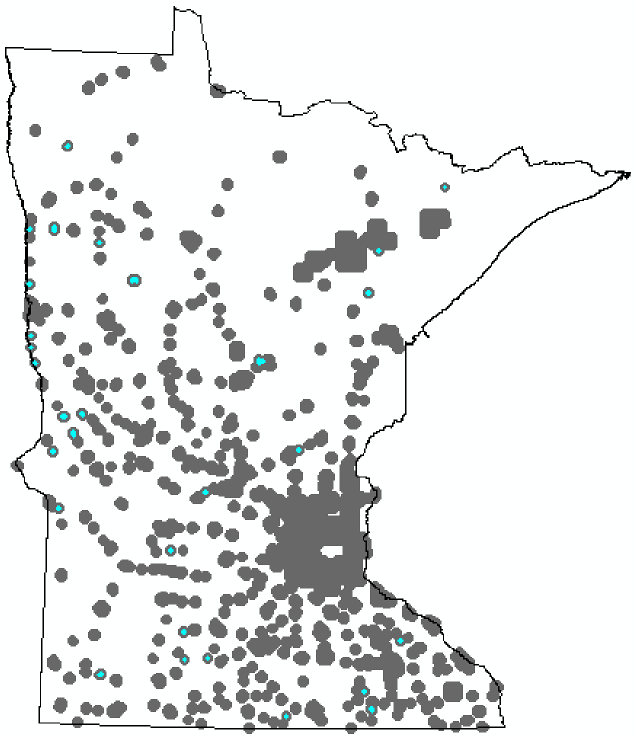
Poverty

Top 10% of DWSMAs when sorted by …

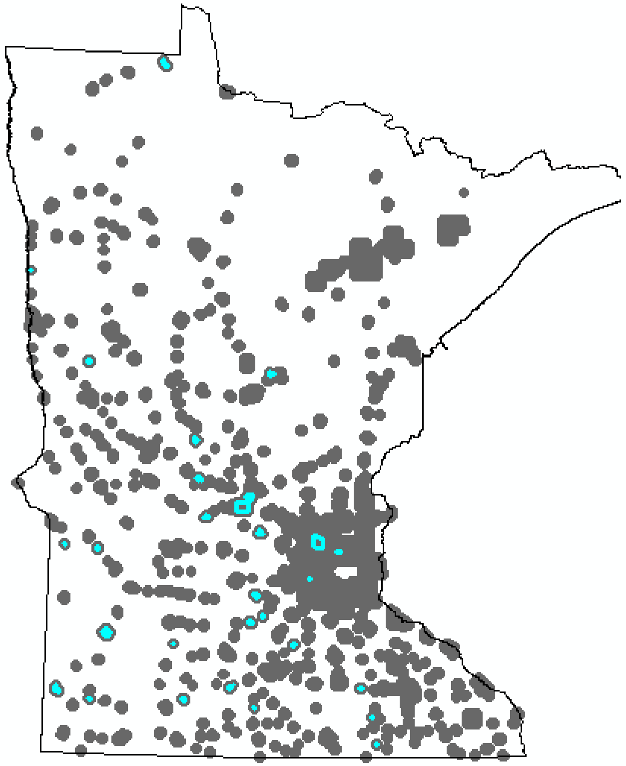
Below Poverty Line



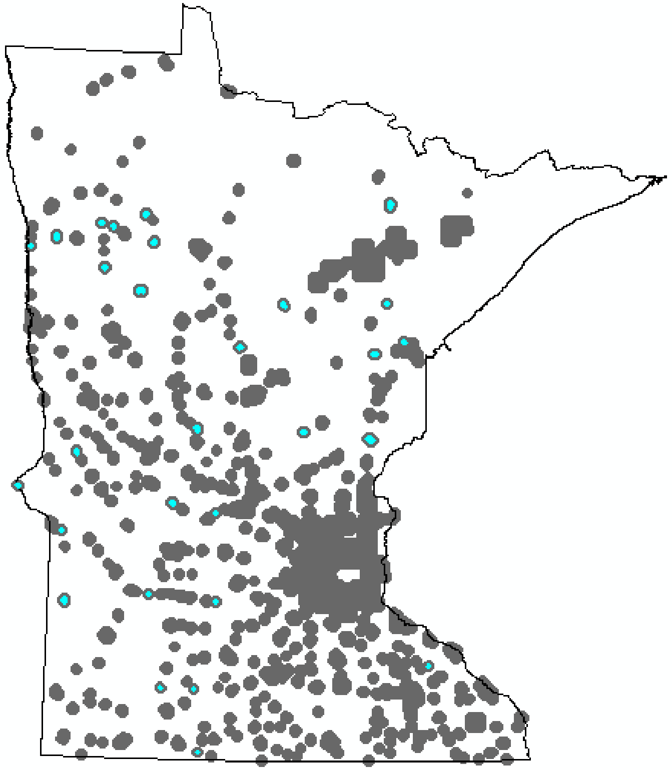
Low Population



English not spoken ‘very well’

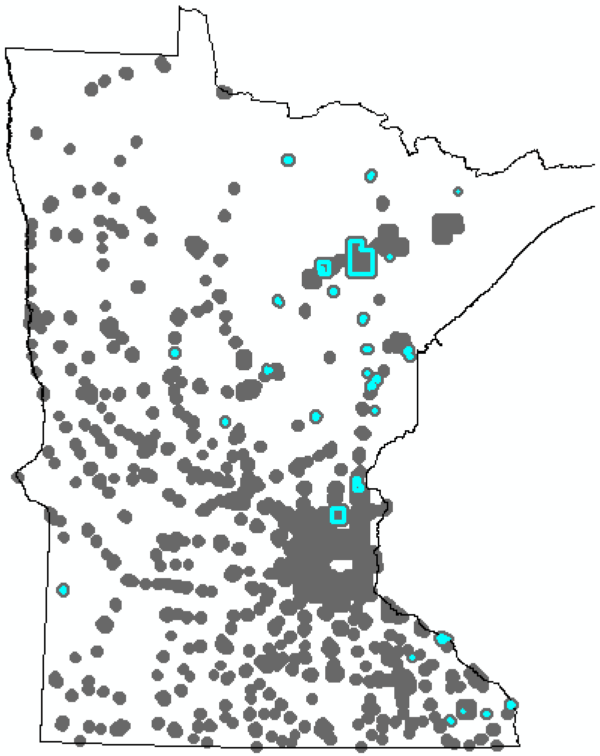


No Computer

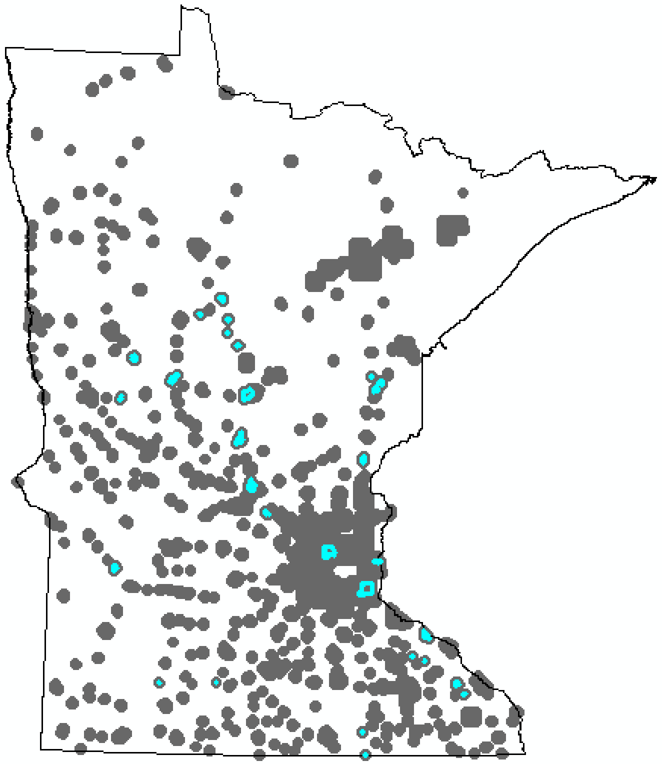


Top 10% of DWSMAs when sorted by …

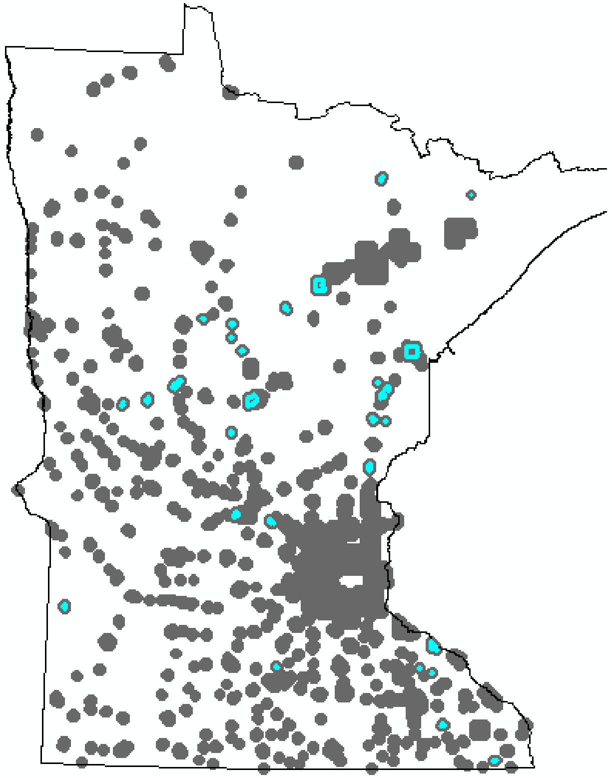
% Undeveloped
Unprotected



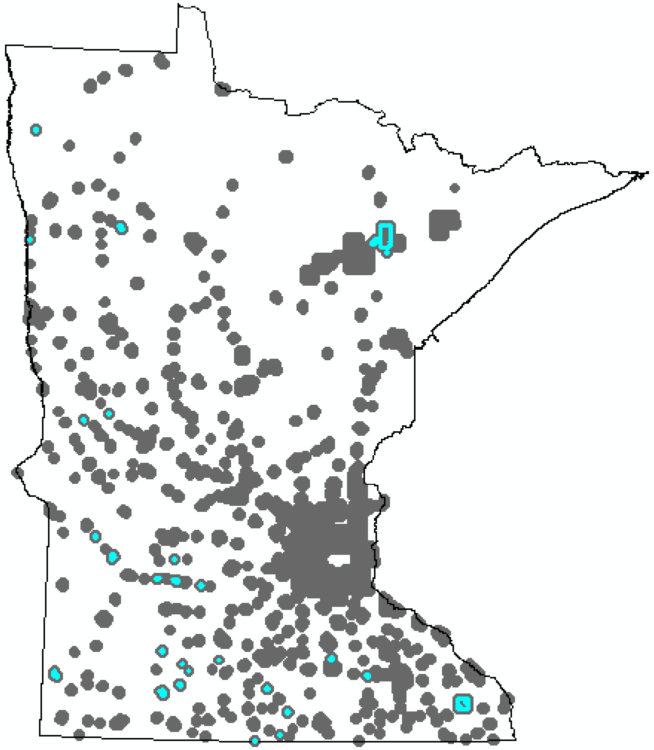
% Very high or High
GW vulnerability

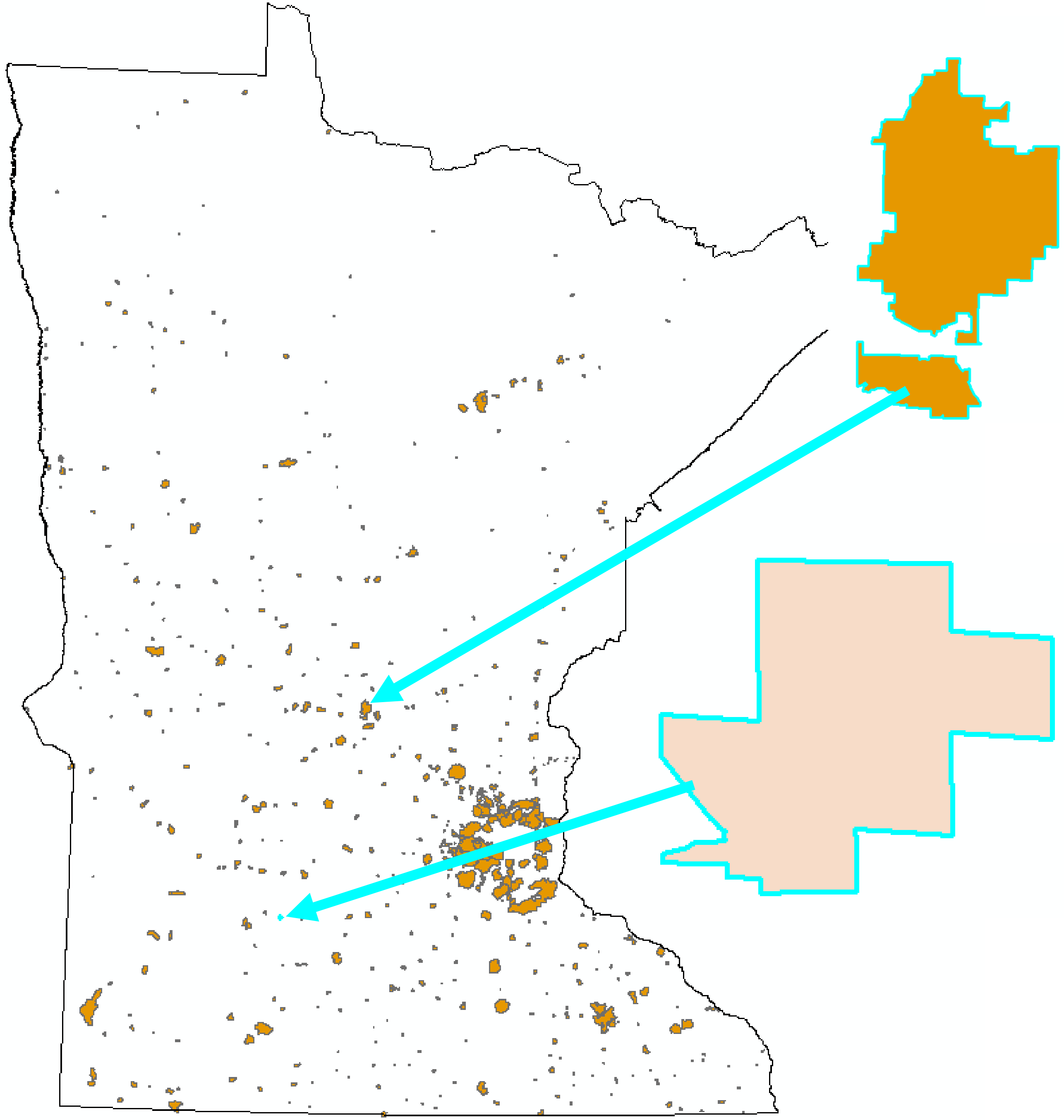


% Undeveloped and unprotected
VH and H GW vulnerability



Ag % trend line

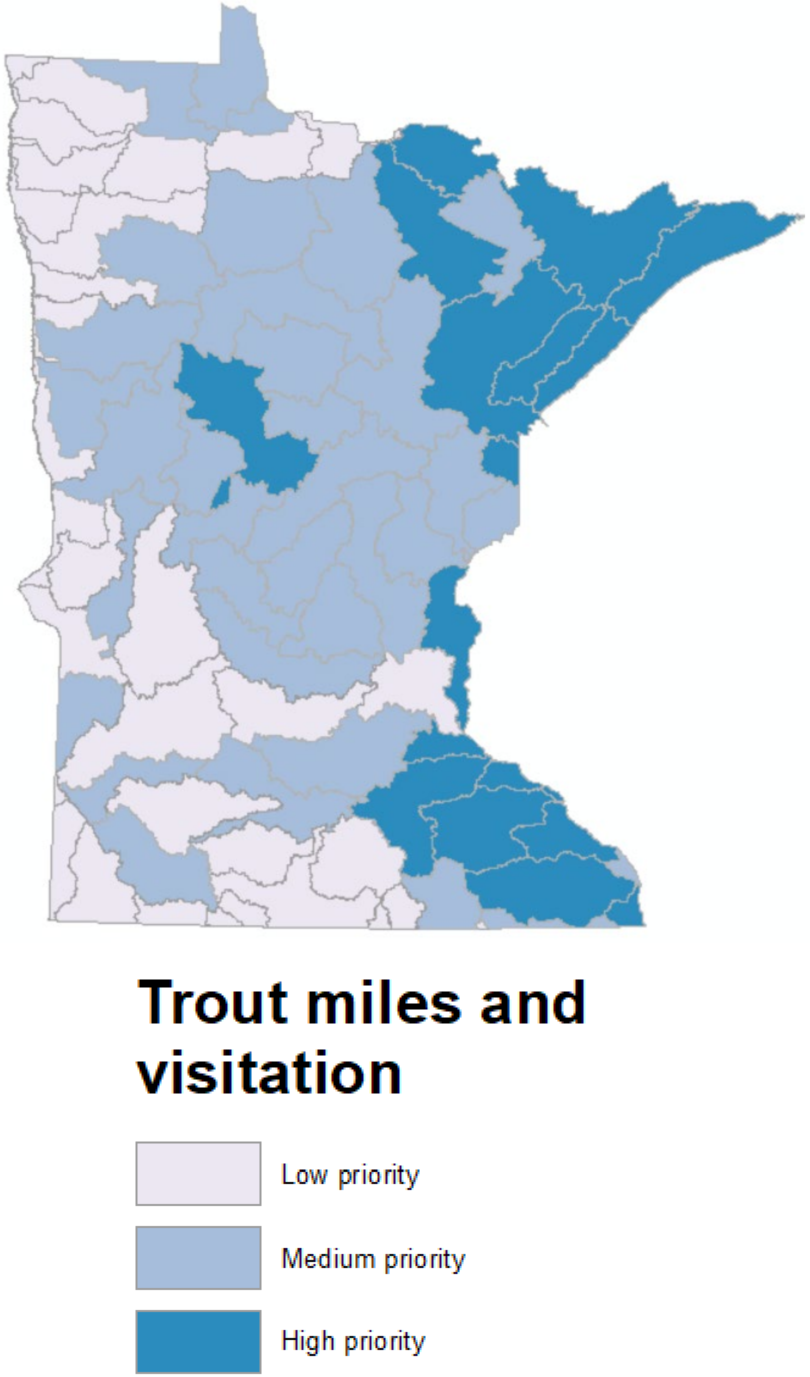


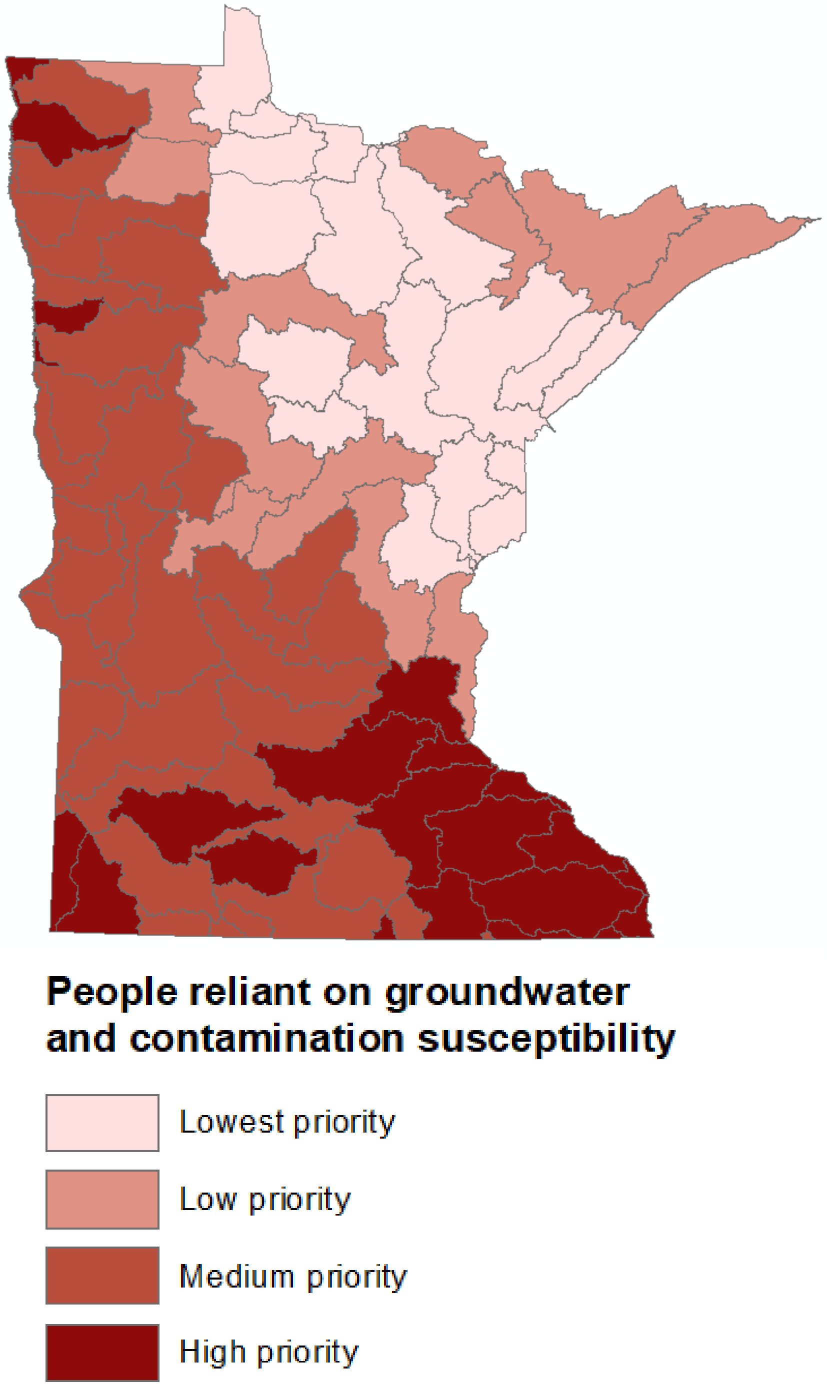


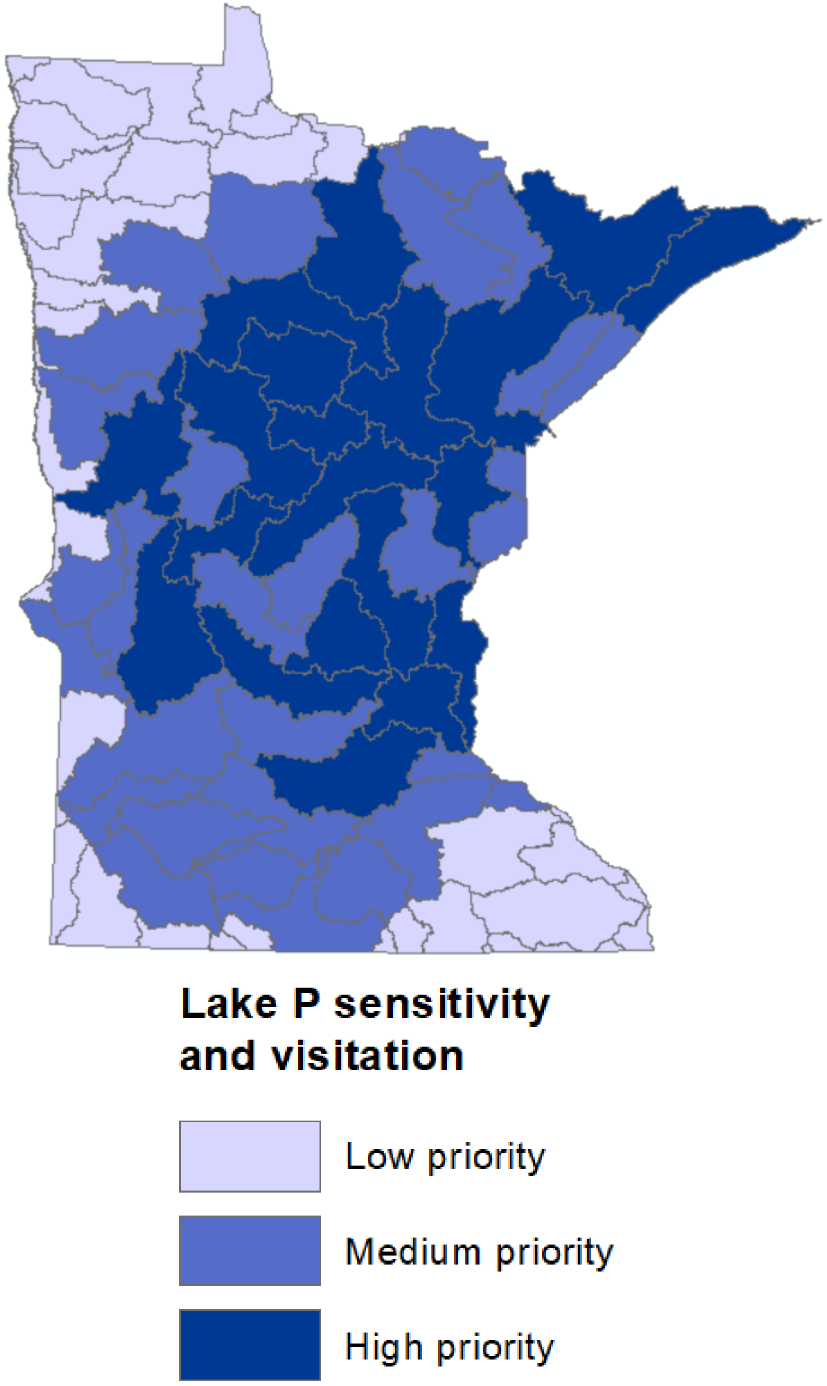
Sourcewater Area Name	Sartell
Total Population	16,442
% public/protected	0
% Undeveloped	54
% High geologic vulnerability	100
% Undeveloped & High geologic vulnerability	54

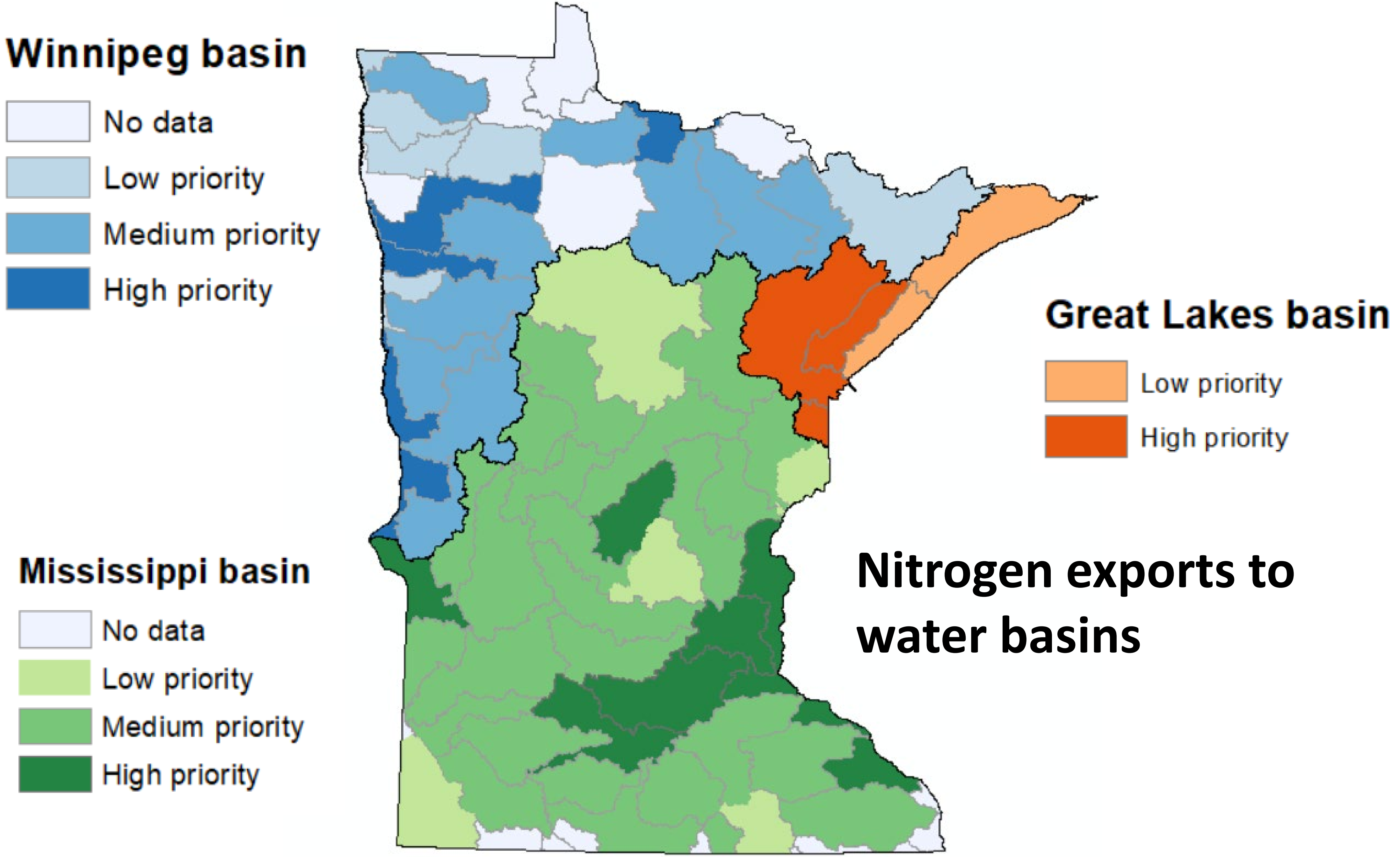
Sourcewater Area Name	Franklin
Total Population	529
% Poor	35.5
% Not Insured	17.4
% Language other than English	66.7
% Renter	32.1
% No Vehicle	7.7

Co-benefits visualization at the HUC8 level


Trout miles and visitation
Low priority
Medium priority
High priority


People reliant on groundwater and contamination susceptibility
Lowest priority
Low priority
Medium priority
High priority


Lake P sensitivity and visitation
Low priority
Medium priority
High priority

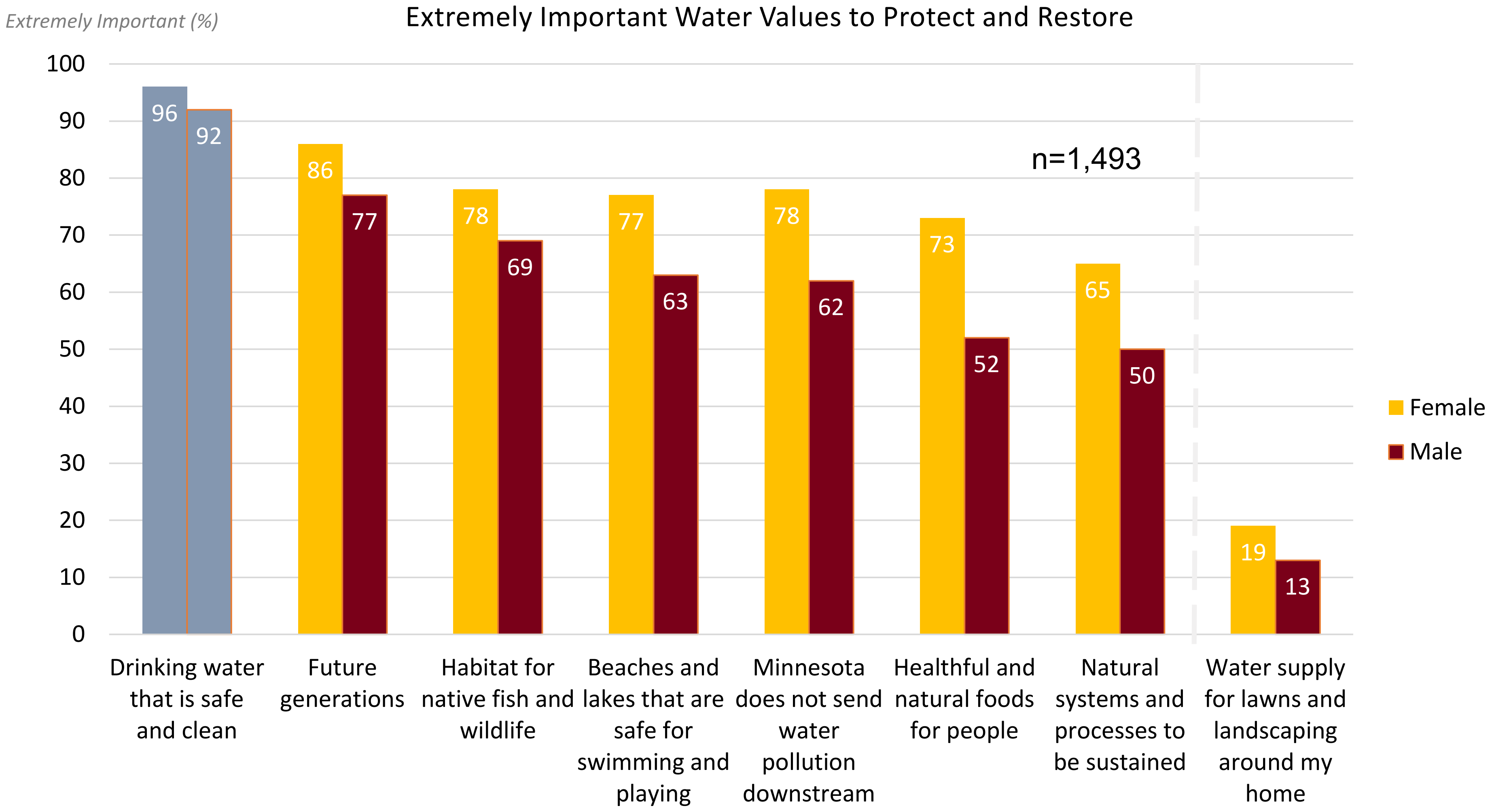


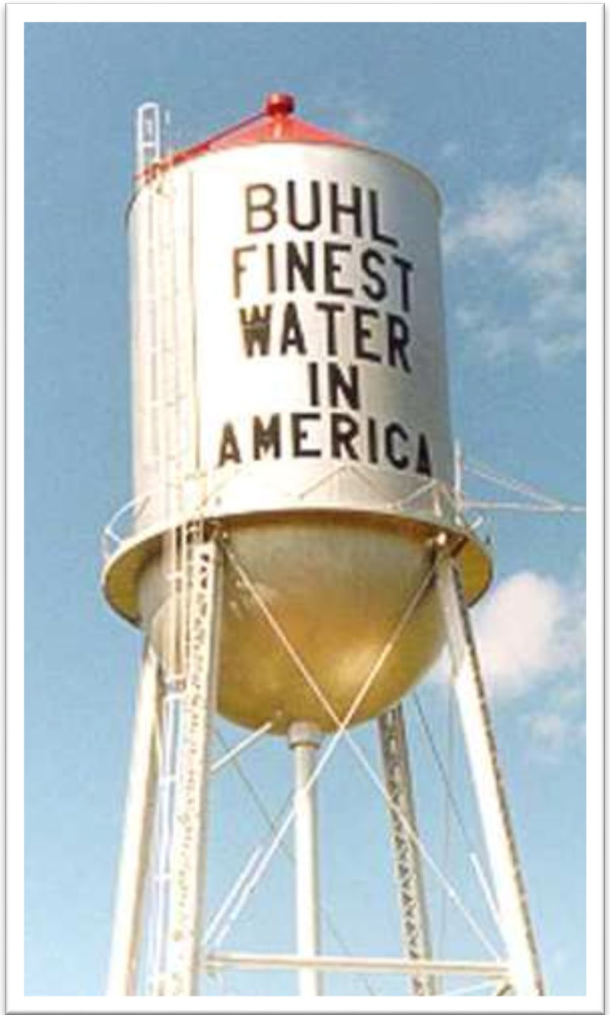
Nitrogen exports to water basins

Minnesota Water Values

A Statewide resident survey

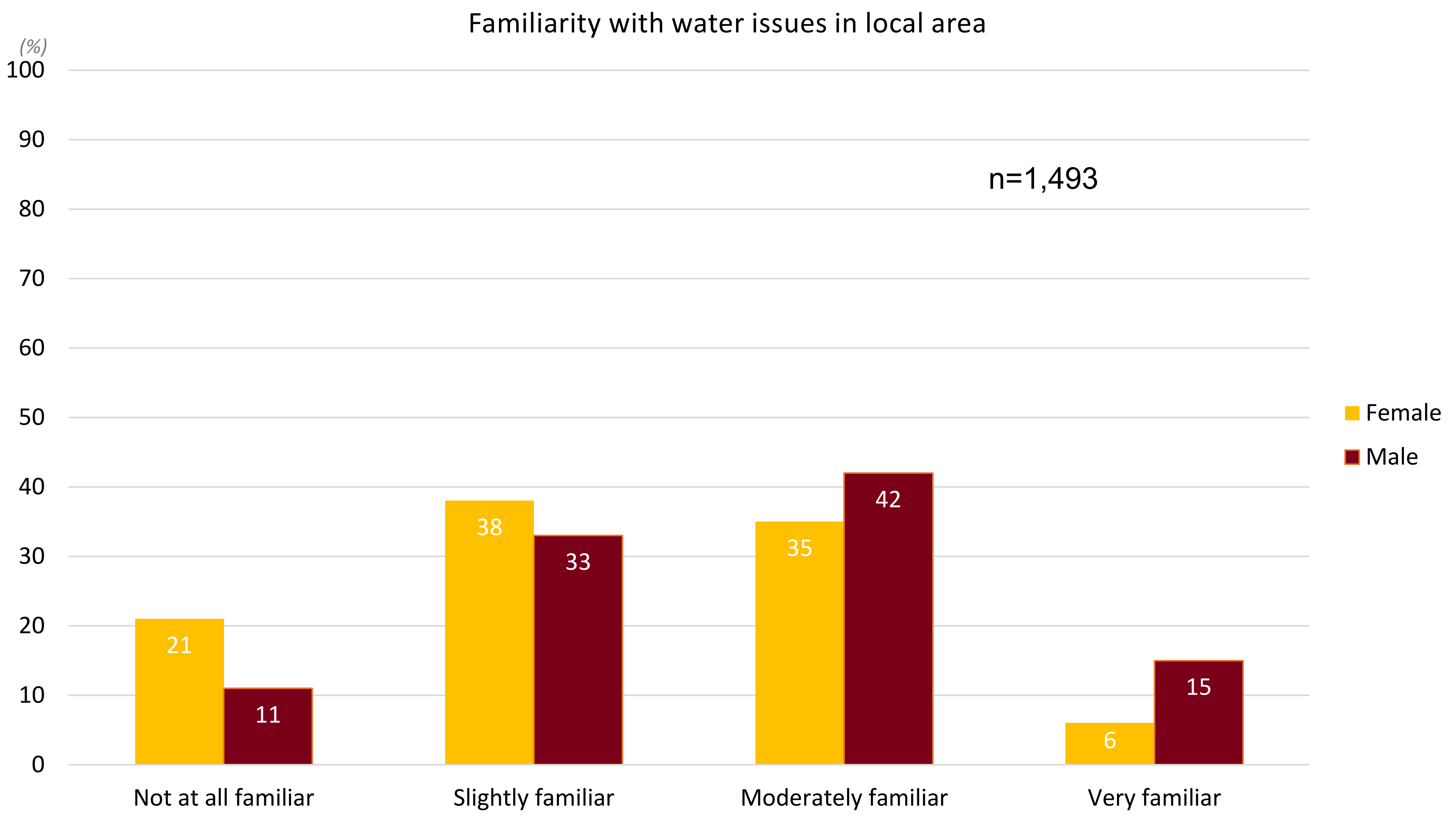
Water Has Many Different Values





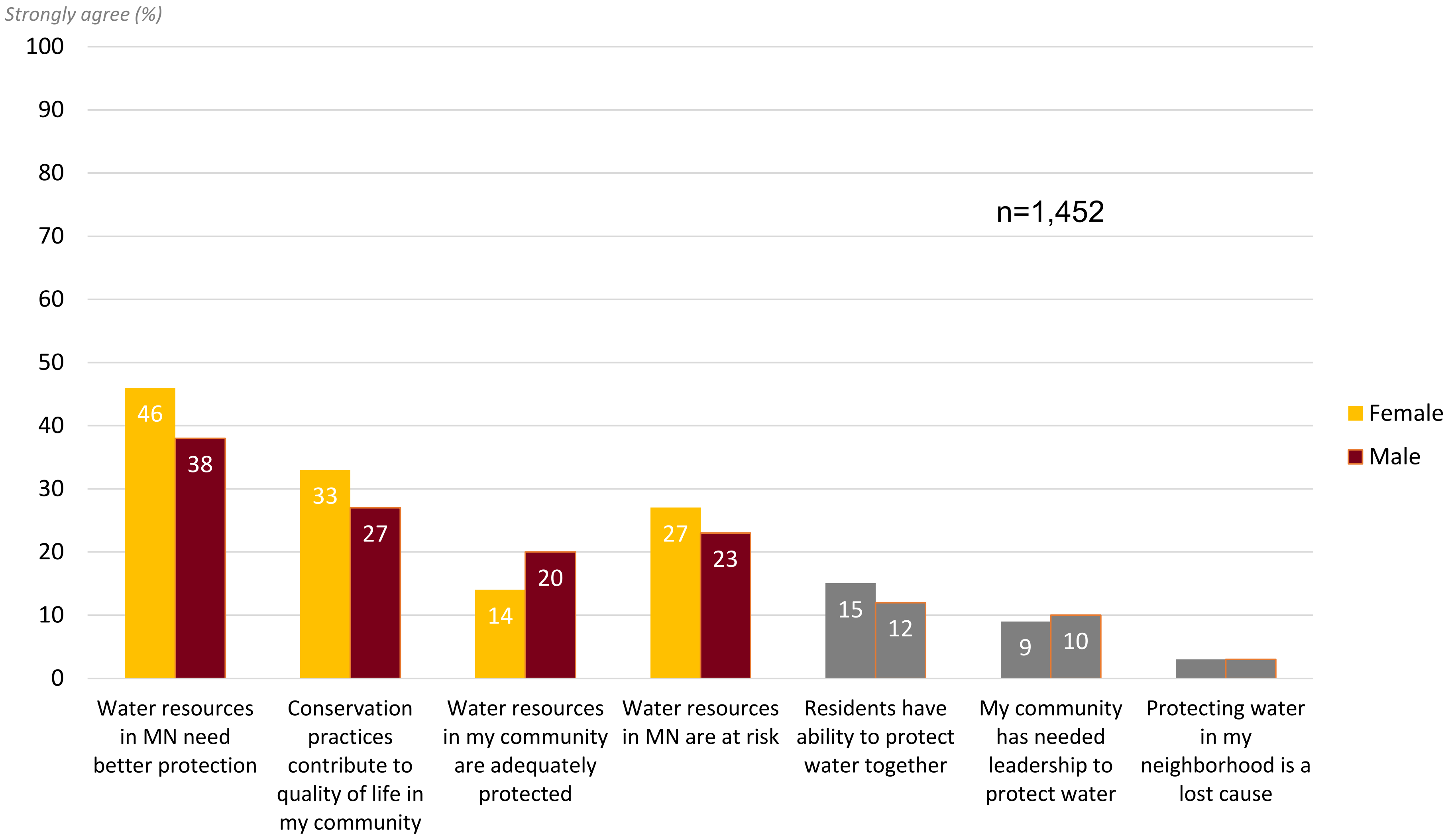
2018 Statewide Survey of Minnesota Water Values

Few are very familiar with local water issues



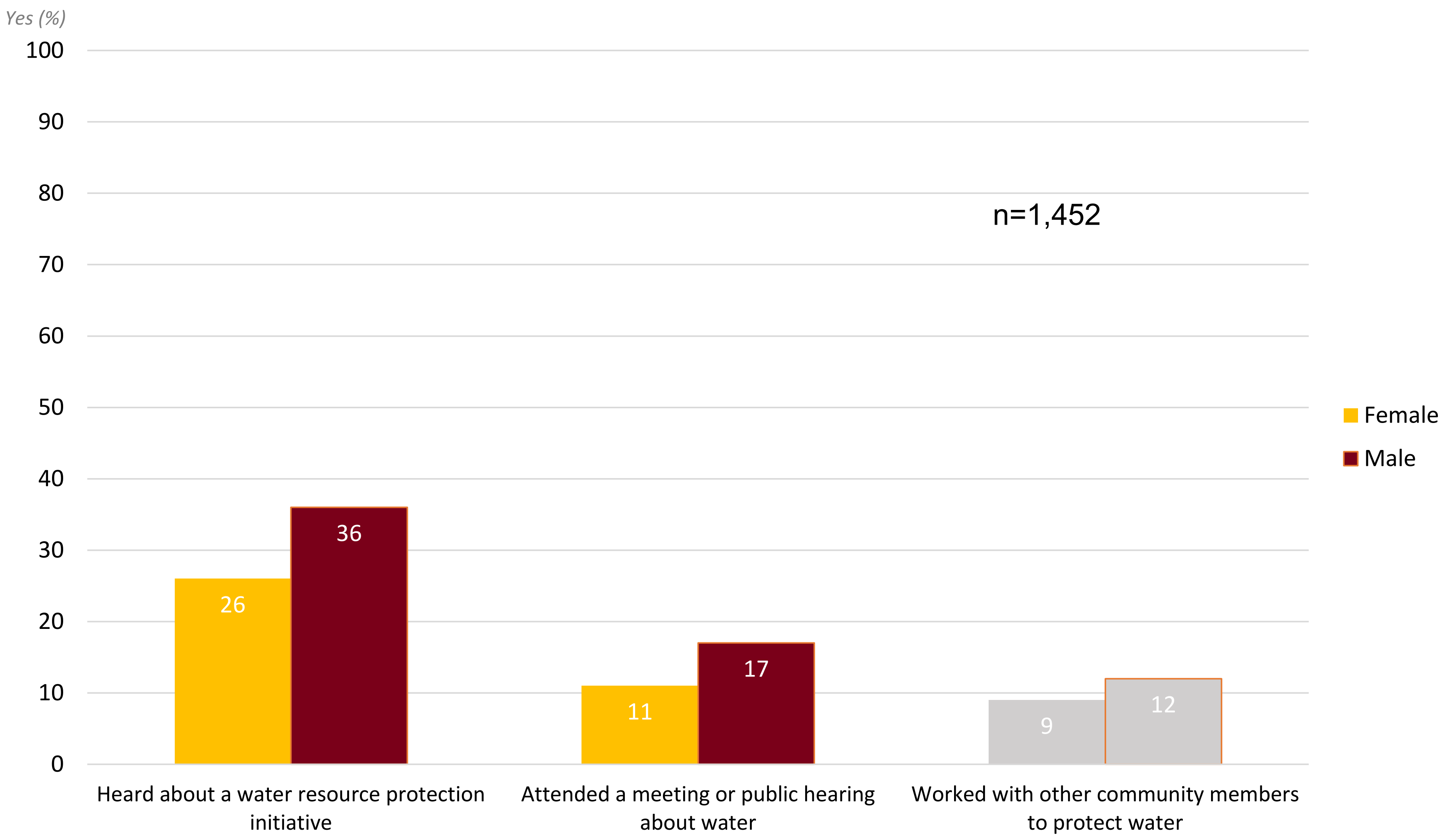
2018 Statewide Survey of Minnesota Water Values

Capacity-building for water protection is needed



2018 Statewide Survey of Minnesota Water Values

Civic Water Action in the Past 12 Months

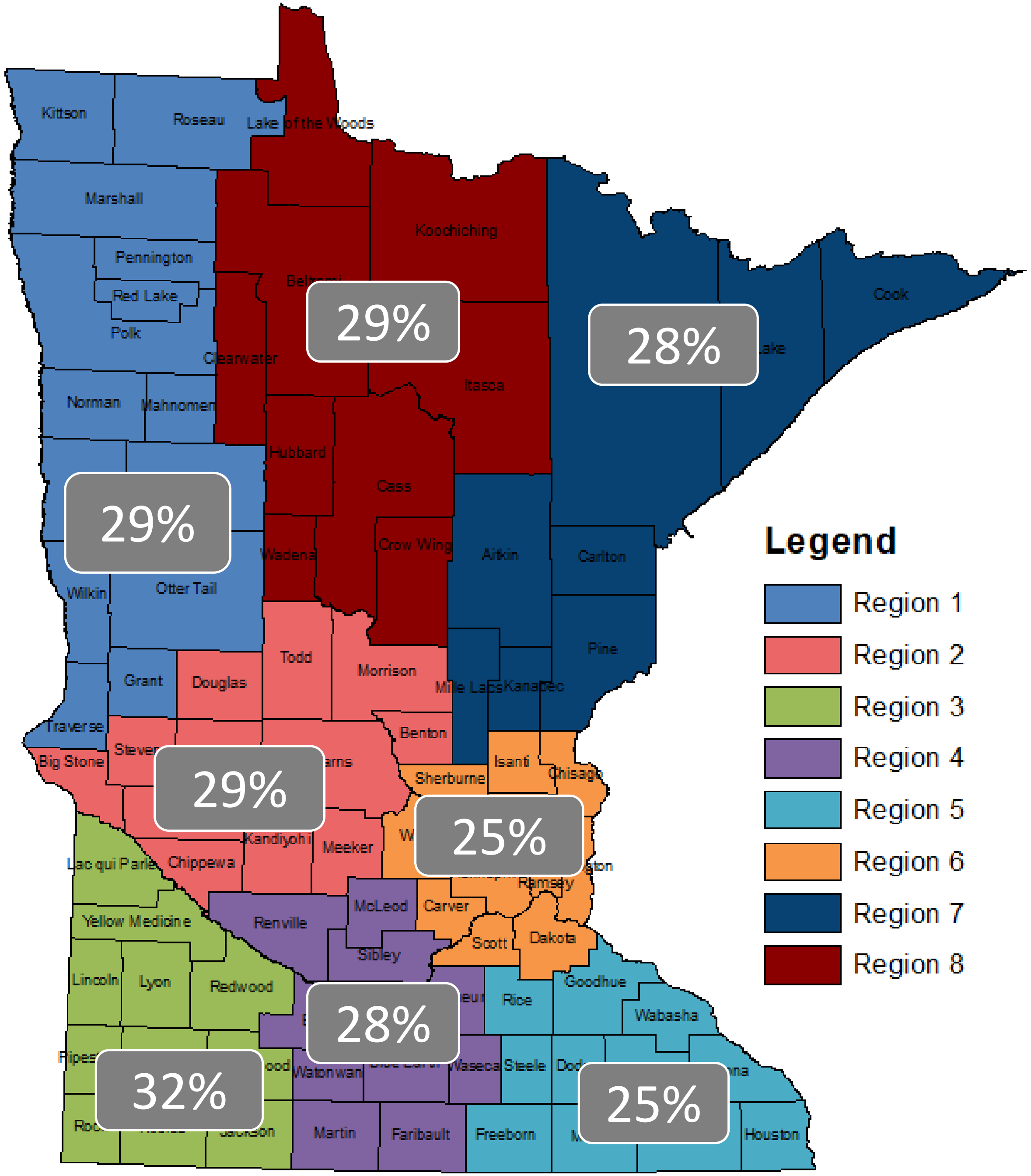


2018 Statewide Survey of Minnesota Water Values

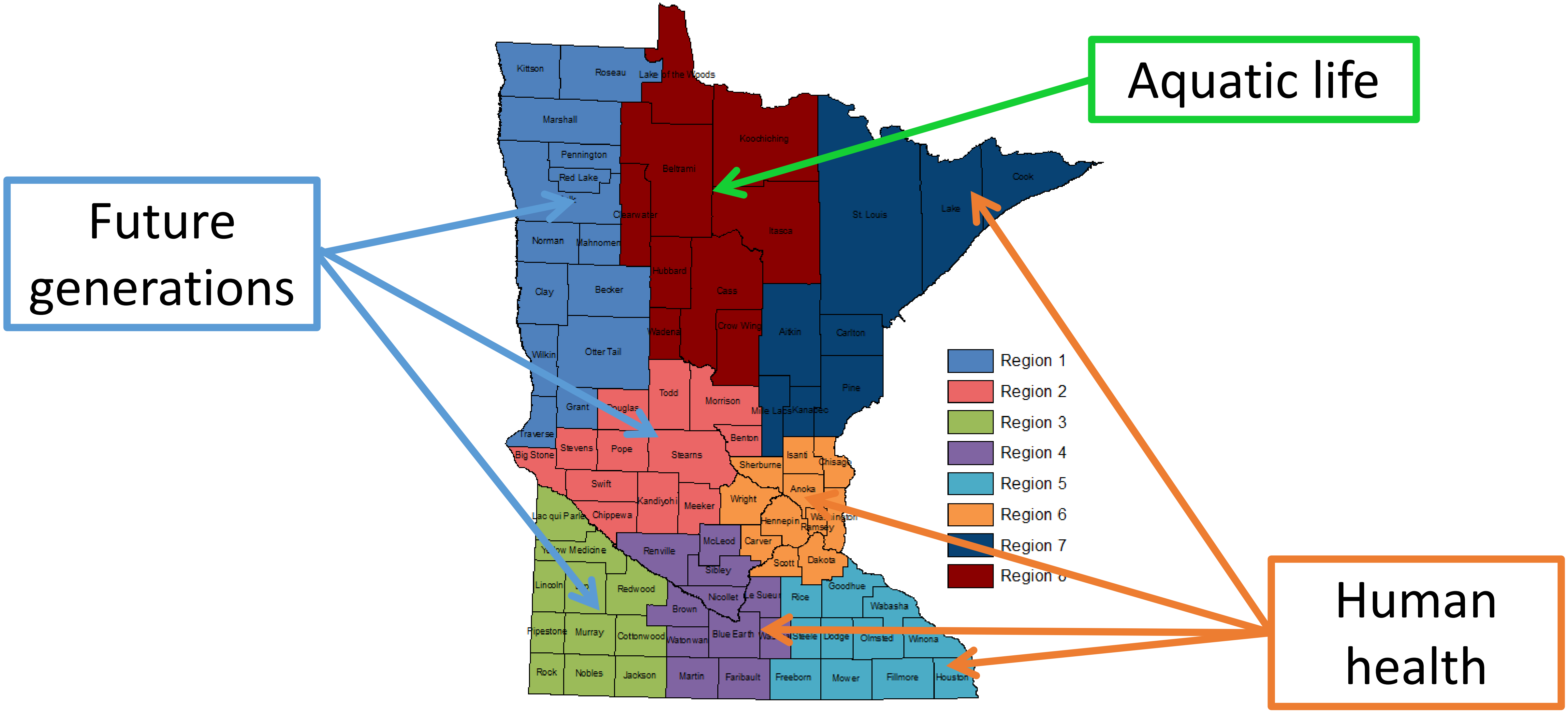
Minnesota Water Values

Regional profiles and comparisons

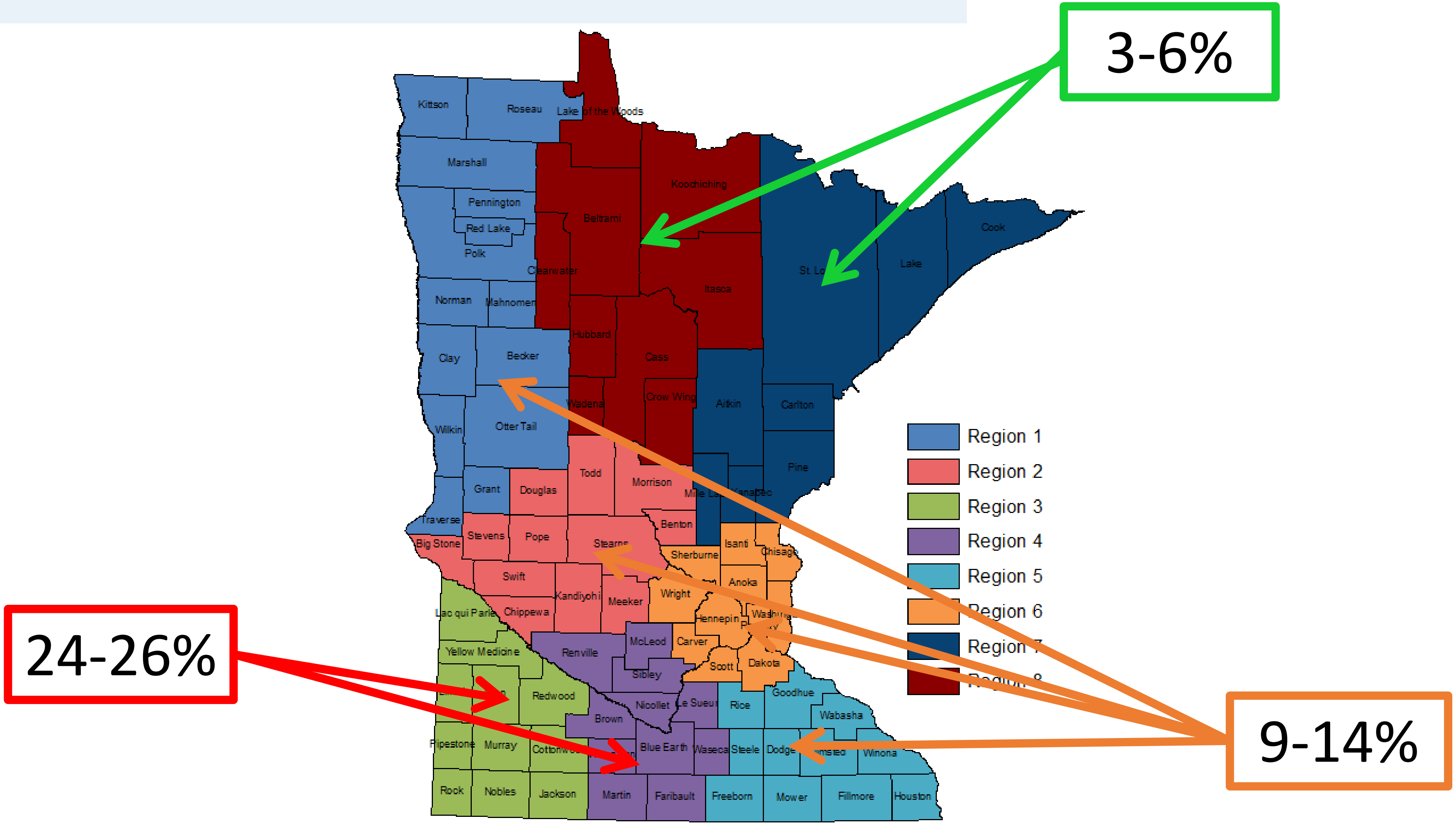
Response rate by region



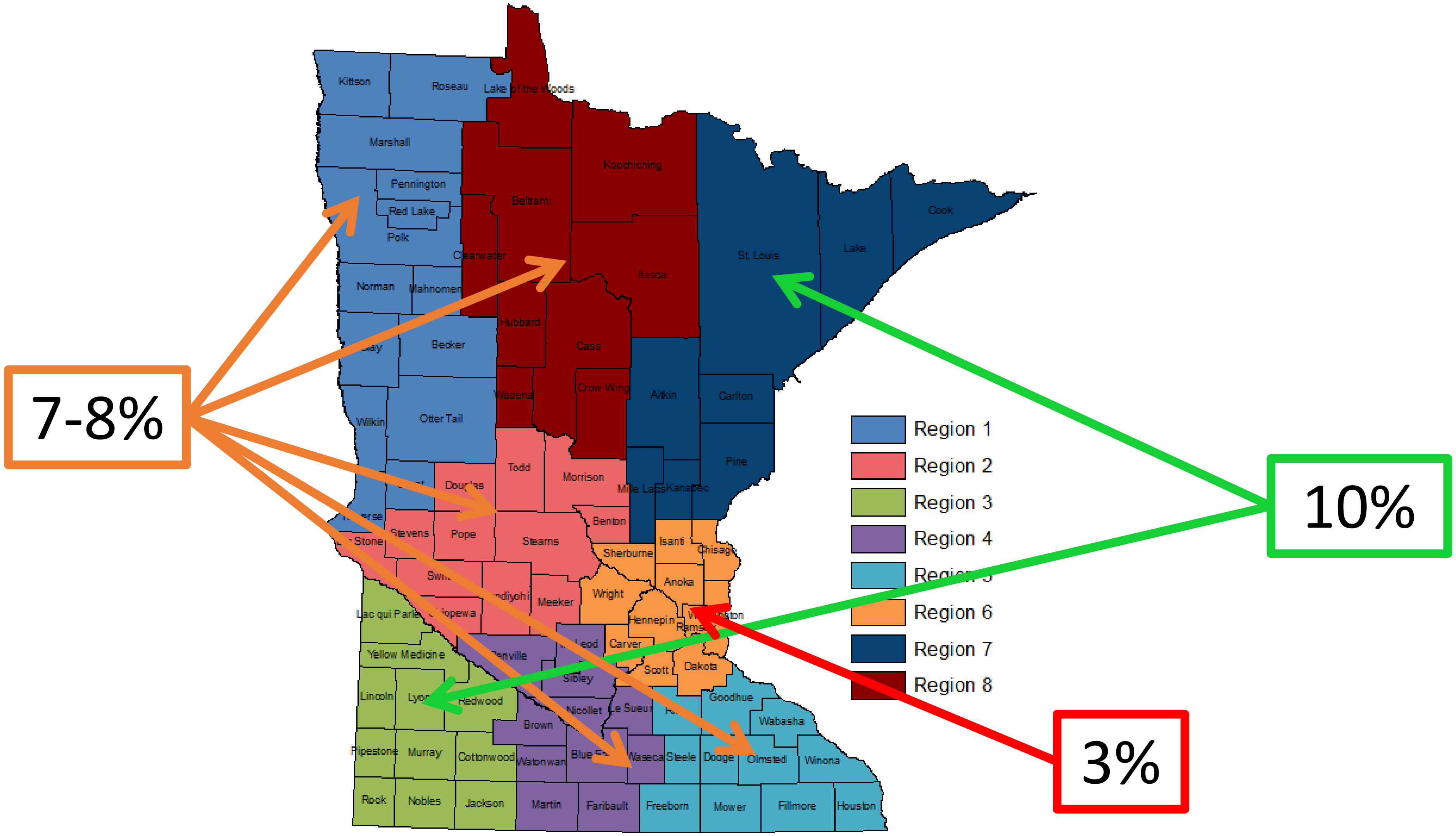
Top three concerns about consequences of water problems



Rated <u>local</u> water quality as "poor" or "very poor"



Rated Minnesota water quality as "very good"



Nature in the Urban Century

A global assessment of where and how to conserve nature
for biodiversity and human wellbeing

The Nature Conservancy

futurearth

Stockholm Resilience Centre
Sustainability Science for Biosphere Stewardship

Stockholm University

www.urbannature100.org

Nature in and near cities is crucial not just for maintaining biodiversity but for ensuring human wellbeing, which depends on the benefits that nature provides.

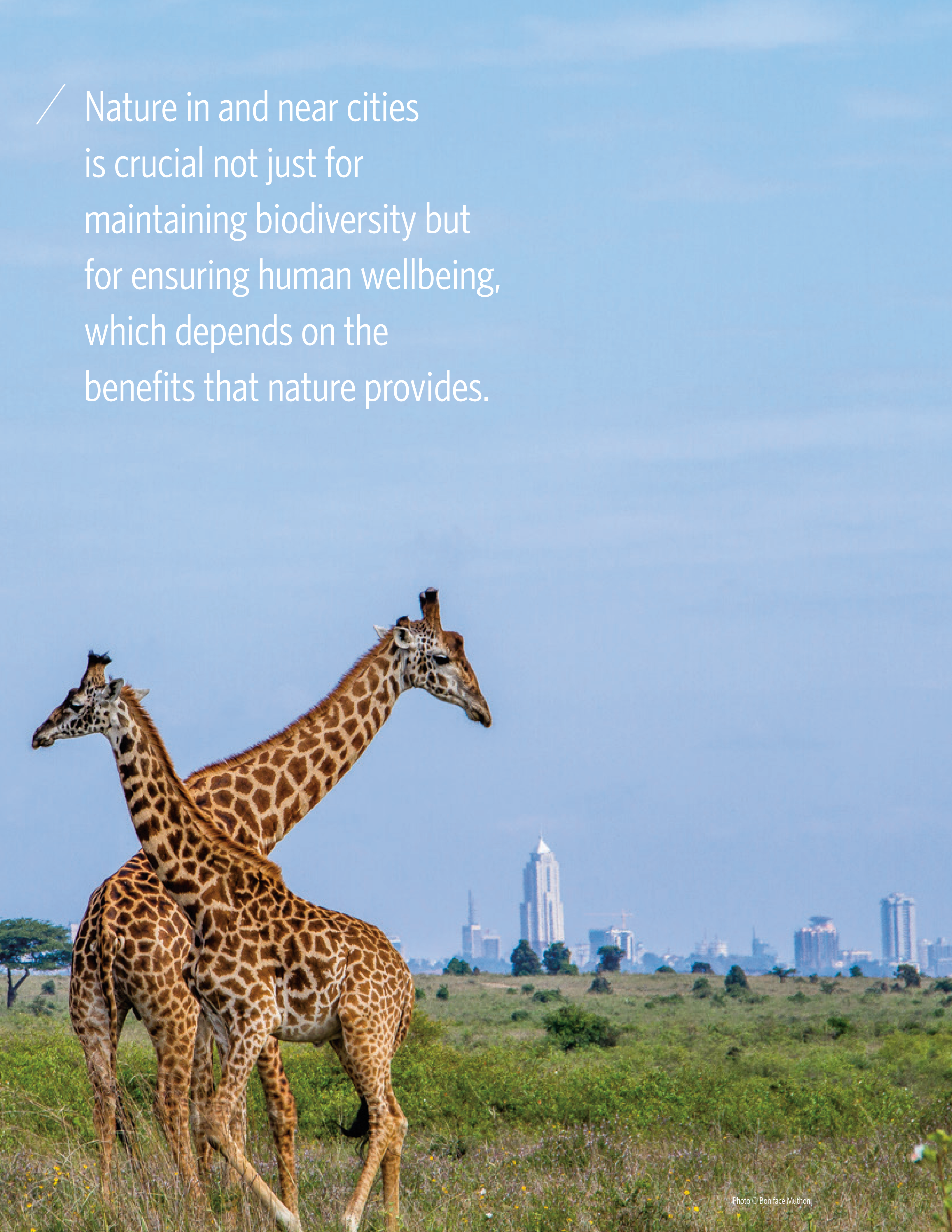


Photo © Boniface Muthoni

Acknowledgments

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Governments around the world need to plan for a positive natural future.

Photo © Leander Urmy

Executive Summary

This century will be remembered as the urban century. Our generation will witness the most significant urban growth in human history. By 2050, there will be 2.4 billion more people in cities, a rate of urban growth that is equivalent to building a city with the population of London every seven weeks. Humanity will urbanize an area of 1.2 million km^2, larger than the country of Colombia (*Figure 1*). Cities have been called humanity's greatest invention, a way of living that can bring many benefits, including increased economic productivity and innovation, greater opportunities for education and individual enhancement, and more efficient use of natural resources and energy. The urban century thus holds enormous opportunity for humanity. However, the Urban Century also presents a challenge to the global environment, both directly through the expansion of urban area and indirectly through urban energy and resource use.

Urban growth is one of the main global issues that the Convention on Biological Diversity (CBD) must address to meet its ambitious goals. Governments must envision a positive natural future for our urban century, a future in which sustainable urban growth occurs in appropriate places while nearby nature is protected, restored, and enhanced. Nature in and near cities is crucial not just for maintaining biodiversity but also for ensuring human wellbeing, which depends on the benefits that nature provides.

// Nature in and near cities is crucial not just for maintaining biodiversity but for ensuring human wellbeing, which depends on the benefits that nature provides.

This report presents a business-as-usual scenario, which assumes that current urban growth trends continue, and quantifies the impact that urban growth could have on biodiversity and human wellbeing. This report also quantifies the significance of natural habitat for climate mitigation and adaptation. We end by highlighting solutions that can help avoid the negative impacts forecasted under our business-as-usual scenario—ways that governments at all levels can plan and implement a positive natural future for our urban century.

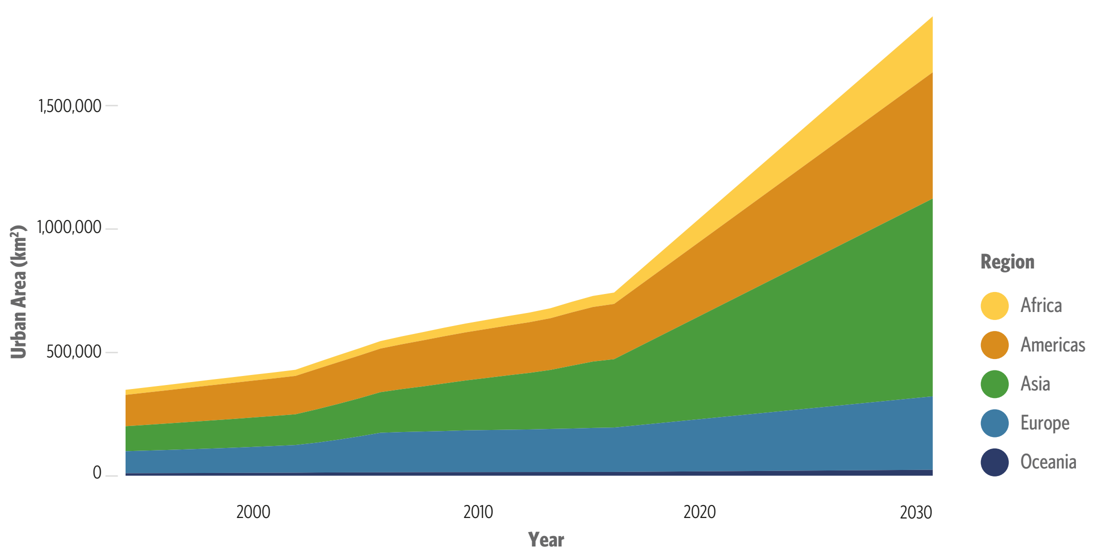


Figure 1: Urban land area by region (1992 – 2030).

The challenge of managing urban growth

This report depicts how the projected rapid rates of urban growth could, if poorly planned, destroy natural habitat and greatly impact biodiversity and human wellbeing. Urban growth, per se, has been considered relatively little under the CBD process to date. However, preventing habitat conversion and increasing land protection are both key goals of Aichi Targets 5 and 11, and both issues are, and will continue to be, affected by urban growth. Urban growth also affects numerous other issues that are related to CBD's Aichi Biodiversity Targets, such as ecosystem service provision (Aichi Target 14) and ecosystem resilience (Aichi Target 15).

Report Findings Dashboard

Urban Growth:

By 2050, there will be **2.4 billion** more people in cities

This rate of urban growth is the equivalent of building a city with the population of London **every 7 weeks**

Humanity will urbanize an area of **1.2 million km²,** larger than the country of Colombia

Natural Habitat:

1992 - 2000

Urban growth was responsible for **190,000 km²** of natural habitat lost

29% of strictly protected areas[1] were less than 50 km from urban areas

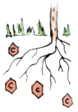
2000 - 2030

Urban growth could threaten **290,000 km²** of natural habitat

40% of strictly protected areas[1] are projected to be within 50 km of an urban area

[1]as defined by IUCN's Protected Area Categories

Carbon Storage:



(as forecast in business-as-usual scenario)

Urban growth would destroy natural habitat that stores an estimated **4.35 billion** metric tons of CO_2

This is the equivalent of carbon dioxide emissions from **931 million** cars on the road for one year

Globally avoiding the release of carbon from habitat loss due to urban growth has a social value of **182.8 billion USD**

assuming the U.S. Environmental Protection Agency's social cost of carbon (USD 42/t CO2 eq)

Coastal Resilience:

Coastal habitats reduce the risk of coastal hazards, such as coastal flooding and erosion during storms.

By 2030, urban area is forecast to more than double, **to 23,000 km²** in low-lying coastal zones where natural habitat plays a critical role in reducing coastal hazards

This increases the number of urban dwellers dependent on natural ecosystems in coastal areas.

Infographic: Rhiannon Hare/TNC.

Where and how much natural habitat could be lost?

Historically, urban growth has been a major cause of natural habitat loss, directly impeding progress toward Aichi Target 5, which aims to at least halve the rate of loss of all natural habitats. This report shows that urban growth was responsible for the loss of 190,000 km^2 of natural habitat between 1992-2000 (*Figure 2*), which equates to 16% of all the natural habitat lost over this period. Biomes with large amounts of natural habitat lost due to urban growth include temperate forests, deserts and xeric shrublands, and tropical moist forests. In the future, this trend will continue, especially in tropical moist forests. This report shows that urban growth could threaten 290,000 km^2 of natural habitat by 2030.

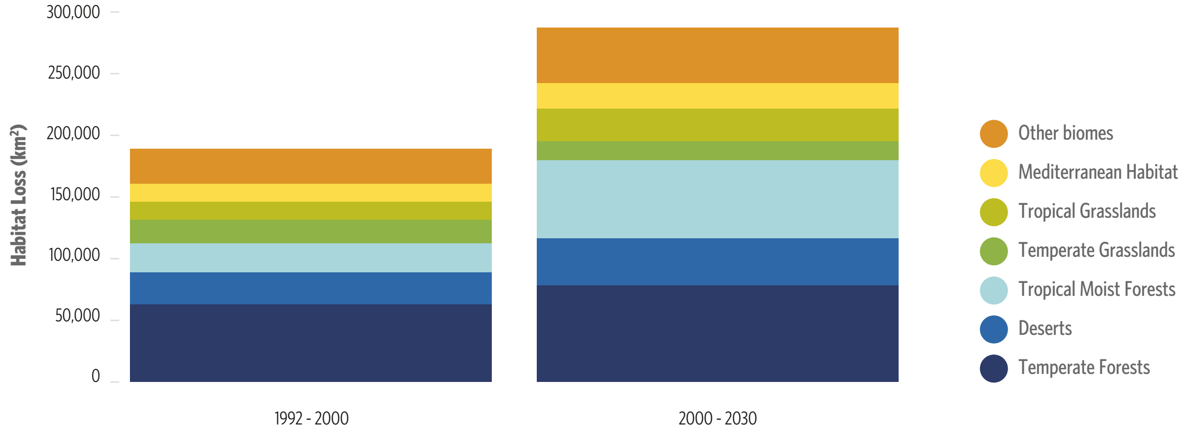


Figure 2: Habitat lost, by biome, due to urban growth, both historically (1992-2000) and projected (2000-2030).

Countries projected to lose the most natural habitat due to urban growth (> 10,000 km²) include the United States, Brazil, Nigeria, and China (*Figure 3*). Though these are the countries with the largest projected natural habitat loss, there are many other countries projected to experience significant habitat loss. Mitigating these losses will be key if countries are to achieve their CBD commitments.

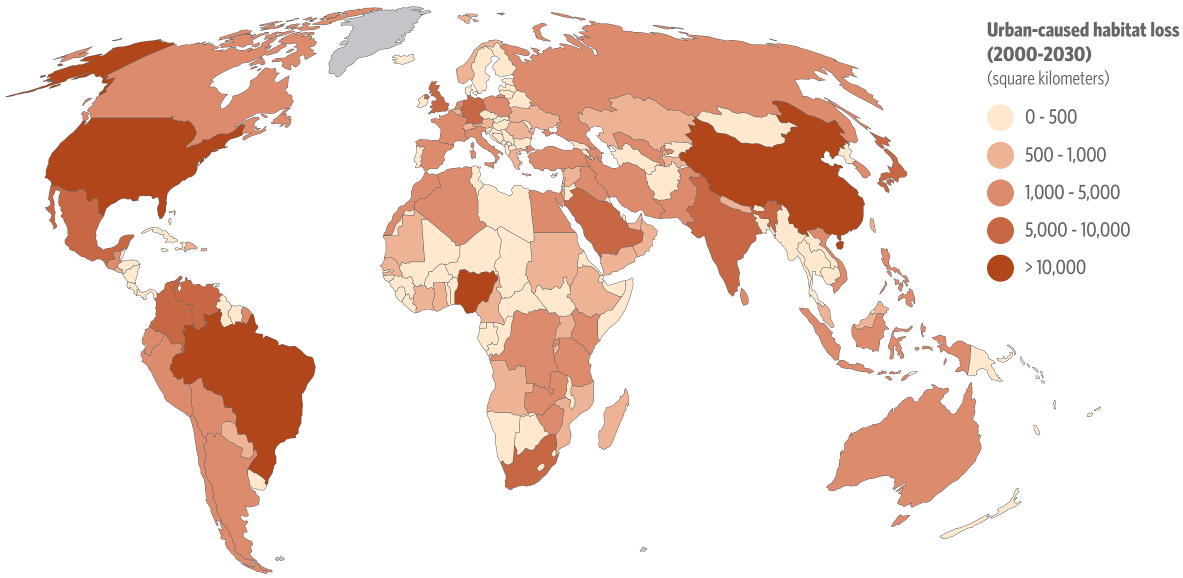


Figure 3: Projected habitat loss due to urban growth by country (2000-2030).

Potential urbanization impacts on areas of high biodiversity and endemism are spatially concentrated (*Figure 4*). This spatial concentration of urban impacts on biodiversity points to definite areas to focus urban conservation actions. For instance, conservation action on just 49,000 km² could help protect Key Biodiversity Areas (KBAs) at risk from urban growth.

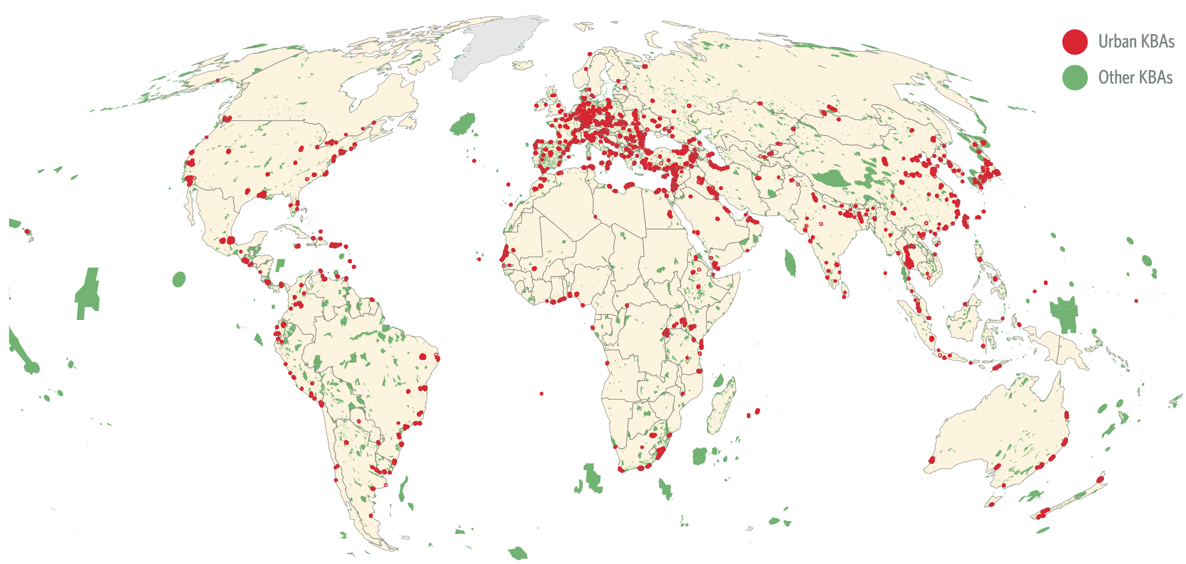


Figure 4. Key biodiversity areas (KBAs) that will be impacted by urban growth are highlighted in red. These KBAs have >5% of their area forecasted to be urbanized by 2030.

How will protected areas be affected?

If current trends continue, urban growth could degrade the global network of protected areas and the benefits they provide. Literature reviews have established that negative impacts from cities on protected areas become more frequent when there is less than 50 km between a protected area and a city. Negative impacts experienced in protected areas near cities include increased poaching, illegal logging and harvesting, trampling or other damage to vegetation, alterations in disturbance regimes like fire frequency, and alterations in abiotic conditions such as increased temperature and higher concentrations of air pollutants. Our analysis shows that in 1992, 29% of strictly protected areas (International Union for Conservation of Nature [IUCN] categories I-IV) were less than 50 km from urban areas. By 2030, we project the percentage to increase dramatically (*Figure 5*), with 40% of strictly protected areas and 1 in 2 loosely protected areas within 50 km of an urban area. This increased proximity will raise the likelihood of negative impacts on these urban-adjacent protected areas, as well as the management costs of trying to prevent negative impacts.

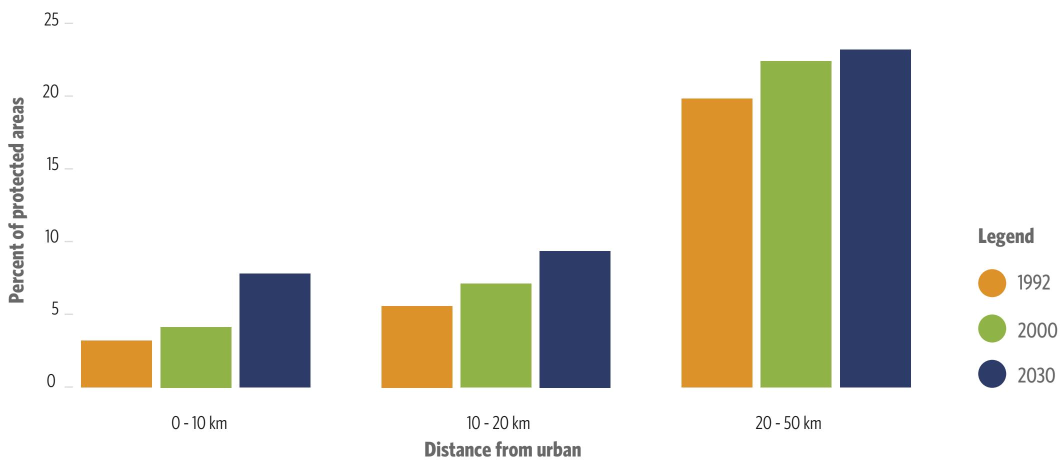


Figure 5: Distance from protected areas (PAs) to urban area for strictly protected areas (IUCN categories I-IV). Summing across all three distance categories, in 1992 29% of PAs were within 50 km of an urban area, while in 2030 40% of PAs will be.

Protected area management techniques exist that can mitigate many of the negative urban impacts on protected areas while fostering closer connections between people and nature. For instance, the IUCN Urban Conservation Strategies Specialist Group offers guidelines for managing protected areas near cities. Over a longer time frame, planned urban growth can prevent ecological degradation and maintain connectivity between patches of natural habitat. By planning proactively for how to manage protected areas in an urban world, countries can safeguard their investments in protected areas and continue to make progress toward their CBD commitments.

Implications for climate action

Natural habitats play an important role in climate mitigation by sequestering and storing of carbon in their biomass. We quantify how much carbon dioxide would be released as a result of natural habitat lost due to urban growth between now and 2030. We find that urban growth, if occurring as forecast in our business-as-usual scenario, would destroy natural habitat that stores an estimated 1.19 billion metric tons of carbon, or 4.35 billion metric tons of carbon dioxide (*Figure 6*). This is equivalent to the annual carbon dioxide emissions from 931 million cars on the road. The greatest potential overall release of carbon from habitat loss due to urban growth will occur in Brazil, the U.S., and Nigeria. We estimate that globally avoiding the release of carbon from habitat loss due to urban growth has a social value of 182.8 billion USD, assuming the U.S. Environmental Protection Agency's social cost of carbon (USD 42/t CO_2 eq).

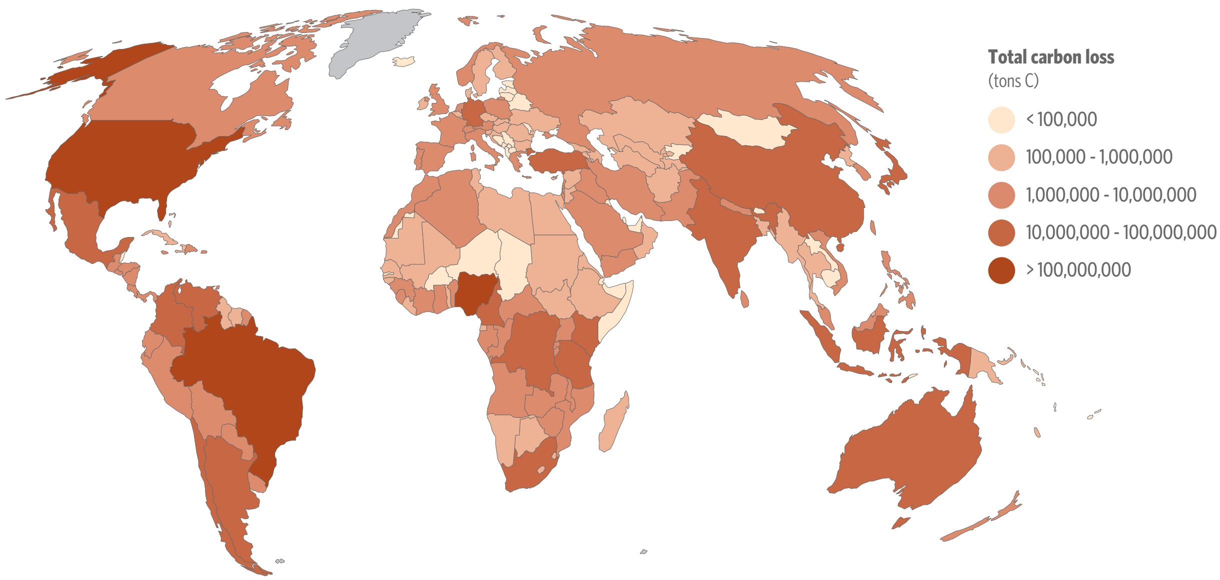


Figure 6. Total carbon (in metric tons) lost due to urban growth into natural habitat (2000-2030), by country.

Natural habitats, whether inside urban areas or in their surroundings, also provide several ecosystem services that are important for climate adaptation, such as reducing the risks of flooding and reducing temperatures in urban areas during heat waves. This report focused on one important service, the role that coastal habitats play in reducing the risk of coastal hazards, such as coastal flooding and erosion during storms. By 2030, urban area is forecast to more than double in low-lying coastal zones where natural ecosystems provide high levels of coastal risk-reduction services, to a total of 23,000 km^2 of urban area. More urban dwellers will be living in these zones, increasing the number of people dependent on these risk-reduction services. At the same time this urban growth, if poorly planned, could destroy coastal habitat and reduce the provision of these same risk-reduction services.

A call to action in the urban century

Governments around the world need to plan for a positive natural future, one where urban growth and development occurs while biodiversity and human wellbeing are protected. Some actions are crucial if we are to take advantage of this unique moment:

Integrate local governments in national planning from the start: Countries use National Biodiversity Strategies and Action Plans (NBSAPs) to delineate how they will achieve progress towards CBD goals. There is an urgent need to better consider urban growth in the next iteration of NBSAPs, as well as in sub-national and local Biodiversity Strategies and Action Plans. National governments should integrate local governments into the planning process and set aside appropriate resources, supporting local governments as they implement these plans. The financial and resource commitments that countries make to urban conservation should match the scale of the challenge that poorly planned urban growth poses to the goals of the CBD.

Empower cities to plan for a positive natural future: Urban growth plans need to incorporate information on biodiversity and ecosystem service value. The Exploring Solutions section of the full Nature in the Urban Century report presents tools and guidelines that cities can use to effectively create "greenprints" of urban growth. These greenprints plan for how to protect and restore existing habitat that is important for biodiversity and ecosystem services, as well as create new natural features (e.g., parks, street trees) that achieve the same goals. Participatory methods can be used to identify positive futures based on the local preferences of different city stakeholders. Governments at all levels should empower cities and metropolitan areas to plan effectively for protecting biodiversity.

Leverage international institutions: International institutions will play a key role in influencing the design and funding of cities of the future. We call for more extensive consideration of urban growth impacts on biodiversity and ecosystem services in the funding decisions of major institutions, both multilateral and bilateral. Major international funding sources, such as the Global Environmental Facility and the Green Climate Fund, should seek to directly appropriate funding to mitigate the impact of urban growth on biodiversity and ecosystem services, focusing especially on key priority areas where the impact is likely to be largest. Similarly, bilateral donors should aim to fund projects that minimize urban growth impacts on key priority areas.

Create a CBD for the urban century: We call upon Parties to the CBD to view the time between now and 2020 as a period to plan what urban conservation investments are needed to meet the challenge urban growth poses to the goals of the CBD. This would require working to ensure full integration of urban issues into the post-Aichi targets. This could be done through the creation of an urban target, or through the creation of explicit urban-related metrics that measure progress against the current Aichi Target 5 (halving habitat loss) and Aichi Target 11, which aims to protect at least 17% of terrestrial and inland water areas and 10% of coastal and marine areas. It is our hope that the next meeting of the CBD in 2020 will be a moment for Parties to the CBD to make significant commitments to protect biodiversity and human wellbeing in the urban century.

// We call upon Parties to the Convention on Biological Diversity to view the time between now and 2020 as a period to plan what urban conservation investments are needed to meet the challenge urban growth poses to the goals of the CBD.

The diversity of life on Earth is integral to human wellbeing.

Photo © Richard Newstead

Nature in the urban century

The diversity of life on Earth is integral to human wellbeing. Natural habitat is important not just for the biodiversity it support, but for the role it plays in supporting human livelihoods, health and wellbeing[1]. Nature provides resources: food, firewood, materials for shelter, forage for livestock. It helps maintain water quality and quantity, helps clean and cool the air, and reduces the risks from natural hazards. Natural areas are places to recreate, for physical and mental health, and places of aesthetic beauty. Human civilization has always depended on these benefits that nature provides. And now we are amid a dramatic change in how humans live and work.

> // Urban planning only occasionally considers the ecosystems and biodiversity found in and around cities.

This century will be remembered as the urban century. The United Nations Department of Economic and Social Affairs estimates that by 2050, roughly 68% of the world's population will be urban (World Urbanization Prospects 2018)[2] – making the next 30 years the scene of the largest human settlement transformation in human history. In Asia alone, projections highlight an urban population jump from 44% in 2010 to 64% in 2050. Cities have been called humanity's greatest invention [3] , a way of living that can bring many benefits, including increased economic productivity and innovation, greater opportunities for education and individual enhancement, and more efficient use of natural resources and energy. The urban century thus holds enormous opportunity for humanity. However, the urban century also presents a challenge to the global environment, both directly through the expansion of urban area and indirectly through urban energy and resource use.

Urban growth is one of the main global issues that the Convention on Biological Diversity (CBD) must address to meet its ambitious goals. Governments must envision a positive natural future for the coming urban century, a future in which sustainable urban growth occurs in appropriate places while nearby nature is protected, restored, and enhanced. Nature in and near cities is crucial not just for maintaining biodiversity but also for ensuring human wellbeing, which depends on the benefits that nature provides.

Yet, urban planning only occasionally considers ecosystems and biodiversity found into and around cities, and where consideration is given, it is often not well integrated in holistic, sustainable urban design. Moreover, few countries have national and subnational policies on sustainable urban development or land use. Without these explicit policies, it is difficult to mitigate biodiversity loss due to urban expansion. There is considerable need for knowledge and tools to aid the planning and management of natural systems at multiples scales.

If we do not adequately plan for urban growth in areas with globally-significant biodiversity, the world may fail to meet its ambitious targets under the CBD. Without considering the important role ecosystems play for human wellbeing through ecosystem services, the international community could also miss its targets under the UN Framework Convention on Climate Change (UNFCCC), the Sustainable Development Goals (SDGs), and the New Urban Agenda.

The Nature in the Urban Century Assessment began as a direct response to policymakers' needs. At the last Conference of the Parties of the CBD in Cancun, Mexico, a gathering brought together many representatives of national governments, international agencies, and civil society to discuss how urban growth is affecting progress toward the goals of the CBD. The consensus at the event was that urban growth was a significant issue, which should be better addressed in the CBD process. Participants identified the urgent need to connect scientific information on urban growth with policymakers. This assessment serves as the first step toward connecting scientific knowledge to action for the CBD's Parties. We hope that by providing key information to the CBD, UNFCCC, Global Environment Facility (GEF), Intergovernmental Panel on Climate Change (IPCC), and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), we can help these institutions accelerate responses to the challenge of global urban growth, catalyzing a turning point for these institutions in how they plan for and respond to global urban growth.

This report presents a business-as-usual scenario, which assumes that current urban growth trends continue, and quantifies the impact that urban growth could have on biodiversity and human wellbeing. This report also quantifies the significance of natural habitat for climate mitigation and adaptation. We end by highlighting solutions that can help avoid the negative impacts forecasted under our business-as-usual scenario, ways that governments at all levels can plan and implement a positive natural future for our urban century.

Why conduct this assessment now?

How cities grow and develop can have negative implications for protecting biodiversity and for climate change mitigation and adaptation. While rapid urban growth will occur over the next several decades, there is a unique urgency to act *now*. Decisions taken by governments in the next few years could significantly change and help shape how cities grow and develop. This section focuses on the unique moment of opportunity for the Convention on Biological Diversity and for the set of international treaties focused on climate change.

An urban opportunity

In 2018, the countries of the world will meet for the 14th Conference of the Parties (COP-14) to the CBD. COP-14 will be a key moment, as Parties to the CBD begin to evaluate progress toward the Aichi targets. These targets will expire in 2020, and discussions have already begun about the next set of targets for the CBD. National governments and international institutions are, in parallel, considering significant new commitments they would like to make to biodiversity conservation in 2020. There is talk of 2020 being the "Paris moment" for biodiversity, where the Parties to the CBD may agree to a major, significant global framework for biodiversity conservation, similar in ambition to the Paris Agreement of the UNFCCC.

Recently, the Global Environmental Facility (GEF) has adopted new programmatic priorities for the GEF-7 funding phase (2018-2022). These priorities shape investments of GEF resources by recipient countries in projects that address some of the world's most pressing environmental problems. GEF-7 expands its existing program on Sustainable Cities from the previous phase to include a wider array of investment opportunities for achieving a range of global environmental benefits. The new strategy has an additional focus on natural infrastructure and includes support for integrated land-use planning and infrastructure integration for cities and surrounding landscapes that will generate benefits for biodiversity.

Now is the time to push for urban issues to be further incorporated into CBD and GEF processes. This report quantifies how much urban growth has converted natural habitat, to give policymakers an understanding of how urban growth has affected achievement of Aichi Target 5, which calls for the rate of loss of all natural habitats to be at least halved by 2020. We also quantify how urban growth has fragmented and degraded protected areas, to increase policymakers understanding of how urban growth has affected achievement of Aichi Target 11, which calls for at least 17% of terrestrial and inland water areas and 10% of coastal and marine areas to be meaningfully protected by 2020. Moreover, the report also presents forecasts of where future urban growth could potentially impact areas of biodiversity and ecosystem service importance. We hope that this data will lead to significant future commitments to manage urban growth, and inform how national governments and institutions including the GEF prioritize their investments.

Climate change adaptation in the urban century

The world's fight against climate change, embodied in the commitment of Parties to the UNFCCC, is also at a significant moment. Through the Paris Agreement, the Parties committed to ambitious Nationally Determined Commitments (NDCs) to reduce greenhouse gas emissions. The Paris Agreement is expected to significantly increase the flow of finance for climate mitigation and adaptation, toward a stated goal of $100 billion per year. Much of this money will go to actions focused on reducing emissions, such as fostering energy efficiency, or grey infrastructure projects that increase climate adaptation capacity, such as new sea walls. However, a fraction of this climate finance will go toward Ecosystem-Based Adaptation (EBA) projects that use the conservation, sustainable management, and restoration of ecosystems to help people adapt to the changing climate.

Several key science institutions are reevaluating their research focus relating to EBA, recognizing the significance of urbanization. The IPCC has recognized the importance of cities in the global climate response and has planned for a Special Report on Climate Change and Cities for its seventh assessment cycle. Working with academia, urban practitioners and relevant agencies , the IPCC also cosponsored an International Conference on Cities and Climate Change Science in March 2018. Working with conference participants, the conference's Scientific Steering Committee has developed a Global Research and Action Agenda on Cities and Climate Change Science. This Research and Action Agenda identifies built and blue/green infrastructure as a key topical research gap to addressing climate change in cities. Similarly, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) is taking an increasing interest in establishing an urban working group, in recognition that urban growth will both impact and depend on ecosystem services.

The CBD can help the UNFCCC identify opportunities for EBA to achieve their climate adaptation goals. This report forecasts where urban areas are most dependent on ecosystems for climate adaptation services, in the hope that knowledge of these priority places can influence major investments in EBA, making these investments more efficient and more successful.

Scope of this report

This assessment is meant to be a brief synthesis for policymakers of data on how urban growth is now affecting and will continue to affect biodiversity in the coming decades. There are a few limitations of the report that readers should bear in mind:

- We have aimed to be concise, summarizing important key trends for the CBD member countries and parties, rather than encyclopedic and comprehensive. Readers should be aware that there is a very large body of scientific literature on cities and nature, which we have tried to reference as appropriate. A good starting place for those looking for more detail is the book *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities*, a thorough assessment of the state of the related literature up to 2013 [4].
- This report focuses on terrestrial biodiversity, only occasionally discussing the impacts on freshwater and marine biodiversity from urban growth.
- Our analysis concentrates primarily on the direct impacts of urban-caused habitat loss on biodiversity. We do not discuss in detail the many indirect effects cities have on the natural environment, as (for example) they use natural resources, consume energy, and produce waste. These indirect effects and the "teleconnections" between cities and the broader landscape can be quite important [5].
- This report's discussion of human wellbeing concentrates on climate adaptation (especially coastal hazard reduction) and climate mitigation, and how urban growth affects these potential benefits. We acknowledge that nature provides many other important benefits for human wellbeing. One useful introduction to the broad set of benefits that urban nature provides is *Conservation in Cities: How to Plan & Build Natural Infrastructure* [6].
- We only briefly discuss the important role that nature can play within cities for improving human wellbeing [7]. This was a conscious choice on our part, since human-designed features within cities (like planted street trees) harbor relatively less biodiversity than remnant natural habitat patches at the fringes of urban area. However, we acknowledge that nature within cities, sometimes called "natural infrastructure", is often essential for human wellbeing [6] and may serve as habitat for important elements of biodiversity.
- We present in this report possible solutions, ways cities can protect biodiversity and ecosystem services as they grow. Our presentation of these solutions is necessarily concise, and we link to longer descriptions where available.

Photo © Kwong Shun Cheong

Urban growth trends

In 1950, just 30% of global population lived in urban areas (World Urbanization Prospects 2018) [2]. Since then, the draw of cities as economic and cultural hubs promising an improved standard of living has resulted in a significant increase in the proportion of the world's population residing in urban areas. In 2018 over half of the world's population (55%) live in urban areas. This increase in the proportion of people in urban areas, coupled with the rapid population increase since 1950, has resulted in significant urban population growth in the last seven decades. In 1950, 751 million people lived in urban areas, while in 2018, 4.2 billion people live in urban areas.

// In 1950, 751 million people lived in urban areas, while in 2018, 4.2 billion people live in urban areas.

Humanity's increasing propensity for city life has broad implications for global patterns of land use. As the number of people living in cities swells, so too does the amount of land required to accommodate them. There are different definitions of urban area [2], which can influence both the measurement and forecasting of urban growth. As this assessment is conducted at the global scale, we adopted the definition of urban area used in remote sensing studies, where urban land cover is composed of more than 50% non-vegetative, human-constructed elements (e.g. roads, buildings) [8]. The European Space Agency's Climate Change Initiative (CCI) provides an annual global land cover dataset from 1992 to 2015, which demonstrates the increase in urban land cover over this period. This dataset is summarized in Figure 7 which shows the increase in total urban land area by region.

In 1992, 349,000 km^2 of the earth's surface were urbanized. By 2015, this area had more than doubled, to 744,000 km^2 (*Figure 7*). The bulk of this growth occurred in Asia, which saw a growth in urban area of 176,000 km^2 over this period, an increase of 174%. The Americas and Europe had the next greatest urban growth, adding 97,000 km^2 and 91,000 km^2 respectively. Urban land in Africa increased by a comparably modest 26,000 km^2, but this figure represents an increase of 124% since 1992, highlighting the rapid urban growth that African countries have experienced over this period.

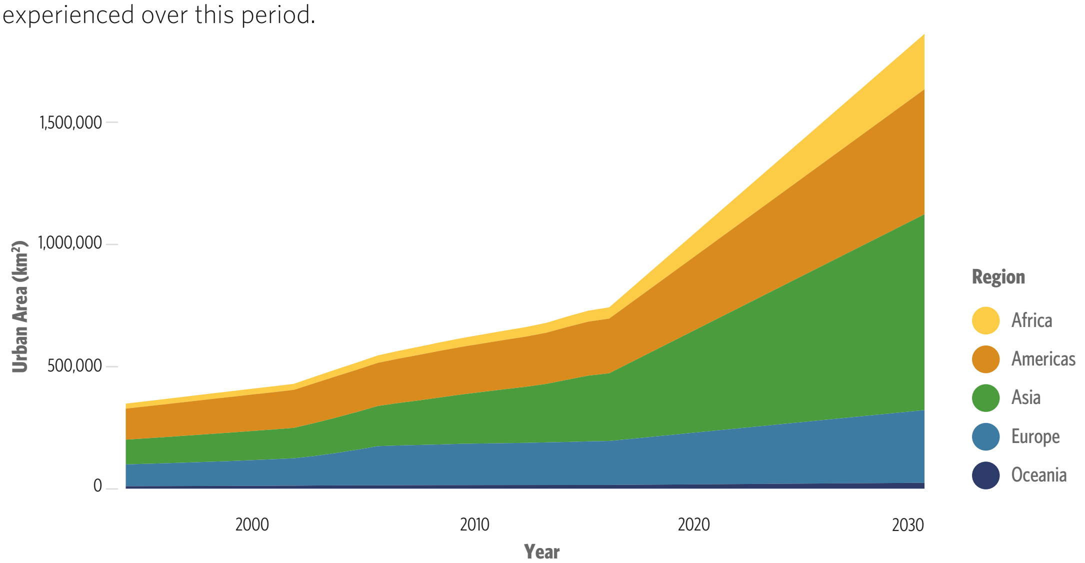


Figure 7: Regional urban land area over time. Historical data for the period 1992 - 2015 taken from the CCI landcover dataset. Future urban area forecasted out to 2030 is taken from Seto et al. (2012). See Methods section for details

This sizable urban growth is expected to continue. By 2050, the total urban population is forecasted to have increased by 2.5 billion people (World Urbanization Prospects 2018) [2] and urban area will need to expand to accommodate this increase in population.

Urban land projections, such as those developed by Seto et al. [9], attempt to predict the future global urban land footprint. By analyzing forecasted population trends, and existing land use, Seto *et al.* [9] have modeled predicted urban growth between 2000 and 2030. The amount of forecasted growth, by region, is shown in Figure 7.

By examining the projected growth in urban land area between 2000 and 2030 at the country level, we can understand where urban growth will primarily be taking place (*Figure 8*). The bulk of urban growth will occur in developing countries. China will see more urban growth than any other country, with a total of 208,000 km^2 of urban growth forecast, equivalent to 18.6% of the global total. India is predicted to have the second largest amount of urban growth at 78,000 km^2. The United States is the developed nation that will see the greatest amount of urban growth, with a predicted total of 76,000 km^2 of new urban land by 2030. Other countries with significant forecasted urban growth include Brazil, Nigeria, Pakistan, Egypt, Japan, and Mexico.

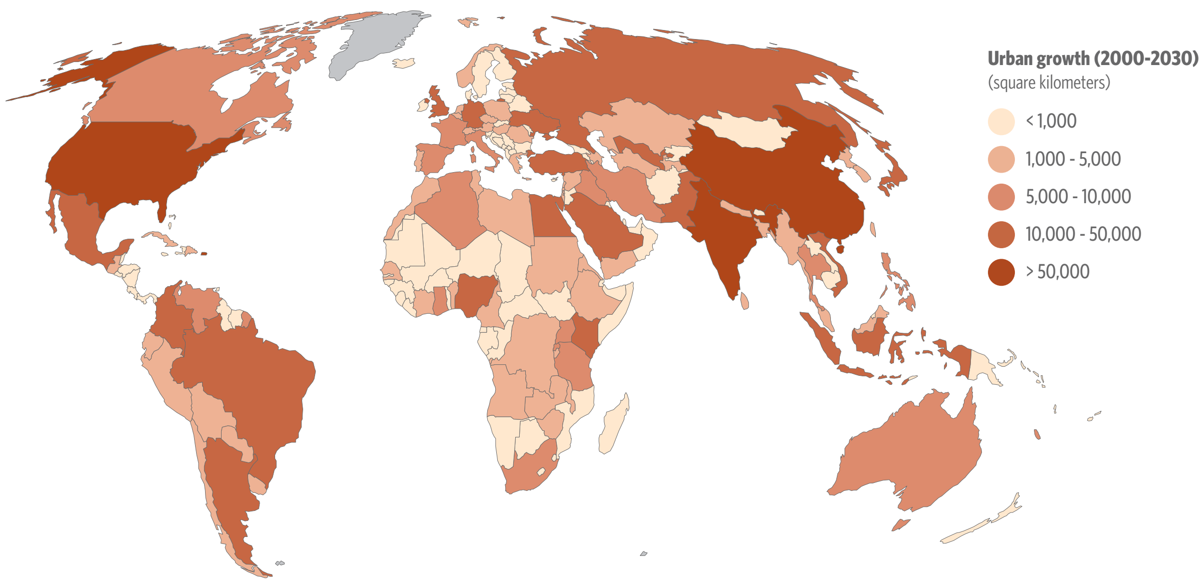


Figure 8: Projected urban land expansion for the period 2000 – 2030, by country

Drivers of urban land expansion

Why is this significant global urban growth occurring? Several key drivers of urban growth are discussed below. In this report, we use "urbanization" to refer to the process by which a greater fraction of the total population lives in cities, while we use the term "urban growth" to refer to the growth (in area or population) of cities. It is important to realize these are different concepts: The United States, for instance, is already a highly urbanized society, with a large portion of its population in cities, but the United States is still forecast to have significant urban growth in many metropolitan areas.

The magnitude of urban growth in area is largely determined by the rate of urban population growth, the urban population density, and the amount of urban land per capita. The relative influence of each of these drivers may differ from one region to another leading to varying rates, magnitudes, and patterns of urban growth across the world.

1. Economic Growth

Historically, economic growth and urbanization have largely been concurrent trends, with economic development over time correlated with an increase in the proportion of people living in cities [10]. This relationship between the two is bidirectional in that strong urban economies pull more people into the city in search of greater economic prospects, and once people are in cities they often have access to better employment and education opportunities, helping to drive further economic growth [10]. In general, therefore, as countries develop economically a greater proportion of people live in cities, thus increasing the urban land footprint. It is expected that some 35% of urban growth between 2018 and 2050 will be in three rapidly developing countries of the Global South: China, India and Nigeria [10].

Economic growth further influences patterns of urban land-use conversion through changes in per capita energy and food consumption, which, are associated with increasing levels of affluence. As economies develop urban households have the financial means to build large single-family homes that occupy a larger footprint than more compact multifamily dwellings. Households of means are also more likely to own a car, which allows them to live further from their place of employment, increasing urban sprawl [11].

2. Demographic Changes

A significant portion of future urban growth will come from large-scale migration of people from rural to urban areas. Studies of historical trends indicate that rural-to-urban migration typically makes up around 40% of total urban population growth [10]. In some cases the motivation for migration will originate in the hardships associated with life in rural areas, known as push factors, which may include rural poverty, lack of employment opportunities, drought, degradation of natural resources or conflict [12]. The decision to migrate may also be motivated by the allure of urban areas, or ‘pull factors’, such as more abundant and higher paid employment opportunities, better education or better access to essential services such as sanitation and healthcare [12].

Urban population can also grow because of intrinsic increase, if births exceed deaths. Urban population growth is affected by fertility rates but also strongly affects fertility rates. All else being equal, urban areas with higher net fertility rates have higher rates of urban population growth. However, fertility rates tend to decline after rural migrants move to urban areas. As the percentage of urban population of the world increased from 30% in the 1950s to over 50% in 2018, the average fertility rate decreased from 5 children per woman to 2.5 children per woman [13]. Despite some regional differences, the inverse relationship between urbanization and fertility rate holds across the world [14]. This decline in fertility can be attributed to factors like more economic opportunities, better education for women, and lower infant mortality rates.

3. Technology

Technological innovations shape economic growth and thus patterns of urban growth. For example, in the United States, steam engine and railway transport in the 1850s allowed food and other commodities to be shipped from the interior of the U.S. to markets on the East Coast. Profiting from this trade, new cities then arose in the interior U.S., perhaps most notably Chicago [15]. Similarly, the technological advancement of the automobile and its increasing availability during the 20th century increased mobility and allowed the development of new suburbs with lower population densities [16]. More recently, the internet has changed patterns of commuting, employment, and firm location, with unclear implications for overall urban form [17].

4. Cultural Influences

Significant cultural differences across the world have traditionally influenced the development and planning of cities. Cities in North America and Australia have lower population densities than those in most of the rest of the world. Though these differences still manifest in differential rates of urban expansion and differences in urban form across different regions, trends for development and planning of cities have been becoming more uniform over the past few decades. Urban population density has been decreasing in most parts of the world (at different rates) under the common influences of increased car ownership [18], decreased average household size [11], and desire to have larger living space [19]. Still, certain regional characteristics persist, such as those found in informal settlements, primarily located in South American, Asian and African cities [20, 21].

5. Governance

Government policies can affect the aforementioned factors, altering the magnitude and location of urban expansion [22]. Land ownership and investment affect the purchase and sale of properties and land in and around cities. Economic policies including taxation, subsidization, or deregulation can alter the scope of economic opportunities, and thus either encourage or discourage rural-urban migration. Specific demographic policies, such as the registration system in China, aim directly to control population growth in major cities, by capping the number of registered urban residents and denying services to unregistered rural migrants [23]; while the country's Western Development Program has accelerated the growth of cities in western China [24]. Policy can also influence population density and thus the size of an urban area. In the United States, for instance, policies including relatively lower taxes on fossil fuel and government subsidies for highway infrastructure encourage automobile over public transit use, leading to urban sprawl [25].

Challenges in Projecting Urban Land Expansion

While significant amounts of urban growth are certain, there is uncertainty in projections of that growth. Developing projections of urban growth first relies on having robust data from which historical trends and relationships can be observed. It is then necessary to make assumptions about how the drivers of urban growth will change in the future. The types of data used and the assumptions made about alternative futures can produce different results and introduce uncertainty. These are explored further in this section.

1. Historical observations

This report utilizes data from rigorous assessments of urban land use that have been widely cited in the global change literature. However, it is important to acknowledge that these data have their own uncertainty. This uncertainty may originate in the different methods to develop datasets that define urban land, such as differences in the spatial resolution of remote sensing products or regional differences in accuracy of urban population censuses. Urban land is also difficult to define, and thus difficult to measure accurately. Urban and rural land uses lie on a spectrum and classification of urban vs. rural land requires a clear demarcation of thresholds. Assessments typically use factors such as the proportion of land occupied by buildings and infrastructure, or the density of the human population to define such thresholds. Differences in the ways that these thresholds are defined will produce different estimates of urban area.

The variability in measurements of urban land can be observed through comparison of datasets. The European Commission's Global Human Settlement Layer (GHSL) [26], a 1-km gridded dataset of urban land cover from which the CCI Land Cover is partly derived, records a global total of 700,000 km^2 of urban land in 2015. The CCI Land Cover data used in this assessment records a relatively similar amount of urban area, 744,000 km^2 in 2015. However, there is greater variability in urban land extent in preceding years. For example, the GHSL recorded 122,000 km^2 more urban area than the CCI Land Cover dataset in 2000.

2. Alternative futures

Uncertainty is inherent in forecasting. A model may only account for a few select factors that are deemed relevant based on historical data and available theory. However, it may add too much complexity to the model to include all of the factors that may significantly influence regional and local urban land expansion such as climatic factors, agricultural productivity, poverty, land-use policies, international capital flows, and infrastructure investments [27]. Significant changes in national urbanization policies such as reforms on land management and fiscal arrangements across the government hierarchy may also alter the spatial pattern of urban land expansion within a country. Large-scale changes in transportation networks, in the spatial distribution of populations, social upheaval and economic crises are other examples of phenomena that are hard to predict. Additionally, large-scale behavioral changes may progress slowly over a long time period but may accelerate upon reaching a critical threshold [28]. However, such uncertainties can be addressed by developing alternative scenarios on which models are run or by incorporating a probabilistic approach in the modeling forecasts to capture as much of the uncertainty as possible [29].

Comparisons of urban land datasets demonstrate that the science of measuring and predicting urban land use is evolving and complex. However, there is a clear indication, across multiple studies, that urban land cover growth will be rapid during the 21st century and that this will have significantly influence biodiversity.

Biodiversity affects human wellbeing directly and through changes to ecosystem services.

Photo © James Folder

Impacts of urban growth on biodiversity

Biodiversity change

Following the Convention on Biological Diversity, biodiversity is defined as the variability among living organisms, from genes to biomes (CBD Article 2). This encompasses diversity within, and among, species and ecosystems. Human activity has affected biodiversity across the planet, resulting in a global extinction rate (an estimated 906 species since 1600) that is now one hundred to one thousand times the historical rate [30]. Estimates of elevated rates of global extinction also come from projections based on the impacts of current and projected habitat loss [30, 31]. Reports of global population declines give another measure of biodiversity change. Trends differ in different ecosystems, with terrestrial systems declining by 38%, marine systems declining by 36% and freshwater systems being reduced to less than 25% of its abundance in 1970 [32-34]. Together, these findings indicate major impacts on global biodiversity, which are projected to be sustained throughout the current century [30, 35, 36].

// Human activity has affected biodiversity across the planet, resulting in a global extinction rate that is now at least one hundred times the historical rate.

While global biodiversity is declining, the rate, magnitude, and even direction of biodiversity change can vary considerably depending on the spatial scale. At smaller spatial scales, such as the scale of tens of kilometers, data assessments reveal systematic declines in biodiversity due to land cover change, including urban growth and human population density [37-40]. However, this picture of biodiversity decline at smaller scales is complemented by data syntheses [41-44] that report evidence for no systematic decline in trends of species richness at very small scales (< 1 km), although strong geographic biases in sampling and the absence of baseline information suggest these findings may not be globally representative [45]. There is also evidence that in many regions and at some spatial scales species richness may be recovering or increasing due to rates of non-native species expansion exceeding rates of local extirpation [46, 47]. Overall, human activity is consistently understood to be the dominant driver of biodiversity change from local to global scales.

Scientists and decision-makers have typically broken down this human impact on biodiversity into five key drivers: habitat loss and degradation, climate change, excessive nutrient loads and pollution, over-exploitation and unsustainable use, and invasive species [48]. The role of urban growth is less often emphasized in relation to biodiversity change, even though urban expansion contributes substantially to these five drivers. Although cities make up a small proportion of worldwide land cover, urban growth has a considerable influence on biodiversity change at multiple scales, from neighborhoods to the globe (*Figure 9*).

Multiscale Biodiversity Outcomes are Mediated by Cross-Scale Interactions

The study of urban impacts on biodiversity change to date has largely occurred at the global scale. Here we emphasize four scales which must be considered to understand biodiversity change due to urban growth: global, regional, city and neighborhood. Both challenges to biodiversity and opportunities for protection and restoration can span these scales. The effects of interactions across scales must be considered to properly account for both urban-biodiversity tradeoffs and synergies arising from decisions to protect biodiversity.

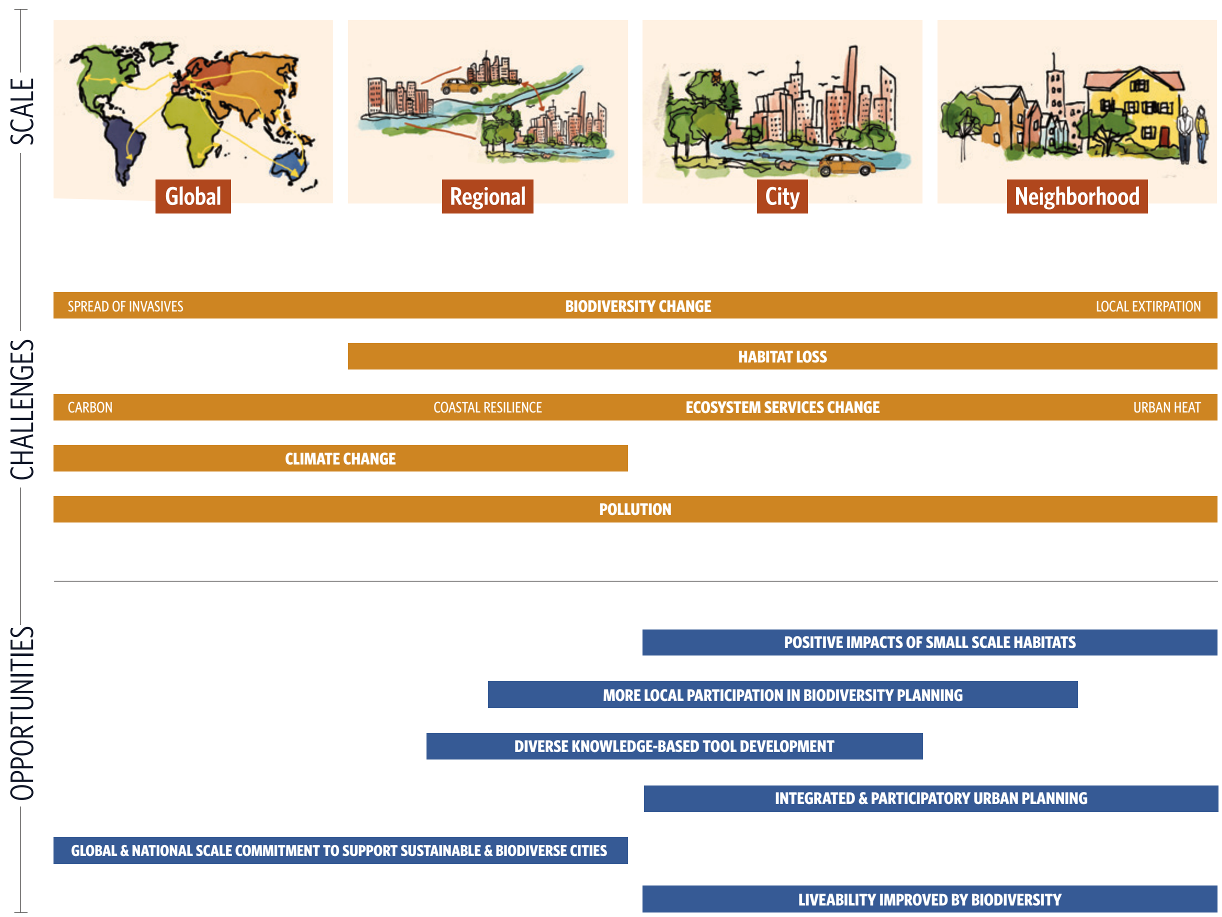


Figure 9: Multi-scale opportunities and challenges.

The effect of urban growth on biodiversity can in turn affect ecosystem services and human wellbeing [4, 49, 50] (*Figure 10*). Urbanization affects both biodiversity and ecosystem services via its influence on many drivers. For example urban sprawl drives habitat loss and fragmentation. Biodiversity change subsequently affects human wellbeing directly, and through changes to ecosystem services. Impacts on ecosystem services influence people's values, the structure of human institutions, and society's decision-making. These socio-economic changes in turn affects people's actions, feeding back to further influence urbanization and drivers of biodiversity change. This general framework can be adapted to understand the effect of urbanization on specific ecosystem services, for example those related to climate mitigation (*Figure 10, middle panel*) and adaptation (*Figure 10, bottom panel*).

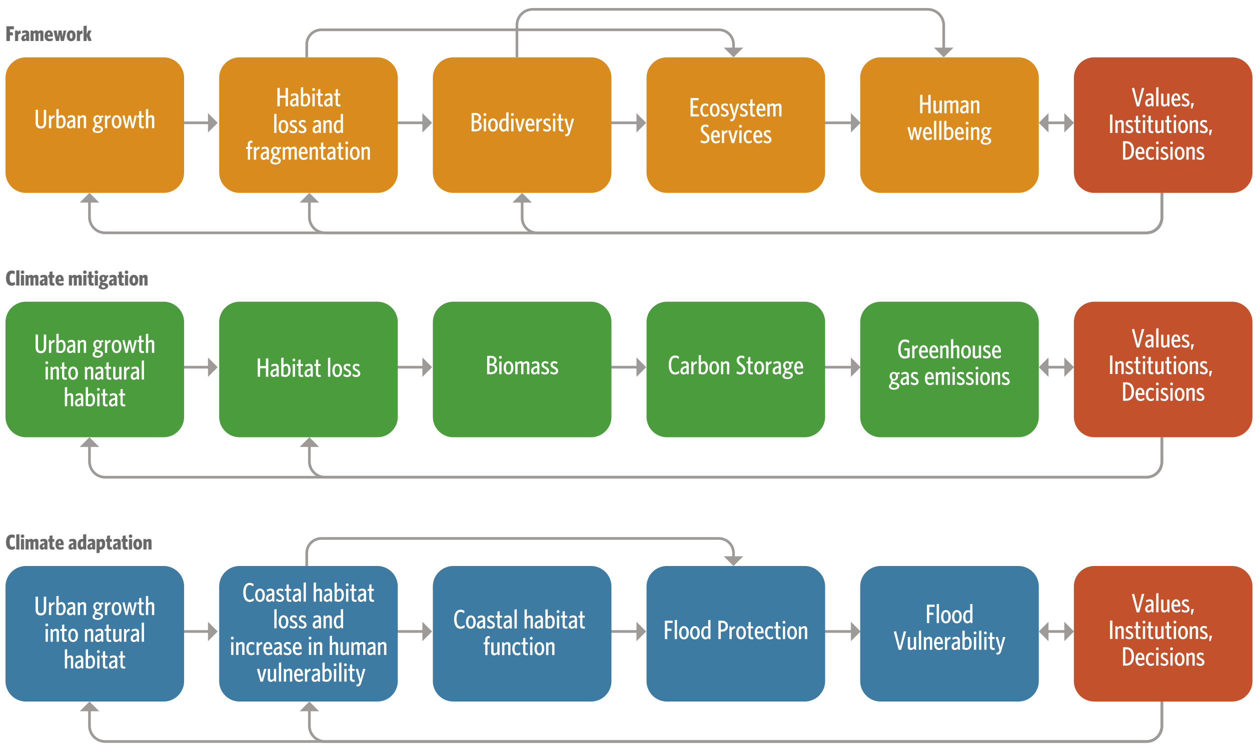


Figure 10: Conceptual linkages between urbanization, biodiversity, and human wellbeing.

For much of this assessment we focus on the direct impact of urban growth on natural habitat, and its consequences, because past assessments have suggested that this direct impact will have significant implications for biodiversity and human wellbeing [4]. We acknowledge that urban areas can also provide important opportunities for conservation. Natural infrastructure within urban areas, for example, may provide support for species of conservation concern [38, 51, 52]. The degree to which cities facilitate many aspects of biodiversity depends on the size, quantity, and quality of green spaces [53]. There is a growing body of knowledge about how to manage cities for increased biodiversity [6, 54, 55].

Urbanization is a major driver of habitat loss

As the section on Urban Growth Trends shows, urban growth has increased dramatically in recent decades. Not all urban growth directly affects natural habitat, because sometimes cities expand onto agricultural land, or other land already converted by humans [56]. However, a significant fraction of urban growth occurs on natural habitat, and historically urban growth has been a major driver of habitat loss. Between 1992 and 2000 urban growth caused the conversion of approximately 190,000 km^2 of natural habitat globally (*Figure 11*). This accounts for 16% of the total natural habitat loss during this period. This kind of large urban impact on natural habitat has directly affected the progress toward the ambitious goals of Aichi Target 5, to reduce the rate of natural habitat loss by at least half.

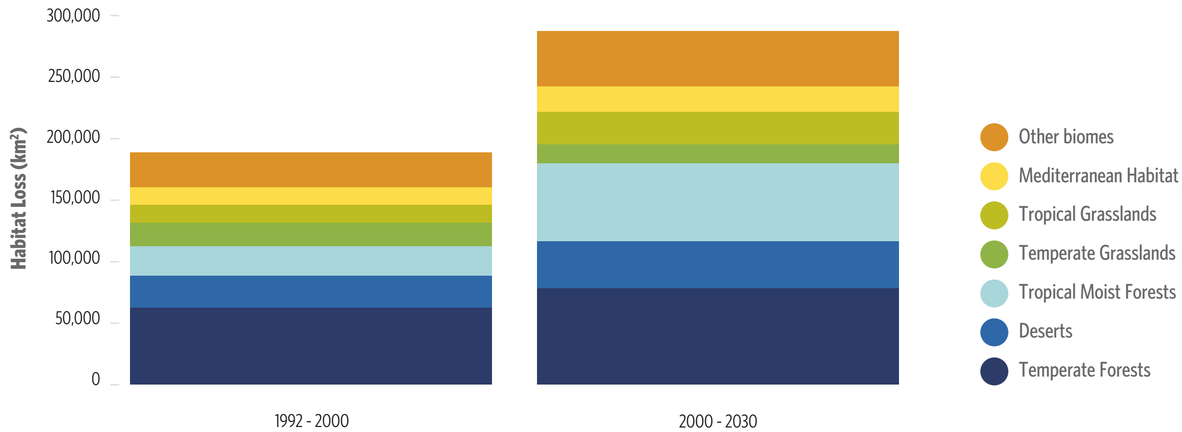


Figure 11: Habitat lost, by biome, due to urbanization, both historically (1992-2000) and projected (2000-2030). Note that a few biomes with comparatively few hectares of habitat lost to urban development are grouped together under the category "Other biomes".

In terms of area, the greatest impact of urban growth on natural habitat during the period from 1992 to 2000 was in temperate broadleaf forests (*Figure 11*), the dominant biome type in Europe, the eastern United States, and northern China. The next greatest impact was in the deserts biome (which includes xeric shrublands), found in the southwestern United States, North Africa, the Middle East, and parts of Pakistan and Central Asia. Tropical moist forests were the third most impacted biome, and are found in southern China, West Africa, and parts of Brazil. Other biomes that were significantly affected in this period include temperate and tropical grasslands, as well as Mediterranean habitat.

Forecasted patterns of urban-caused impacts on natural habitat from 2000 to 2030 are similar to historical patterns but they show an increase of urban growth affecting biomes more frequently found in developing countries (*Figure 11*). The area affected by urbanization will increase relative to the 1992 to 2000 period in almost all biomes, but the increase will be most notable in tropical moist forests. This biome is home to some of the most rapidly expanding urban areas such as those along the Brazilian coast, in West Africa, Southeast Asia, and Indonesia. As the tropical moist forest biome is also the most biodiverse, the rapid growth of cities poses a substantial threat to the goals of the CBD if not properly managed.

Urbanization is forecast to convert a total of 290,000 km^2 of habitat between 2000 and 2030, the equivalent to the size of Italy or the Philippines. Note that measuring urban growth's impact by the total area impacted can be misleading, since biomes with a small total area can easily be lost in the analysis (See Table 1), and therefore the percentage of the biome that will be lost due to urban growth is also important to quantify. In proportional terms urban growth during this period is forecasted to cover around 2.9% of the total area of the mangrove biome, much more than any other biome type. The Mediterranean biome is also forecast to be highly impacted in proportional terms, with 0.6% of this biome affected by urban growth between 2000 and 2030. By contrast, the tundra and boreal forest/taiga biomes are forecast to be minimally impacted by urban growth between 2000 and 2030, simply because there are so few cities at the high latitudes at which these biomes occur.

Country-level forecasts of urban growth's impact on natural habitat are shown in *Figure 12*. In terms of the total area of natural habitat forecast to be lost, four countries exceed 10,000 km^2: the United States, Brazil, Nigeria, and China. However, there are many countries on each continent (excluding Antarctica) that are forecasted to have high levels of urban-caused habitat loss. It is interesting to compare the patterns of habitat loss in Figure 12 with the patterns of total urban growth shown in Figure 8. Some countries, such as India, have a large amount of urban growth forecasted, but only a moderate amount of habitat conversion forecasted, because a large fraction of urban growth is happening on agricultural lands rather than natural habitat. China is an interesting case study, because growth in northern China is primarily occurring in agricultural lands, while growth in southern China is more heavily affecting natural habitat [56].

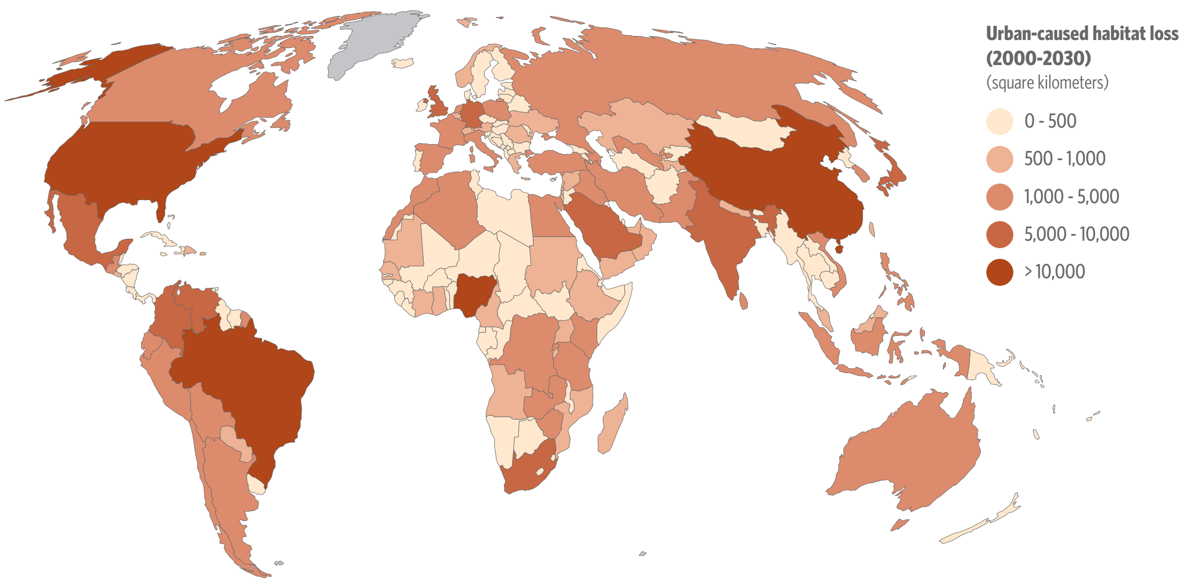


Figure 12: Habitat loss projected (2000-2030) by country.

Urban growth causes habitat fragmentation

Urban growth doesn't just reduce habitat area, it also fragments and affects the remaining habitat, often leading to a consequent decline of species richness and abundance [57, 58]. Habitat fragmentation may be defined as a discontinuity in the spatial distribution of environmental resources and ecosystem conditions. Fragmentation can affect the survival, reproduction, and mobility of multiple interacting species [59]. Habitat loss and fragmentation are rarely spatially uniform and may occur across a landscape over a period of decades [60, 61], leaving a discontinuous mosaic of remnant habitat fragments of many sizes, interspersed with other land cover types, including agriculture, disturbed vegetation and built human infrastructure.

Habitat fragmentation in urban environments results in lasting alterations to the physical environment (e.g. light and temperature), degrading ecosystem function [58, 62, 63] which leads to declines in ecosystem service provision [49]. Changes in habitat patterns resulting from urban sprawl cause important impacts on biodiversity in urban areas, namely the loss of diversity and a more homogenized species composition [64]. In fact, habitat area and fragmentation are known to have important impacts on biodiversity for a wide range of groups including plants, amphibians, birds and insects [65]. Populations occupying smaller and more isolated habitat areas experience harsher environmental conditions, and therefore face a higher risk of extinction [66, 67]. The types of species lost from fragmented landscapes depends upon species' traits, including their size and mobility [67, 68].

Patterns of habitat loss and fragmentation due to urban sprawl

Habitat loss and fragmentation result in a reduction of habitat patch size and an increase in their isolation. During urban area growth, the degree of habitat fragmentation generally increases with habitat loss [69]. Different fragmentation patterns exist across cities. Angel et al. [70] found, using a global sample of 120 cities, that fragmentation decreases with city size but increases with average income in a city. Cities with higher levels of car ownership, and those that constrain urban development through zoning or land-use regulation, are also less fragmented. Importantly, these outcomes occur within municipal boundaries, but also beyond the geographic limits of the city proper in the suburbs and exurbs of the metropolitan area. Figure 13 shows patterns of urban growth for a few example cities.

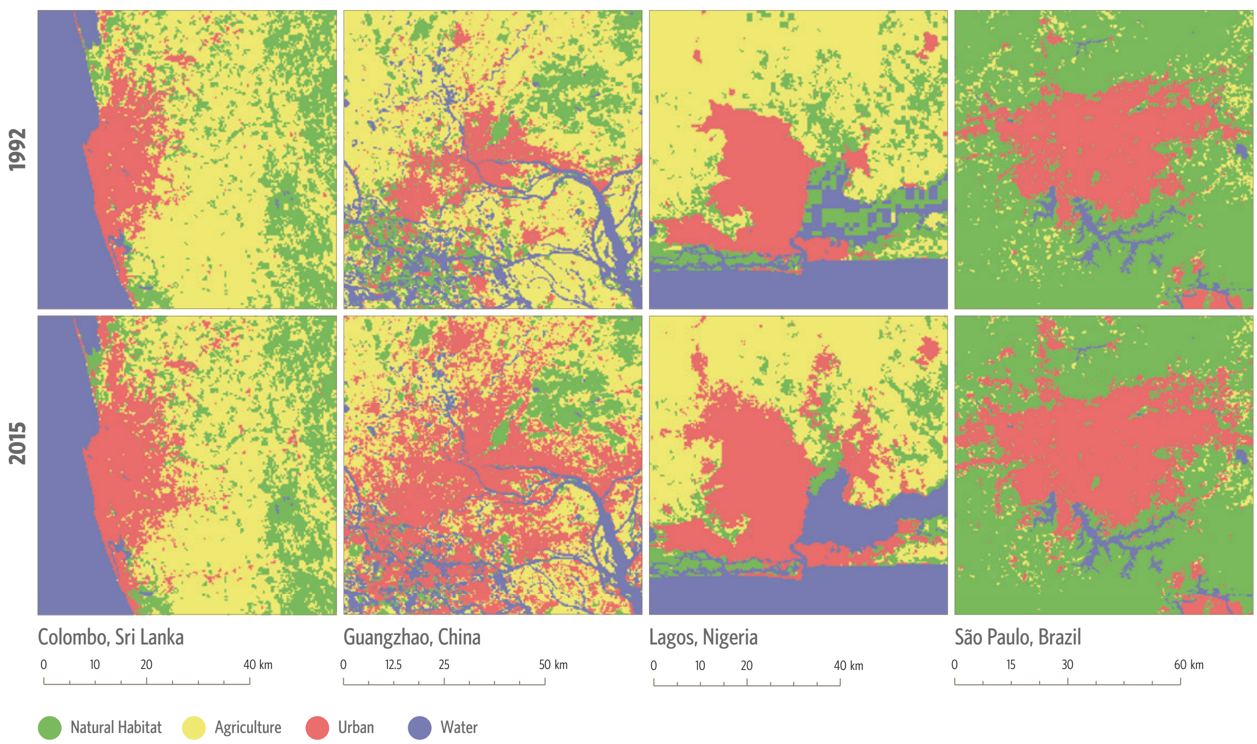


Figure 13: Changes in land-cover of Colombo, Guangzhao, Lagos, and São Paulo (1992-2015), based on the CCI Land Cover.

Moreover, as urban areas expand, linear infrastructures including roads, railways, fences and power lines also expand, further fragmenting the metropolitan area and surrounding natural habitats. For example, China has experienced extremely rapid urban growth since the 1990's with an average annual urban growth rate of ca. 8-9% [69, 71]. Fragmentation by major transportation systems within China varies widely, with almost all eastern provinces, especially areas near big cities, having high levels of fragmentation; and several eastern-Chinese provinces having among the most severe landscape fragmentation in the world [72, 73]. This massive linear infrastructure has resulted in significant natural habitat loss in some areas of China [71].

Linear infrastructure, beyond further reducing or degrading habitat quality, can have additional negative impacts for species inhabiting and passing through metropolitan areas. Above all, they can be responsible for direct mortality (roadkill, collisions and electrocution), which may significantly imperil animal population persistence in urban areas. For example, most animal species are susceptible to becoming roadkill, and high rates of mortality have been recorded throughout the world, including for insects [74], amphibians [75], reptiles [76], birds [77], and mammals [78].

Urban-caused habitat loss is associated with imperilment

Habitat loss— whether driven by urban growth or by the expansion of other anthropogenic land-use, like agriculture— is the preeminent cause of terrestrial vertebrate species imperilment. One systematic review, Evolution Lost: Status & Trends of the World's Vertebrates [79], stated that "overwhelmingly, habitat loss is the greatest threat to all vertebrate groups." Agriculture and logging are the two most common drivers of habitat loss, followed by residential and commercial development from urban growth, which is listed as a threat to approximately one in three threatened vertebrate species.

For this report, we wanted to examine how frequently species listed as threatened on the International Union for Conservation of Nature (IUCN) Red List had a fraction of their habitat urbanized (*Figure 14*). Threatened here was defined as listed as Vulnerable (VU), Endangered (EN), or Critically Endangered (CR). After analyzing the ranges of all IUCN Red List terrestrial mammals and amphibians, we found that 14.8% of these species had between 1% and 5% of their range converted to urban area in 2000. Another 4.7% of these species have lost between 5% and 20% of their range to urban growth. A further 1.1% of these species are highly impacted by urbanization, with more than 20% of their range lost to urban growth.

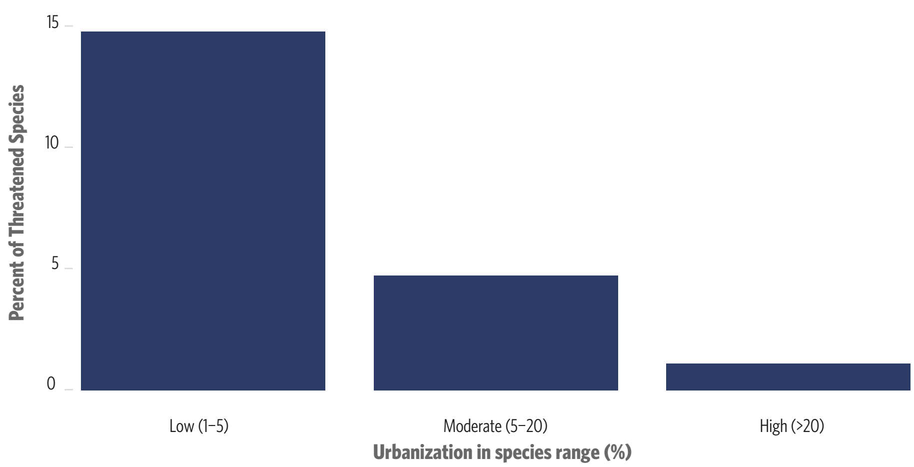


Figure 14: Percent of IUCN Red list species listed as threatened (defined as being listed as Critically Endangered, Endangered, or Vulnerable), that have a fraction of their range urbanized in 2000.

Habitat loss is, of course, far from the only factor that leads to species imperilment. Species with small ranges are more likely to be imperiled, and there are other characteristics of a species' life cycle that make them more or less likely to be imperiled [79]. Nevertheless, it is instructive to look at a list of some IUCN Red List species that are listed as threatened and have more than 20% of their range lost to urban growth (See Table 2).

Photo © milehightraveler

A larger proportion of amphibians have small ranges than mammals, and species with small ranges are more likely to have a large fraction of their range urbanized than those with large ranges. This explains the greater frequency of threatened amphibians than mammals in Table 2. Indeed, most of the species listed in Table 2 (both amphibians and mammals) have very small ranges, having been observed in only a few localities.

Table 2 only lists threatened species with more than 20% of their area urbanized. However, there are species with larger ranges that still have significant fractions of those ranges urbanized. For instance, several mammals along the Atlantic coast of southeastern Brazil have been affected by urban growth near Sao Paulo and Rio de Janeiro: the southern muriqui (*Brachyteles arachnoides*, Endangered), which has a range of 86,000 km^2, 7.8% of which is urban; and the buffy-tufted marmoset (*Callithrix aurita*, Vulnerable), which has a range of 160,000 km^2, 5.8% of which is urban. Another mammal species with a similar degree of urban conversion is the water deer (*Hydropotes inermis*, Vulnerable), which has a range of 182,000 km^2, 5.8% of which is urban, including urban areas such as Shanghai and Seoul. Among the amphibians, the Arroyo toad (*Anaxyrus californicus*, Endangered) has a range of 58,000 km^2, 6.5% of which is urban, including urban areas like Los Angeles, San Diego, and Tijuana.

Many of these species would likely be rare and listed as threatened by the IUCN regardless of the amount of urban area nearby, because of other threats to their persistance. However, the significant degree of urban area in their surroundings means that urban issues must be considered in these species' management plans. It is important to emphasize that habitat loss need not be a death sentence for a species. With proper land protection and management, species can survive even when a portion of their habitat is lost due to urban growth or other forms of land conversion, if the remaining habitat is large enough to support a viable population.

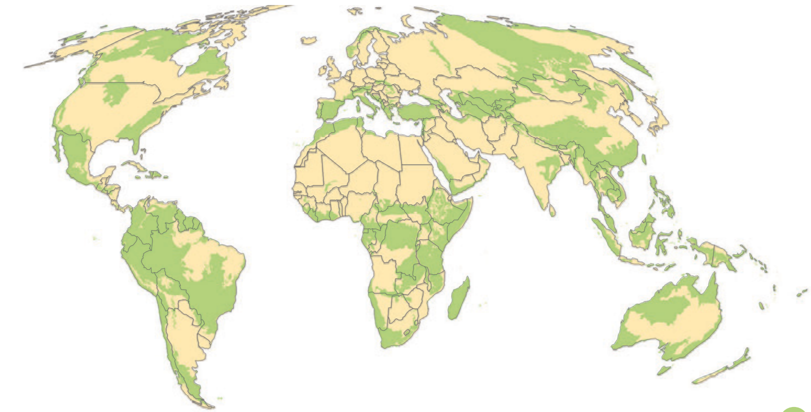
Photo © Marbá-Jonathan Díaz

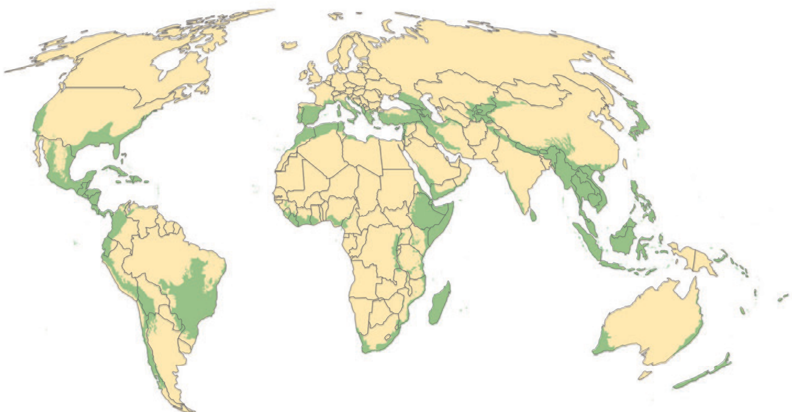
Urban impacts on biodiversity are spatially concentrated

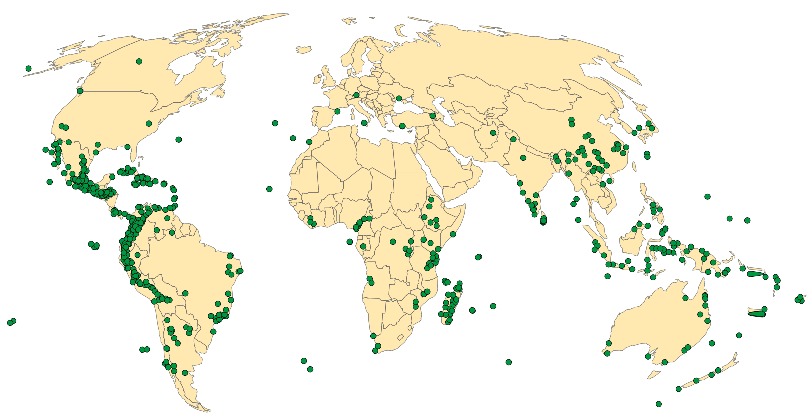
As shown above, urban growth will significantly imperil many different types of habitat, from tropical forests to deserts to temperate grasslands. Insight into conservation priorities can be gained by comparing our scenario of habitat loss with metrics of global biodiversity importance. One challenge, though, is that there are many different metrics of biodiversity importance currently in use. On the web site associated with this assessment (www.urbannature100.org), there is an interactive map to visualize the threat urban growth poses. In this report, where we can only present static images, we show the spatial patterns of multiple metrics of biodiversity. We then present in the next section a more focused analysis of the impact of urban growth on one commonly-used metric of biodiversity importance, Key Biodiversity Areas (KBAs).

Figure 15 presents some commonly used metrics of conservation importance. The Global 200 ecoregions (top left) are a selection of ecoregions identified as conservation priorities due to having high species richness or endemism, or due to having a high degree of threat [80, 81]. Within the Global 200 ecoregions, areas we have forecasted to have significant urban growth include central Mexico, the southern coast of Brazil, and southern China. The Biodiversity Hotspots (bottom left) are regions with more than 1,500 endemic vascular plants that have lost more than 30% of their original natural habitat [82]. Areas forecasted to have significant urban growth within the Biodiversity Hotspots are broadly similar to those in the Global 200 ecoregions, and include central Mexico and the southern coast of Brazil. The Alliance for Zero Extinction (AZE) sites (top right) are where the only known population of a particular species exists [83]. AZE sites forecasted to have significant urban growth are in the regions mentioned above, but are also disproportionately found on islands, such as in Madagascar, Indonesia and Papua New Guinea. Finally, Key Biodiversity Areas (bottom right) are identified following the IUCN's Global Standard for the Identification of Key Biodiversity Areas. Sites must meet one or more of 11 criteria, such as threatened biodiversity, geographically restricted biodiversity, ecological integrity, biological processes, or irreplaceability [84, 85]. For instance, AZE sites and surrounding natural habitat are often designated as KBAs.

// Biodiversity loss is forecasted to be highly spatially concentrated.







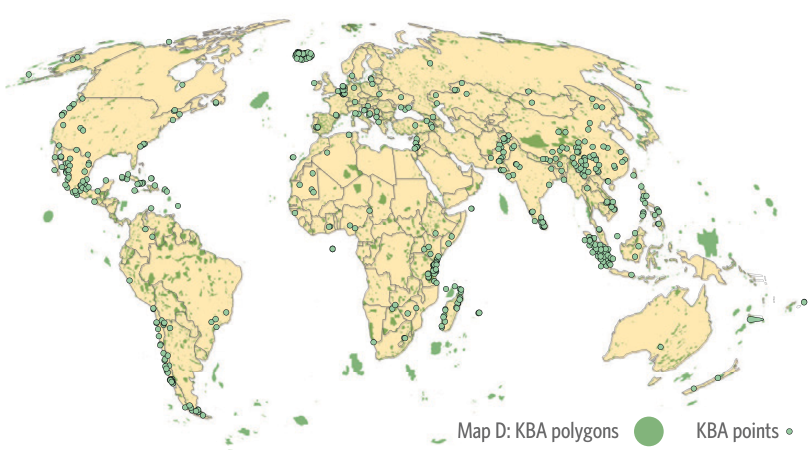
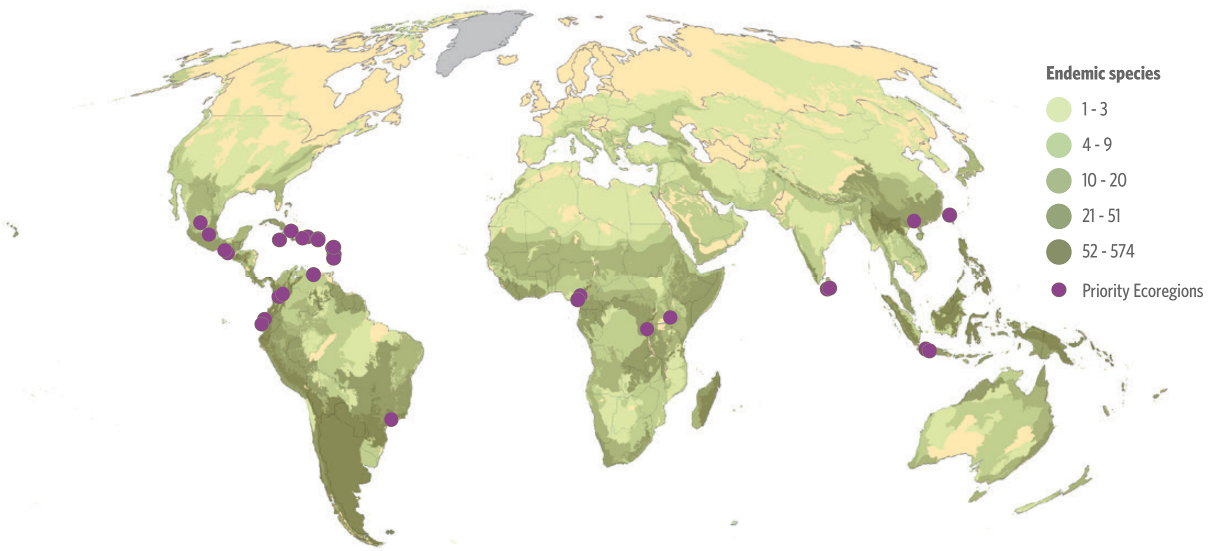


Figure 15: Maps of conservation priorities. **A:** The Global 200 Priority Ecoregions are ecoregions identified as conservation priorities for their richness, endemism, threat, or other characteristics. **B:** The Biodiversity Hotspots, regions with more than 1,500 vascular endemic plants and that have lost more than 30% of their original natural vegetation. **C:** The Alliance for Zero Extinction sites are locations where the only known population of extremely rare species exist. **D:** Key Biodiversity Areas, that meet criteria in five broad categories of threatened biodiversity; geographically restricted biodiversity; ecological integrity; biological processes; and irreplaceability.

At least two studies have compared information on conservation importance with urban growth scenarios, to identify urban conservation priorities (*Figure 16*). First, vertebrate endemism for some well-studied taxonomic groups (amphibian, birds, mammals, and reptiles) is shown in Figure 16 (top). A recent paper by McDonald et al., "Conservation Priorities to Protect Vertebrate Endemics from Global Urban Expansion" [56] systematically compared urban growth scenarios with endemism data, and found that globally, 13% of endemics are in ecoregions under high threat from urban expansion. Biodiversity loss is forecasted to be highly spatially concentrated, with 78% of endemics threatened by urban growth occurring in just thirty priority ecoregions (4% of all ecoregions). Many of these priority ecoregions occur on islands, such as Sri Lanka, Puerto Rico, Hispaniola, and Jamaica. Natural habitat protection of 41,000–80,000 km^2 would be needed in these 30 priority ecoregions to safeguard endemic vertebrates. Table 2 from McDonald et al. [56] lists ecoregion priorities, along with the cities affecting them, and the forecasted range of potential natural habitat loss.



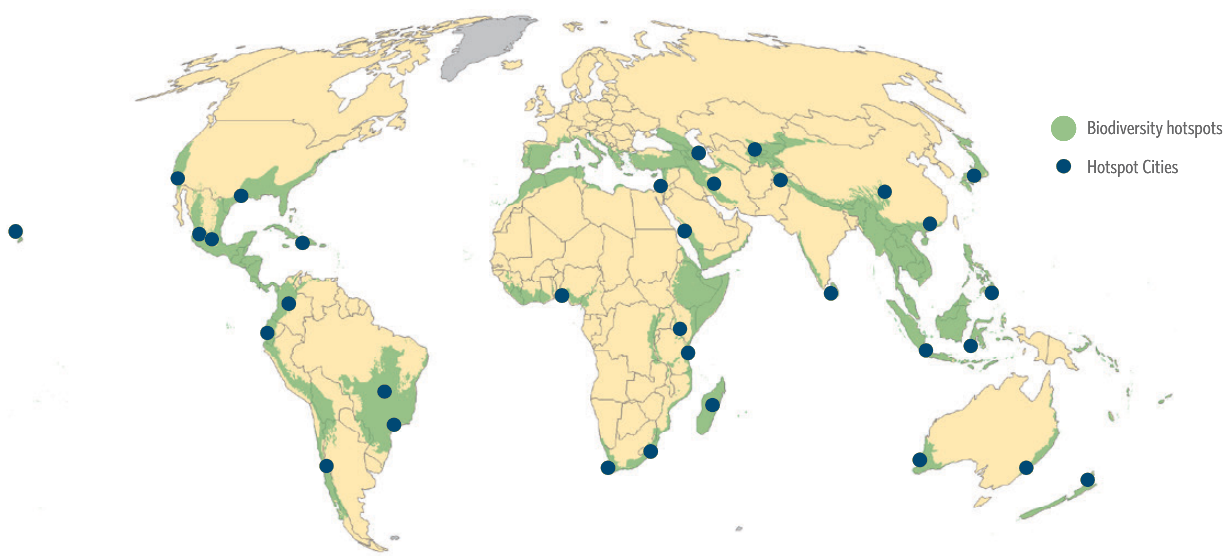


Figure 16: Conservation information can be used to set urban conservation priorities. Top: Endemic vertebrate species (amphibians, birds, mammals, and reptiles) in ecoregions. Marked with purple dots are the 30 priority ecoregions identified by McDonald et al. (2018), which selected ecoregions with high endemism and substantial natural habitat loss forecasted. Bottom: The Biodiversity Hotspots. Marked with blue dots are the 33 cities identified as urban conservation priorities in Weller et al. (2017), which selected the city in each hotspot with the largest forecasted population growth.

Photo © Atakorn

Second, a recent report by Weller et al., "Atlas for the End of the World" [86], identified cities in Biodiversity Hotspots. For each hotspot, they selected the city with the largest forecasted increase in population from 2016 to 2030. *Figure 16* (bottom) shows the thirty-three cities they identified. Note that most selected hotspot cities are along coastlines and on islands, such as Sri Lanka (Colombo) and Hispaniola (Port Au Prince). The Hotspot Cities section of the Atlas [86] lists all 33 cities, along with detailed city-level maps of potential urban growth impacts on natural habitat.

Urban impacts on Key Biodiversity Areas

We now focus on urban impacts on the world's Key Biodiversity Areas (KBAs), as they are one of the most accepted measures of conservation importance [84, 85]. A large fraction of the world's terrestrial KBAs are or will be impacted by urban growth (*Figure 17*). By 2030, 9.1% of KBAs will have between 1-5% of their area urbanized. 3.2% of KBAs will have between 5-10% of their area urbanized. Summing up, one in ten KBAs (9.9%) will have more than 5% of their area urbanized by 2030. Surprisingly, around 2.1% of the world's KBAs will have more than 50% of their area urbanized and will be extremely impacted by urban growth.

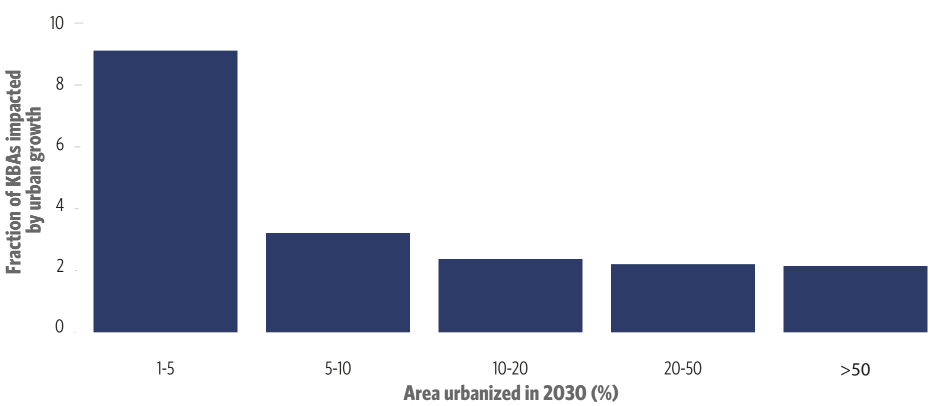


Figure 17: The fraction of the world's terrestrial Key Biodiversity Areas (KBAs) that are impacted by urban growth. KBAs are divided into categories, based upon the area urbanized within the KBA by 2030.

KBAs that will be impacted by urban growth are shown in Figure 18, where impact is defined as having more than 5% of their area urbanized by 2030. Many of these urban impacted KBAs are found in Europe. Another concentration of urban-impacted KBAs is in Latin America, especially in Central America, the Caribbean, and the western and southern coasts of South America. East Asia has a concentration of urban-impacted KBAs, especially in China, Taiwan, Korea, and Japan. In Africa, urban-impacted KBAs are most commonly found along coastal regions such as along the Mediterranean, the Gulf of Guinea, and the coast of South Africa. Uganda, Rwanda, Kenya, and Tanzania have another cluster of urban-impacted KBAs.

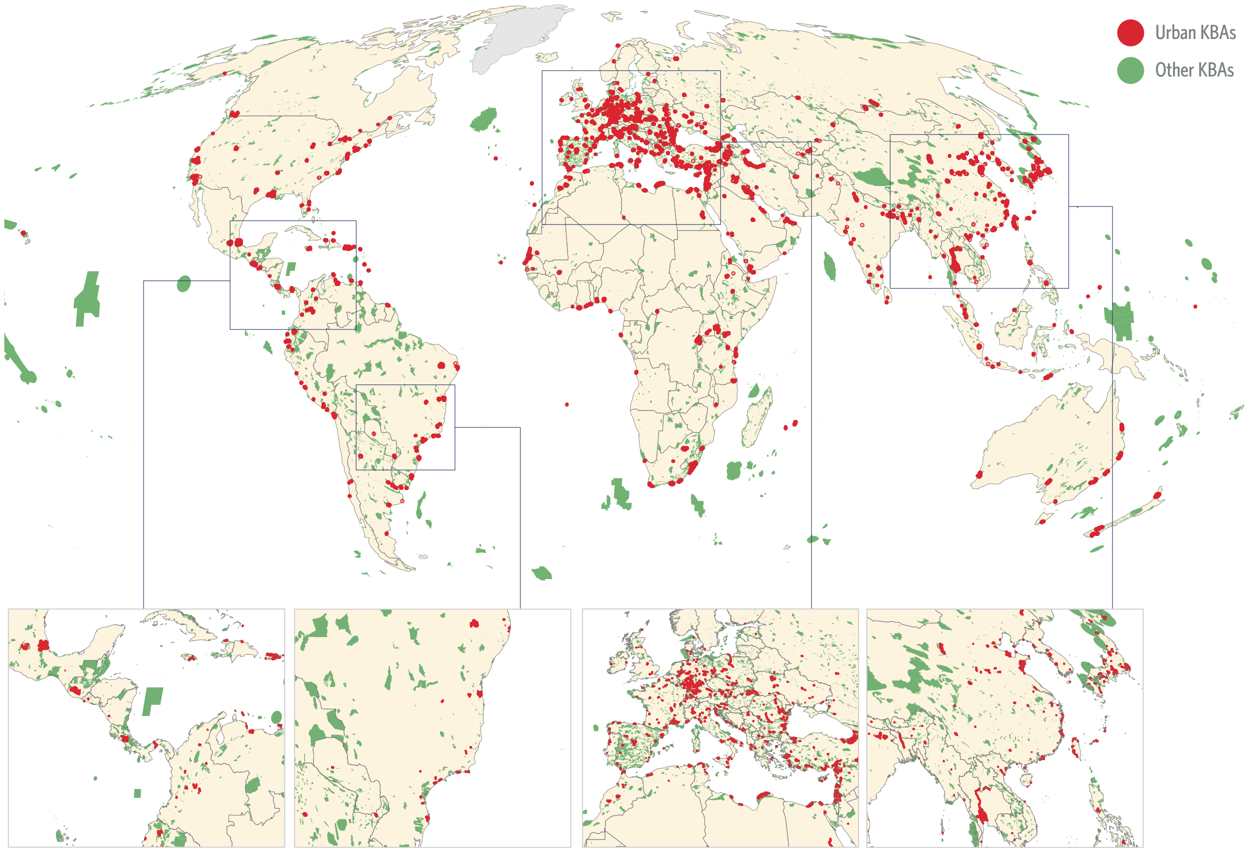


Figure 18: Key biodiversity areas (KBAs) that are impacted by urban growth (>5% of their area forecasted to be urbanized by 2030). Shown is a global map (top panel), as well as inset maps for Central America, Europe, Brazil, and China.

Photo © Kwong Shun Cheong

While the large fraction of KBAs that are or will be impacted by urban growth can be daunting, it is worthwhile to consider the positive side to this spatial concentration of biodiversity impact. The urban-impacted KBAs in Figure 18 have a total area of 320,000 km^2. On average, around 16% of the area of these KBAs will be urbanized by 2030. That implies that there will be 52,000 km^2 of area within these KBAs that could be lost to urban growth, unless growth is otherwise limited or managed. Compared to the 290,000 km^2 of habitat globally between 2000 and 2030 that is forecast to be urbanized, this is fairly small. Conservation action to protect these urban KBAs could serve as a focused first step toward mitigating the impact of global urban growth on biodiversity.

Urban impacts on freshwater and marine biodiversity

This report has focused on terrestrial biodiversity. This is primarily a reflection of the fact that there are more studies of the direct impact of urban growth on terrestrial habitats than on freshwater or marine habitats, and because it is more straightforward analytically to intersect maps of urban growth with terrestrial habitats than it is to model the complex effects urban growth has on the hydrologic cycle. Nevertheless, it is clear from existing scientific reviews that urban growth can have a significant impact on freshwater and marine biodiversity. In this subsection, we try to highlight major types of impact, citing works that discuss these issues in more detail.

Freshwater

It is clear that cumulatively, cities and associated development have a significant impact on freshwater biodiversity [79]. Freshwater ecosystems are only 0.8% of the Earth's surface, but harbor about 6% of all described species. The best studied freshwater taxonomic group is fish (*Pisces*). Across both freshwater and marine fish, around 15% are listed as threatened on the IUCN Red List. There is some evidence that freshwater fish are more threatened than marine fish, with an estimated 65% reduction in monitored freshwater fish populations since 1970. Urban growth is associated with an increase in water pollution and sedimentation, which is the most common threat to freshwater fish species. Similarly, urban growth often increases road construction and energy-sector development, which often leads to dams and other barriers to fish migration, the second most common threat to freshwater species. Residential and commercial development, often associated with urban growth, is listed as a threat to around one in five freshwater fish species.

By overlaying information on urban growth on maps of the freshwater ecoregions of the world [87], we can gain insight into which areas are likely to be most impacted by urban growth (*Figure 19, Top)*. Freshwater ecoregions that will be highly urbanized in 2030 include those in China such as the lower Huang He and lower Yangtze, as well as those freshwater ecoregions that comprise much of Japan and Taiwan. In the United States, the Florida peninsula is one freshwater ecoregion that will be highly urbanized in 2030. Also important in setting conservation priorities is the degree of freshwater species richness and imperilment in a freshwater ecoregion. For instance, previous scientific studies [88] have called out the Western Ghats freshwater ecoregion in India as one place with significant future forecasted urban growth and with high levels of fish richness and endemism.

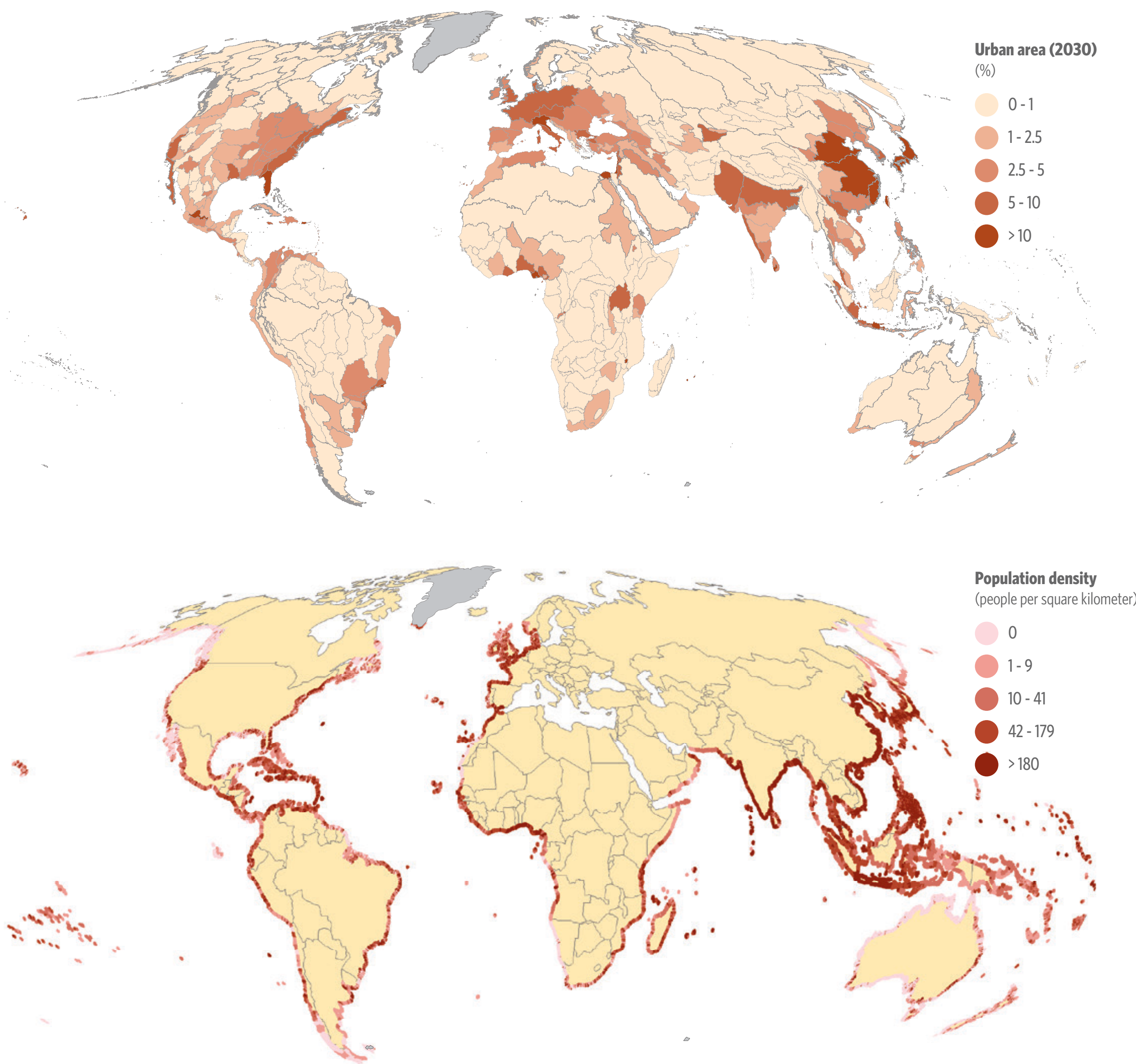


Figure 19: Urban growth impacts on freshwater and marine ecosystems. **Top:** The proportion of area urban in 2030 in the Freshwater Ecoregions of the World. **Bottom:** The population density along coastlines in 2020.

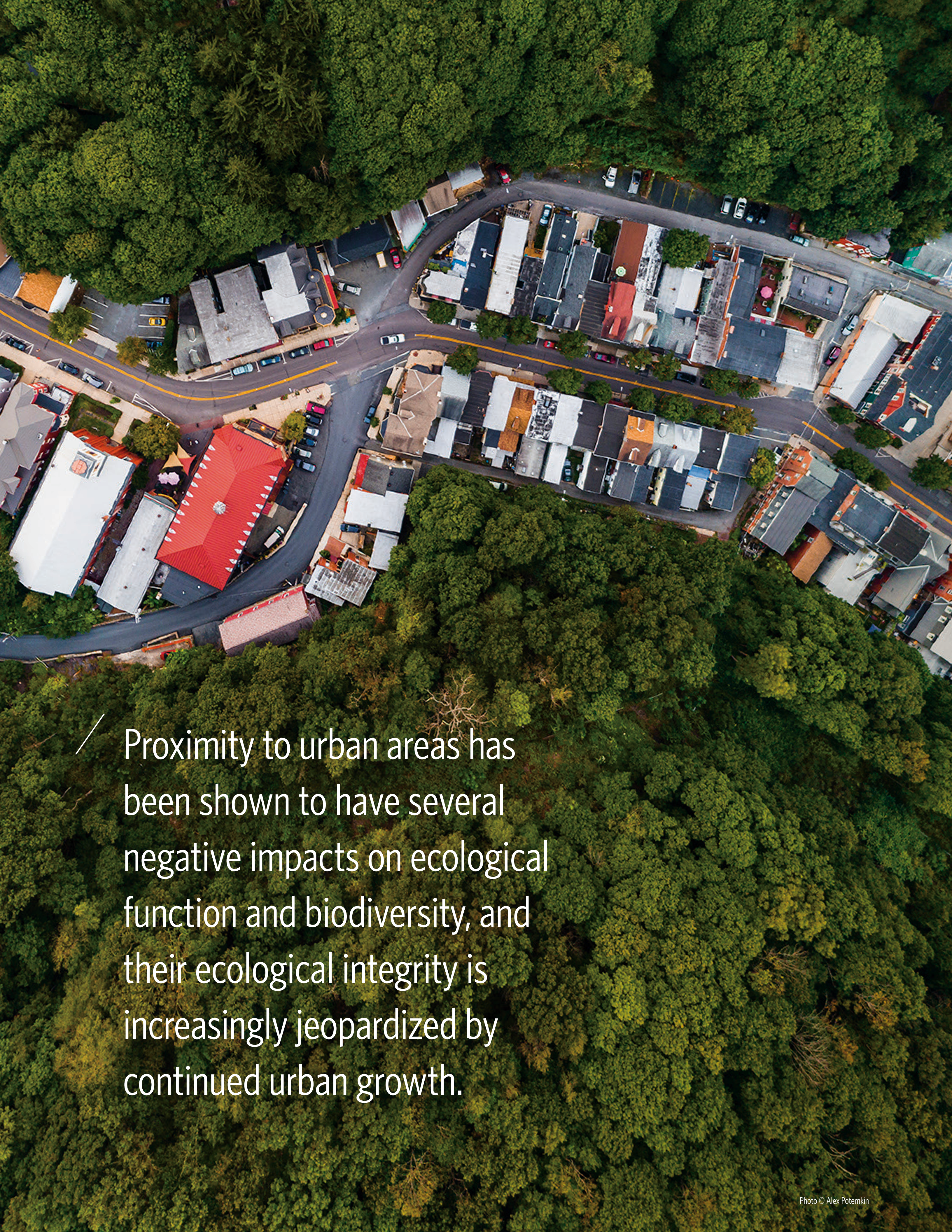
This section has focused on the impacts of urban growth on freshwater ecosystems, but of course cities also depend on ecosystem services from freshwater ecosystems for human wellbeing. Perhaps foremost among these is drinking water. Intact natural ecosystems, both freshwater and terrestrial, play a crucial role in maintaining water quality and, in some cases, quantity [89, 90]. Freshwater ecosystems, in conjunction with wetlands and floodplains, provide many other ecosystem services of importance to urban dwellers, such as stormwater management and flood risk mitigation [6]. See the section on "Integrating nature into cities" for more discussion of how these ecosystem services can be incorporated into cities, for the benefit of biodiversity and human wellbeing.

Marine

The evidence suggests that urban growth also has significant impacts on marine biodiversity, although perhaps of slightly lower magnitude than for freshwater biodiversity. For instance, for marine fish, there has been a 20% reduction in population observed since 1970 for monitored populations [79]. For IUCN Red List marine fish species, residential and commercial development is listed as a threat for around one in five Red List species. The discharge of untreated sewage and other pollution to ocean waters may also impact many near shore marine ecosystems. Pollution is listed as a threat to one in three Red List marine fish species. The most common threat to marine fish is overfishing. Urban seafood consumption patterns drive the levels of harvesting from wild fisheries, as well as the level of production from aquaculture, with significant indirect effects to marine ecosystems.

In Figure 19 (bottom) we show the sections of coastlines that are forecast to have the greatest population density in 2020. Human population will be especially high along the coastline for much of South and Southeast Asia, West Africa, Northern Europe, and portions of the eastern United States and the Caribbean. Nearshore habitats of value for marine biodiversity include coral reefs, mangroves, salt marshes, and kelp forests. Along these stretches of coastline with high human population density, maintaining these habitats will be important to preventing marine biodiversity loss.

Urban areas also depend on coastal habitats for ecosystem services essential to human wellbeing [91]. The section of this report on climate adaptation focuses on the benefits coastal habitats provide in reducing the risks of coastal flooding and hazards. There are of course a variety of other benefits that coastal habitat provides, many of which are catalogued on the Naturally Resilient Communities website. Finally, in the Integrating Nature into Cities section we discuss how these ecosystem services can be incorporated into cities, for the benefit of biodiversity and human wellbeing.



Proximity to urban areas has been shown to have several negative impacts on ecological function and biodiversity, and their ecological integrity is increasingly jeopardized by continued urban growth.

Photo © Alex Potemkin

Impacts of urban growth on protected areas

Urban growth not only directly affects natural habitat through land conversion, it also affects protected areas in many other ways. Land protection has been the preeminent strategy for biodiversity conservation over the past fifty years, and the creation of protected areas (PAs) is the primary goal of Aichi Target 11. Arguably, the rapid increase in terrestrial protected areas over the last few decades, from 8% in 1972 to 15% today (Protected Planet Report 2016) [92], has been one of the major successes of the CBD. Proximity to urban areas has been shown to have several negative impacts on ecological function and biodiversity (*Figure 20*), and therefore the significant investment by Parties of the CBD in protected areas is increasingly jeopardized by continued urban growth.

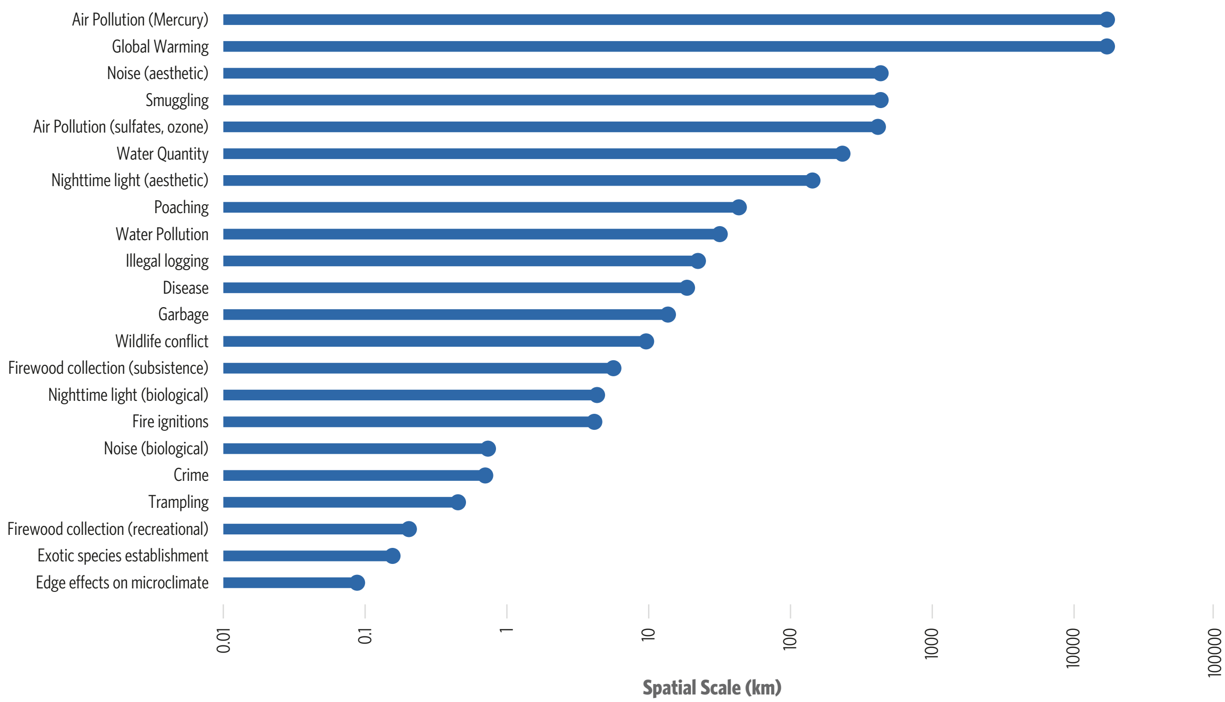


Figure 20: Impacts on protected area of being near a city, adapted from McDonald et al. (2009). A literature review identified from each study the maximum spatial scale at which negative and positive effects from urban areas propagate out and have observed to affect protected areas. Each line represents an average of the reported distances in the literature.

The scale at which urban areas affect PAs varies depending on the type of effect. Some impacts are very local, such as the alteration of temperature and other abiotic conditions along habitat edges, an effect that extends into the protected area a few tens of meters. Habitat edges also become pathways by which invasive, non-native plants and animals can spread, which often have deleterious effects on the native flora and fauna within the PA. Some actions that can severely affect protected areas include resource extraction (legal or illegal), such as hunting or logging, which can extend into the PA by tens of kilometers. Other impacts of urban areas on PAs are regional or global in scale, such as those from light and air pollution like NO_x and SO_x, spreading 100s of kilometers from cities. Greenhouse gas emissions have global impacts. Our analysis presented below follows the rule of thumb suggested by McDonald et al. [93], in which PAs within 50 km of urban areas are considered at increased risk of significant anthropogenic impacts.

As the human population has increased, there has been a significant increase in the average population density in the surroundings of protected areas. The average population density, both rural and urban in a 50 km buffer zone around strictly protected areas (IUCN categories I-IV) has increased 24% from 2000 to 2020 (estimated population), from 51 to 63 people/km^2 (*Figure 21*). Similarly, for loosely protected areas (IUCN categories V-VI), the population density has increased 28% over the same period, from 53 to 68 people/km^2. Individual countries may have much higher values. The Netherlands, for instance, is forecast to have 808 people/km^2 in 2020 in the surroundings of its PAs, while Bangladesh is forecast to have 1,265 people/km^2.

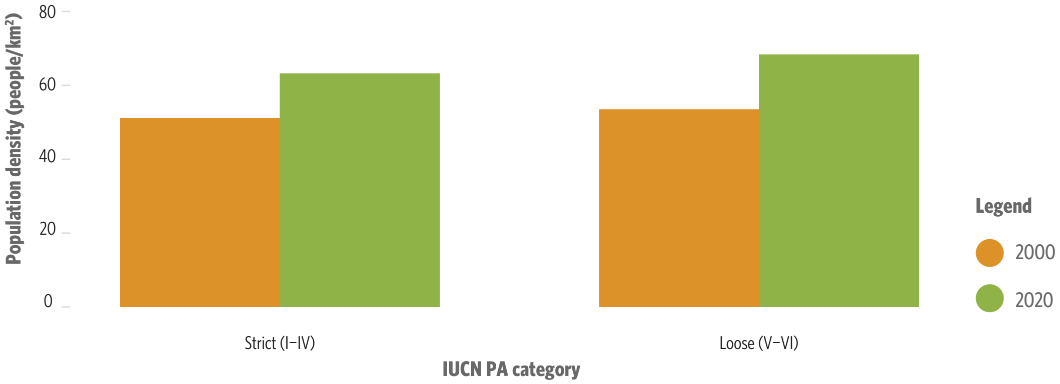


Figure 21: Population density near protected areas, in 2000 and 2020 (estimated).

Along with urban population increase often comes urban area expansion. Urban areas continue to move closer to PAs (*Figure 22*). In 1992, only 3% of strictly protected PAs (IUCN categories I-IV) were within 10 km of cities, while roughly 6% of PAs were between 10 and 20 km from cities and 20% of PAs were between 20-50 km from a city. By 2030, we project that these numbers will have increased dramatically, with 8% of strictly protected PAs within 10 km of cities, 9% between 10-20 km from cities, and 23% within 20 and 50 km from a city. Trends for loosely protected PAs (IUCN categories V-VI) are similar, although these PAs tend to be closer to urban areas than do strictly protected PAs. By 2030, more than one in three strictly protected PAs and one in two loosely protected PAs will be in the 50 km buffer zone around cities. Managing PAs near cities will be a common challenge in our urban century, and close to half of all PAs will require special management if they are to retain their ecological functions.

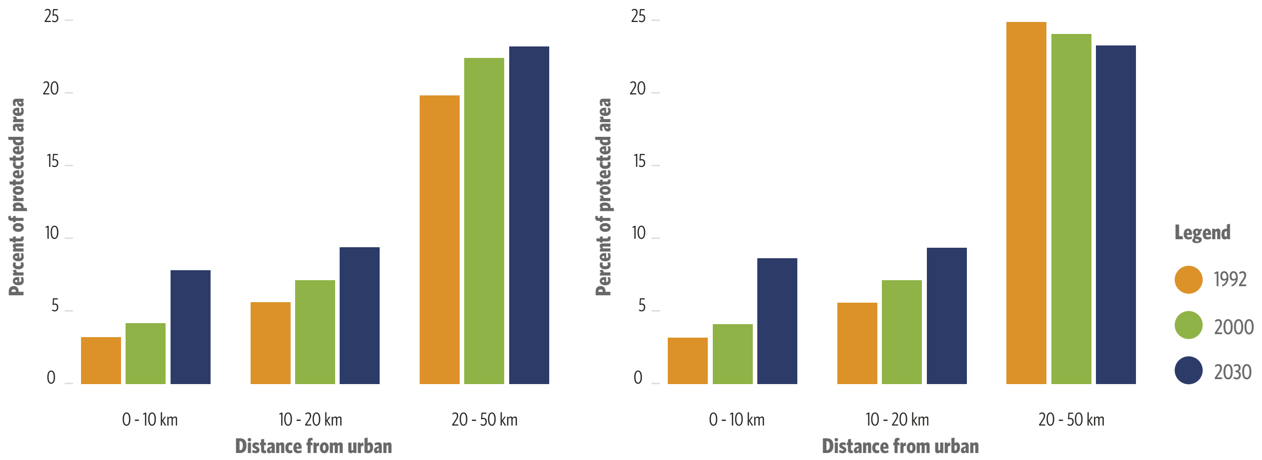
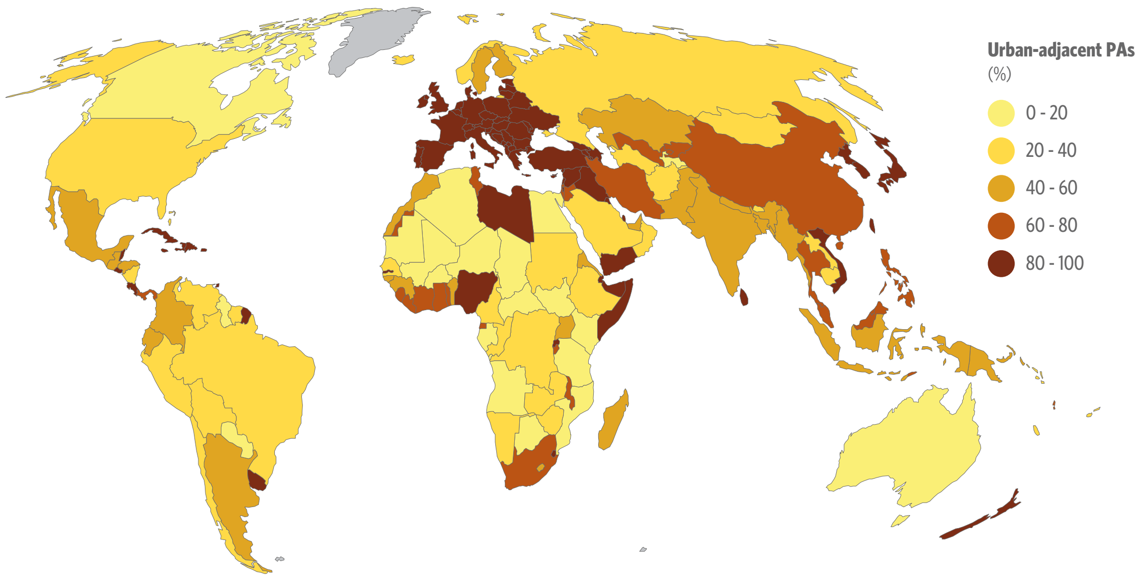


Figure 22: Distance from PA to urban area in 1992 and 2030. **Left:** Strictly protected areas (IUCN categories I-IV). **Right:** Loosely protected areas (IUCN categories V-VI).

The degree of urban impacts on protected areas vary widely from country to country (*Figure 23*). By 2000 more than 80% of PAs in most European Countries were within 50 km of a city. Conversely, countries in Latin America and Africa have relatively low fractions of PAs that are within 50 km of a city. By 2030, there will be a significant increase in proximity of PAs to cities globally. The biggest increases will be in Latin American, the Indian subcontinent, and parts of sub-Saharan Africa. While in China the fraction of PAs near cities will remain low, due to the relatively sparsely populated west of the country, PAs along the coastline will see a sharp increase in urban area-adjacency.



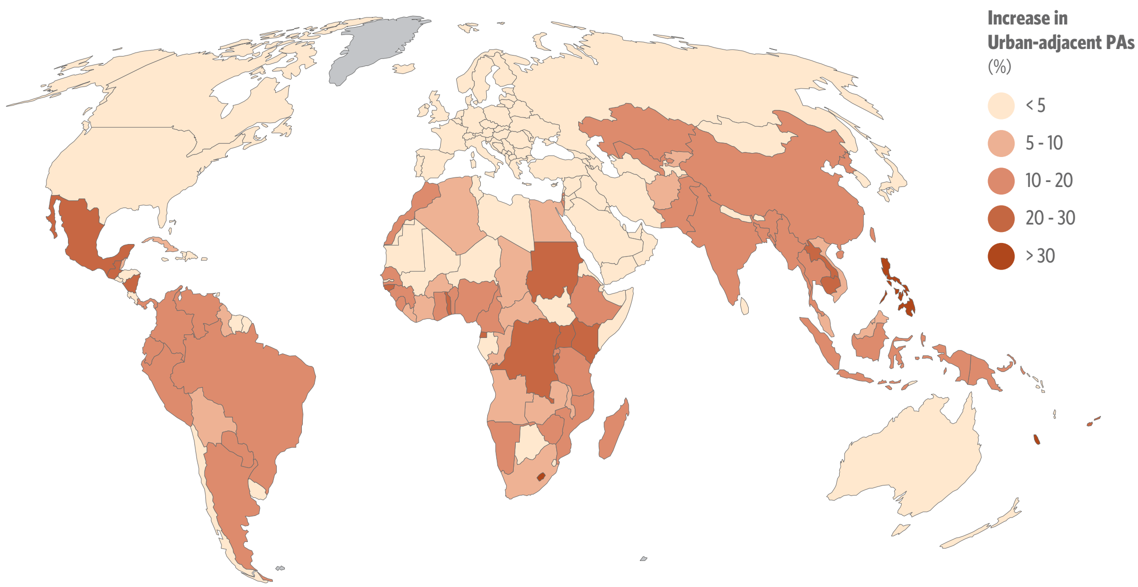


Figure 23: Country-level trends in in the fraction of all protected areas (IUCN categories I-VI) that are urban adjacent (within 50 km of an urban area). A.) Percent of protected areas that are urban-adjacent (2000), by country. B.) Increase (%) in the fraction of protected areas that are urban-adjacent (2000-2030).

Photo © Evgeny Pylayev

The same sort of analysis can be applied to individual protected areas, to examine the potential impacts of urban growth on specific PAs. Table 3 shows large (> 500 km^2), strictly protected areas (IUCN categories I-IV) that already have large amounts of urban area within 50 km. Note the multiple protected areas in already highly urbanized countries, such as Italy, Taiwan, and United States. Brazil also has two PAs on this list, both near the coastline.

The protected areas that will experience the most rapid urban growth (2000-2030) within 50 km are shown in Table 4. Protected areas in Table 4 tend to be concentrated in countries that are still urbanizing rapidly. For instance, Sundarbans National Park in India will have a significant increase in urban area in its surroundings, as Calcutta and other urban settlements rapidly expand. Many of the potentially impacted PAs highlighted in Table 4 are in developing countries, with a special concentration in sub-Saharan Africa. Importantly, inclusion in Table 4 does not mean that urban growth will necessarily occur inside PA boundaries, but just that significant urban growth is forecast within 50 km.

We find that urban growth, if unplanned, could impact natural habitat that currently stores carbon equivalent to emissions from 931 million cars on the road for one year.

Photo © alisa24

Impacts of urban growth on climate change

Natural habitat and carbon storage

Climate change mitigation has been defined as any intervention to reduce the sources or enhance the sinks of greenhouse gases [94]. High concentrations of carbon dioxide and other greenhouse gases in the atmosphere contribute significantly to global warming and associated climate change [95]. The UNFCCC's 2015 Paris Agreement states as its long-term goal to keep the increase in global average temperature well below 2°C, relative to pre-industrial levels. The reduction of carbon dioxide emissions is one of the main mechanisms by which this goal can be achieved.

Carbon dioxide is released into the atmosphere through a number of different processes, including the burning of fossil fuels and land use change such as deforestation. Globally, emissions from fossil fuels and industry amounted to 9.9 ± 0.5 billion tons of carbon (GtC) per year in 2016, while emissions from land use changes totaled 1.3 ± 0.7 GtC/year [96]. Natural habitat stores carbon in the form of biomass, and when it is cleared or burned to make way for urban development, carbon dioxide is released. Intact natural habitat therefore fulfills an important climate service by storing carbon. Protecting natural habitat from unplanned urban growth directly contributes to Aichi Target 15: *By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced, through conservation and restoration,… thereby contributing to climate change mitigation and adaptation*.

This climate mitigation service can be quantified by calculating the amount of above- and below-ground carbon stored in biomass and converting that figure into the amount of carbon dioxide that could potentially be released if this biomass were cleared or burned for urban land use [97]. We find that urban growth, if unplanned, could impact natural habitat that currently stores an estimated 1.19 GtC, or 4.35 billion tons of carbon dioxide ($GtCO_2$) (*Figure 24*). This is the same amount of carbon dioxide emissions from 931 million cars on the road for one year [98]. Assuming the avoided emissions are spread equally over the period between 2000 and 2030, avoiding urban-caused habitat loss would prevent emissions of 0.15 $GtCO_2$/year-. Compared to the large numbers associated with cities' overall direct and indirect CO_2 emissions (see next section), the emissions of 0.15 $GtCO_2$/year that are potentially released due to expansion into natural habitat might appear relatively minor. However, this amount still represents between 2.0% and 6.6% of total annual greenhouse gas emissions associated with global land use change [96].

We find that the greatest potential overall loss of carbon from urban growth will occur in the United States, Brazil, and Nigeria. The highest rates of average carbon loss per hectare of habitat lost will occur in Central Africa and Southeast Asia, as well as Brazil and Australia, as the vegetation types which are expected to be lost due to urban growth (such as tropical forests) store large amounts of carbon.

// Urban growth, if unplanned, could affect natural habitat that currently stores an estimated 4.35 billion tons of carbon dioxide.

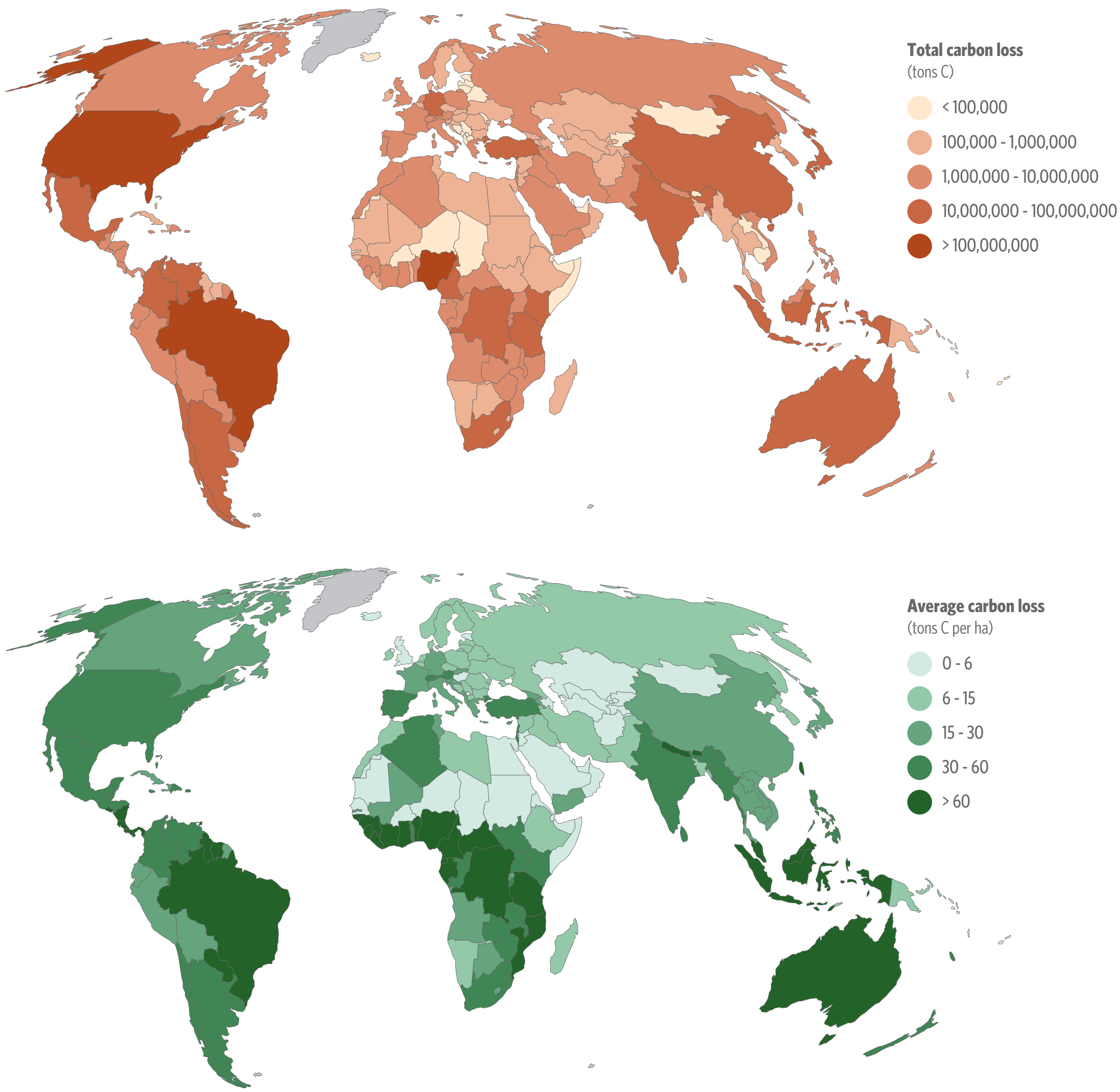


Figure 24: Country-level trends in the total carbon (in tons) (top), and average carbon (in tons per hectare) (bottom) lost due to urban growth into natural habitat.

Unlike many other impacts of urban development that play out at the local scale, the impacts of increasing carbon dioxide emissions are felt at the global scale. To quantify the severity of impacts an estimate of the social cost of carbon (SCC) can be calculated. The SCC is a measure of the economic harm caused by climate change and its consequences, such as flooding, food shortages, and the spread of diseases [99]. It is usually expressed as the dollar value of the long-term damages from emitting one ton of carbon dioxide. There are a number of integrated assessment models that can be used to calculate the SCC, though none of the models currently include the full range of important biophysical and socioeconomic impacts of climate change (mainly due to limited data availability) [95]. Here we use an estimate of the SCC based on the US Environmental Protection Agency's modeled SCC estimates (USD 42/t CO_2 eq) [100]. Our estimate of the carbon stored in natural habitat that is forecast to be lost to urban growth (2000-2030) has a potential social cost of 182.8 billion USD.

Alternatively, the value of avoided carbon emissions can be equated with the average price of carbon offsets in voluntary carbon markets, which currently trade at a much lower value than the SCC. The 2016 average price of carbon offsets on these voluntary carbon markets was USD 3.0/t CO_2 eq [101]. We estimate that the carbon stored in natural habitat that is forecast to be lost to urban growth (2000-2030) would have a value of 13.1 billion USD on voluntary carbon markets.

In the context of global greenhouse gas emissions, the emissions associated with urban growth into natural habitat may seem minor. However, for some countries protecting natural habitat on the urban fringe can meaningfully contribute meaningfully to achieving greenhouse gas emissions targets, as pledged at the Paris Climate Conference in 2015. Taking into account the potential mitigation benefits of natural habitat can be an important tool in the arsenal of urban planners to reduce the climate change impacts of their cities.

Uncertainty in estimating carbon stored in biomass

Carbon storage in vegetation can be calculated in different ways. One approach is to use globally consistent default values for biomass of different vegetation types, and then convert those biomass values to above- and below ground carbon stocks using the carbon fraction for each vegetation type [97]. Essentially, this method creates a database of carbon values for over 120 different types of carbon "zones", each associated with a different land cover, vegetation type, continental region, and forest age. This means that carbon values can be estimated for all regions of the globe, except for urban areas.

More recent methods base carbon values on remotely-sensed aboveground biomass estimates. This approach may be more accurate than the database approach described above, but so far studies have either been limited to certain vegetation types or regions, like the pan-tropics [102, 103], or have a coarse spatial resolution (>10 km) [104].

Nevertheless, comparisons between different types of data can be useful to assess the level of uncertainty associated with carbon storage values. Here we compare the global Ruesch & Gibbs [97] method with the Baccini et al. [102] approach that covers only tropical forests. Figure 25 shows the difference in carbon storage values (in kg/ha) between the two methods for the central Africa region. The Baccini et al. [102] data, based on remote-sensing technology, distinguishes more detail and variation within the forest vegetation, while the Ruesch & Gibbs [97] data covers a wider range of different vegetation and land use types.

For urban growth areas and vegetation types where the two different data sets overlap, the Ruesch & Gibbs [97] data estimates an average of 73.1 tons of carbon stored per hectare. In contrast, the Baccini et al. [102] data estimates an average of 48.0 tons of carbon stored per hectare. The Ruesch & Gibbs [97] estimates are therefore 52% higher, on average, than the Baccini et al. [102] estimates. In part, this is likely due to the fact that the Ruesch & Gibbs [97] data takes into account above- and below ground carbon, while Baccini et al. [102] focuses only on aboveground carbon. This raises an interesting question as to whether urbanization processes are likely to set free below-ground carbon, the same way that agricultural conversion of natural habitat might. Nevertheless, the difference in results might also indicate an overestimate of carbon storage values by the Ruesch & Gibbs [97] approach, at least in high-biomass areas like tropical forests.

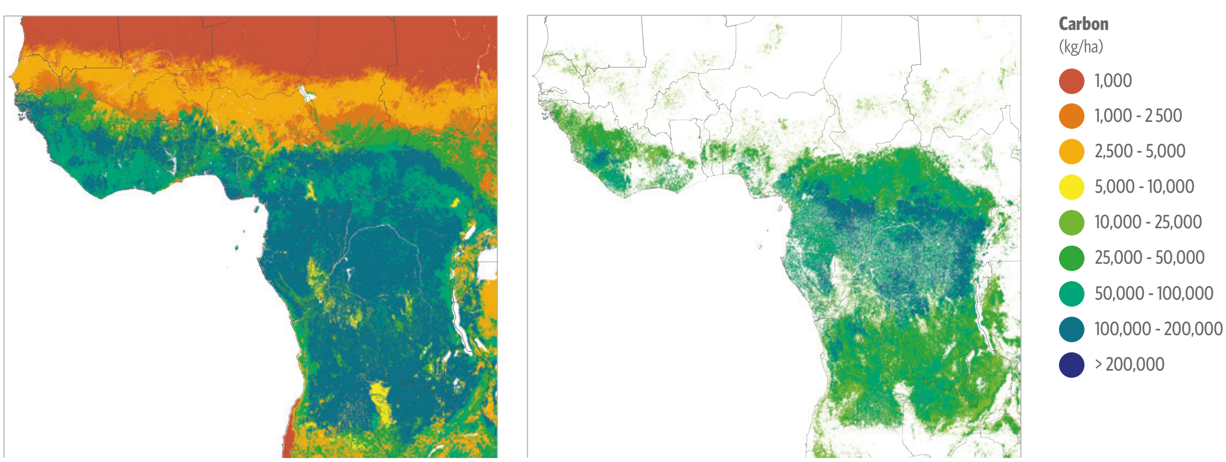


Figure 25: Comparison of results for carbon stored in biomass (kg/ha) in the central African region, as calculated using the Ruesch & Gibbs (2008) method (left) and the Baccini et al. (2012) method (right). The Baccini et al. (2012) method only considers tropical forest vegetation, while the Ruesch & Gibbs (2008) method takes into account all vegetation types.

Consumption and emissions within cities

As outlined above, 1.19 GtC stored in vegetation may be released into the atmosphere by unplanned urban expansion into natural habitat. Over the thirty year period under consideration (2000 – 2030), that translates into annual emissions of 145 million tons of CO_2. However, beyond emissions related to habitat loss, cities are responsible for a range of other greenhouse gas emissions associated with urban activities such as energy consumption, industry, transport, and waste disposal, as well as the import and export of goods.

The calculation of the total contribution of cities to greenhouse gas emissions depends on how urban emissions are defined. However, it has been estimated that cities account for as much as 70% of all human-induced greenhouse gas emissions [105]. Given the total global annual greenhouse gas emissions of 49 Gt CO_2 eq in 2010 [95], the contribution of cities would be estimated at 34 Gt CO_2 eq.

To facilitate standardized accounting, emissions are often categorized as either direct or indirect. In an urban context, direct emissions are emissions from sources within cities, such as industry. Indirect emissions are emissions that result as a consequence of a city's consumption of resources that are harvested or produced somewhere else. A recent global analysis of consumption-based (indirect) emissions estimates that emissions from the top-500 most emissions-intensive cities totaled approximately 9.9 ± 0.2 Gt CO_2 eq in 2015 [106].

Indirect emissions of urban areas are often estimated in studies that consider a city's "footprint". Urban areas consume large amounts of water, agricultural products, marine resources, and other renewable resources that are provided by areas outside of cities, and they produce waste that needs to be assimilated [107]. A city's ecological footprint can be expressed as the amount of biologically productive land that is needed to meet its demand for resources. For example, London's ecological footprint was calculated to be an area the size of Germany and Denmark combined [108]. When assessing a city's impact on biodiversity and ecosystem services, it is therefore important to consider the wider ramifications of urban consumption and growth beyond encroachment into natural habitat.

Natural habitat and climate change adaptation: a case study of coastal resilience

Climate change adaptation is the process of adjustment to actual or expected climate, with the aim of moderating or avoiding harm or exploiting beneficial opportunities [94]. Some of the most destructive consequences of climate change include increases in the frequency and severity of weather-related extreme events, such as hurricanes. In addition, global warming is causing the thermal expansion of seawater and melting of land-based ice sheets and glaciers, which results in sea level rise. Coastal communities are therefore especially vulnerable to the impacts of climate change, with increased risks of storm waves and surge, as well as sea level rise and subsidence [109]. It has been estimated that forty million people are currently living in areas that are at risk from one in one-hundred-year coastal flood events in major coastal cities around the world - a number that is projected to triple by 2070 [110]. Furthermore, extensive built infrastructure is often found close to the shore. The total value of exposed assets in major port cities was estimated at 3,000 billion USD in 2005, with the highest values recorded for the United States, Japan and the Netherlands [110]. By 2070, this figure is projected to increase tenfold. Likewise, Hallegatte *et al*. [111] estimate global flood losses in the world's largest coastal cities to reach 60-63 billion USD per year by 2050, mainly due to climate change and subsidence.

Coastal habitats such as coral reefs, salt marshes, seagrass beds, mangroves, and coastal dunes play a crucial role in reducing the impacts of coastal hazards which are expected to be exacerbated by climate change [112-114]. Coral reefs and mangrove forests dissipate wave energy. Similarly, seagrass beds and marshes stabilize sediments that help to slow down waves. Globally, it has been estimated that the topmost 1 m of coral reefs provide flood reduction benefits that result in more than 4 billion USD annually in avoided damages [91]. Coastal wetlands reduced flood damages in the northeastern United States by an estimated 625 million USD during Hurricane Sandy in 2012 [115]. Coastal habitats provide a climate change adaptation service which reduces the vulnerability of coastal communities.

Some coastlines are more at risk than others. Along with the presence or absence of natural habitats, factors such as relief, wave exposure, and surge potential play roles in determining the vulnerability of coastal communities [116]. Taking these factors into account, we have assessed the relative importance of natural habitat along the coastline by modeling the overall risk of physical exposure with and without habitat. Figure 26 (top panel) shows the resulting distribution of critical coastal habitat around the world. Areas where habitat is significantly reducing the exposure to coastal hazards and sea level rise are mainly found in the tropics, especially in the Caribbean, eastern Africa, and Southeast Asia. In many of these places, such as Indonesia, Bangladesh, Tanzania, Cuba, and the eastern United States, population densities along the coast are high, making the service provided by natural habitats even more important *(Figure 26 bottom panel)*.

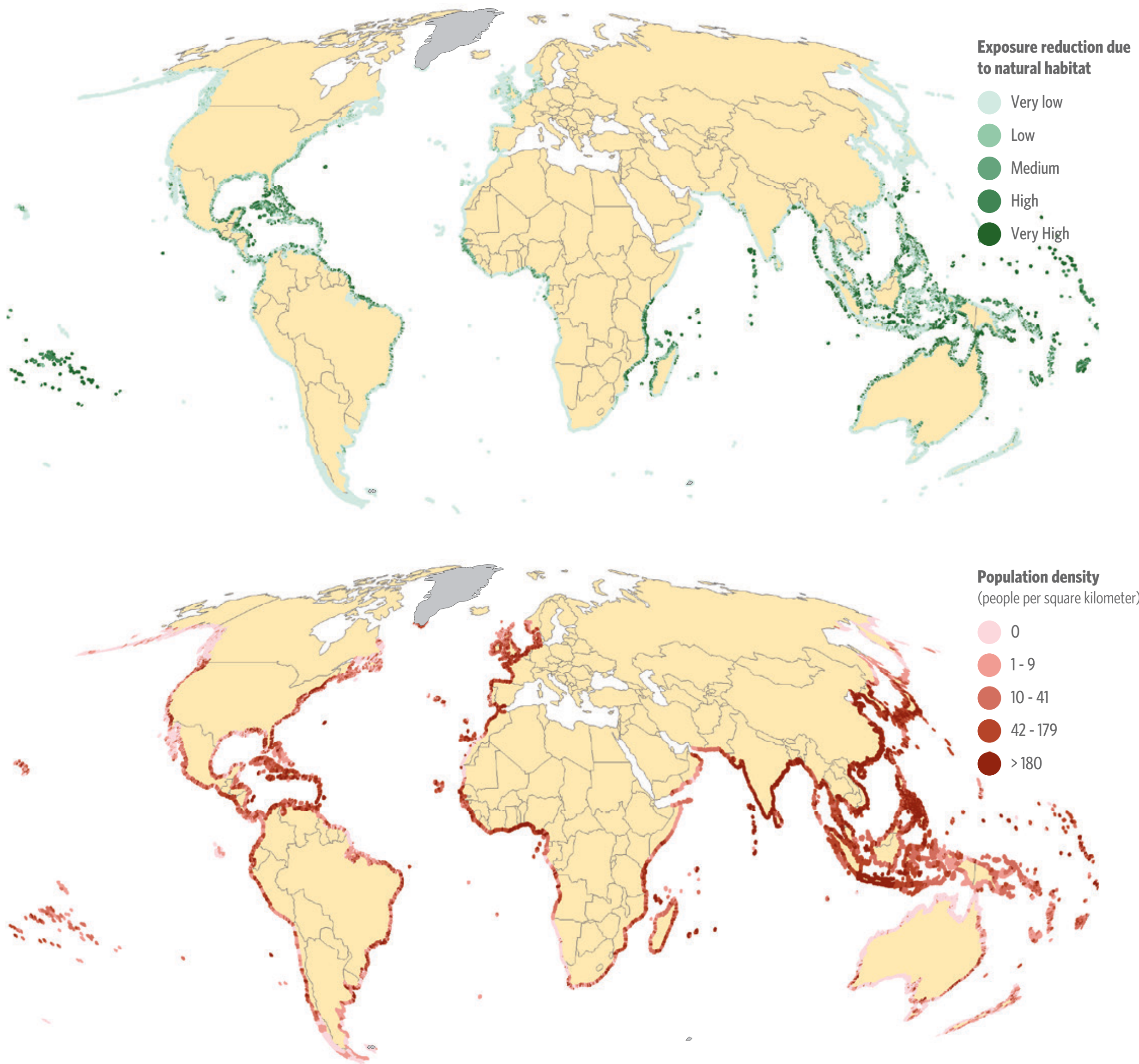


Figure 26: Distribution of coastal habitat that reduces exposure to coastal hazards such as storm waves, surges, and sea level rise (top panel). Coastal habitats considered here include coral reefs, mangroves, seagrass beds and salt marshes. The bottom panel shows population density along coastlines.

As cities on the coast expand, some of the critical natural habitats may be lost or degraded due to coastal development. As a result, many urban communities could find themselves at higher risk of damage from storm surges and sea level rise. Especially vulnerable are those communities within the low elevation coastal zone (LECZ), which is land area less than 10 m above sea level [117]. Along those stretches of coastline where natural habitat plays a critical role in reducing the risk of coastal hazards and sea level rise, 10,100 km^2 of urban area was within the LECZ in 2000. By 2030, this figure is projected to more than double to 23,000 km^2. Similarly, in 2000, 95 million people lived in rural and urban areas within the LECZ along coastlines with critical natural habitat. This number is expected to increase to 125 million by 2020. Figure 27 shows the growth in urban area in the LECZ along critical habitat stretches at the country level between 2000 and 2030. Our findings indicate that Nigeria and Brazil, followed by the US, China, and Indonesia, will have the greatest amount of urban growth along high-benefit coastlines by 2030.

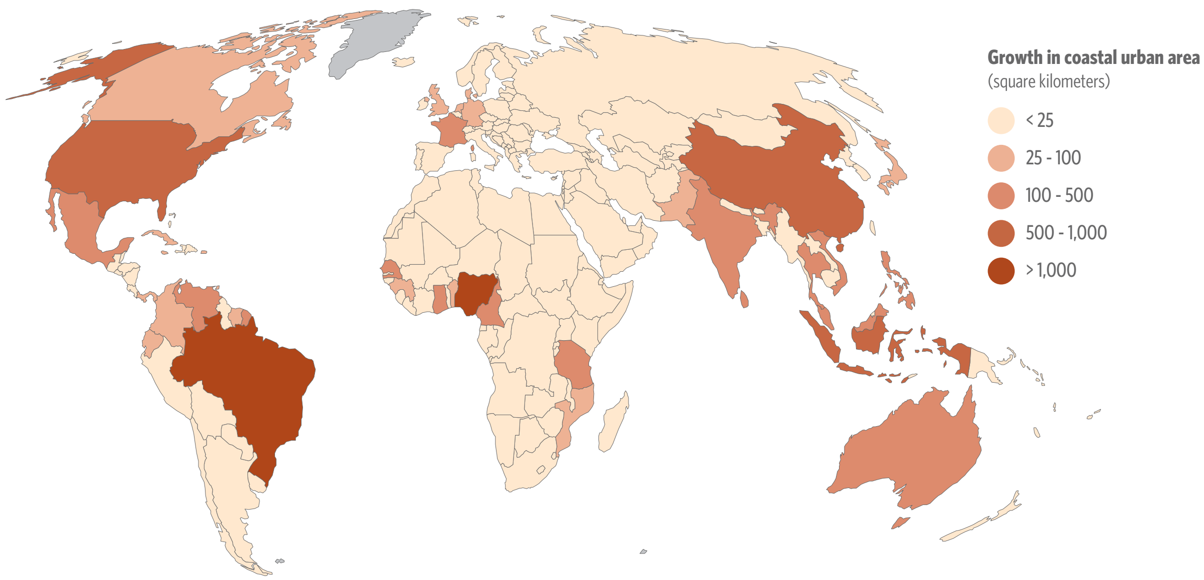


Figure 27: Country-level estimates for the growth in urban area (in km2) found within the low elevation coastal zone, along stretches of coastline where natural ecosystems provide high-levels of coastal risk-reduction services. Time period considered is 2000 – 2030.

These findings suggest that protecting natural habitat that provides this critical climate adaptation service should be a priority when planning for sustainable urban growth and risk reduction. This is especially important in cities where low-lying coastal areas are predominantly occupied by poor and marginalized residents, since these communities often have lower capacity to prepare for, respond to, and recover from extreme events [118-120]. Our results demonstrate that the protection and restoration of critical coastal habitat contributes directly to Aichi Target 14: *by 2020, ecosystems that provide essential services… are restored and safeguarded…*

In recent years, scientists and practitioners have come to recognize that nature-based solutions can be a cost-effective complement to built infrastructure to reduce risks from coastal hazards in urban areas. However, the effectiveness of nature-based solutions (NBS) can vary significantly from one urban area to the next, depending on factors such as space availability, the intensity of storms, and the distribution of vulnerable populations [121]. Strategies to urbanize coastal environments therefore require an integrated, cross-sectoral approach that accounts for these factors.

Other important climate mitigation and adaptation services

Beyond carbon storage and coastal protection, ecosystems in and around cities may provide a number of other services that contribute to climate mitigation and adaptation. For example, urban areas typically experience higher temperatures than surrounding rural areas, a phenomenon known as the urban heat island effect [122]. This effect is expected to become more intense with global warming [123]. Excessive heat is already a major cause of deaths worldwide. For example, the heat wave that struck Europe in 2003 claimed an estimated 70,000 lives [124]. In 2010, heat waves in India killed more than 1300 people in the city of Ahmedabad alone [125]. Parks, street trees, and water bodies have been shown to significantly reduce ambient temperatures, by absorbing the sun's heat energy and shading urban surfaces such as streets, sidewalks and buildings [126]. These green and blue spaces in cities therefore provide an important climate adaptation service to urban dwellers – especially to poor and vulnerable residents who cannot afford technological solutions such as air-conditioning. Moreover, the shading of buildings and general reduction of ambient temperatures by trees and other vegetation decreases the amount of energy needed to cool buildings from within, thus reducing energy costs and carbon dioxide emissions associated with energy use [127, 128]. Depending on the source of a city's energy (i.e. fossil fuel-derived vs. renewable), this may translate into a substantial climate change mitigation service provided by natural habitat.

Climate change is also predicted to increase other risks, including the frequency and intensity of wildfires and the frequency and severity of precipitation events, leading to an increased risk of flooding in some urban areas [129, 130]. Green spaces within a city, but also natural habitat on its fringes, can play an important role in adapting to these extremes by intercepting rainfall, increasing water infiltration into the ground, and slowing down the lateral flow of water [131].

These examples illustrate the many benefits associated with natural habitats in and around cities. Benefits also extend beyond climate change mitigation and adaptation. For instance, natural habitats—especially trees—have the potential to improve air quality by acting as a filter for particulate matter and other sources of pollution [132]. Green spaces and natural habitats in and around cities provide many opportunities for tourism and recreation, and they can contribute to improved physical and mental health, and can be significant for cultural and religious practices. In some parts of the world, urban dwellers depend on natural habitat on the fringes of cities for their livelihoods, through activities such as harvesting food, obtaining materials for shelter, and keeping livestock. Urban growth, if unplanned, may therefore impact benefits that city residents rely on for their everyday wellbeing.

Cities can plan for their urban growth in ways that avoid negative consequences.

Photo © Roger Lee

Exploring solutions

This report has documented the potential negative consequences of unplanned urban growth. In the next few decades, urban growth could cause significant biodiversity loss and reduce the contribution of natural habitat to both climate change mitigation and adaption. This section discusses three potential solutions. First, we discuss how cities can plan for their urban growth in ways that avoids these negative consequences. Second, we present how cities can manage urban protected areas, which are crucial for human wellbeing but pose some special management challenges. Third, we describe how nature can be integrated into cities, by restoring or creating natural infrastructure that enhances human wellbeing.

// Nature can be integrated into cities by restoring or creating natural infrastructure that enhances human wellbeing.

Planning for a natural future

One common way that cities try to harmonize urban growth and the natural world is to plan how natural habitats or natural features (e.g., street trees, public parks, open space, constructed wetlands) can be protected, restored, or created to maximally protect biodiversity and enhance human wellbeing [6]. The term *urban greenprint* was popularized in the United States in the 1990s [133], and has been widely used by groups such as the Trust for Public Land. There are many other alternative terms in use, such as *urban natural resource planning, eco-urban assessments, and urban conservation planning*. We will use the term *urban greenprinting* in this report, but we acknowledge that there are a variety of terms commonly in use for similar planning tasks (see the review in the Current Biodiversity Activities by Municipal Governments section).

Urban Greenprinting seeks to do two things:

- *Bring biodiversity and ecosystem service information into spatial planning* - By incorporating information on key natural features into plans that affect how cities develop, cities can grow while protecting biodiversity and human wellbeing.

- *Silo-busting* - In many urban areas, there is a lack of coordination between different government agencies and other stakeholders. The act of bringing together groups to craft a joint spatial vision (a greenprint) can often help overcome the lack of coordination that impairs urban areas.

This assessment has focused on analyzing how poorly planned urban growth could negatively impact natural habitat that is important for maintaining biodiversity or for climate-related ecosystem services (both mitigation and adaptation). Urban plans (such as comprehensive, sustainability, zoning, and transportation plans) formulated through a greenprinting approach can allow urban growth in certain appropriate places, while avoiding urban expansion on to habitat that is crucial for biodiversity or ecosystem services. This approach need not restrict the overall growth of a city, or prevent the achievement of other goals such as adequate, affordable housing for an increasing urban population. In most metropolitan areas, there is enough land for urban expansion that is of lesser importance for biodiversity and ecosystem services, such as degraded land (brownfields) or land already cleared for agriculture. Cities may also be able to avoid some expansion by allowing more density in new urban settlements, to the degree appropriate to a particular city's context, thus concentrating new settlements and avoiding urban sprawl.

While urban greenprints incorporate information on biodiversity and ecosystem services provided by natural habitat, they also consider a broader range of natural infrastructure including human-designed parks, planted street trees, and water management infrastructure such as bioswales and rain gardens. It is common in urban greenprints to plan for multiple ecosystem services from these natural features, including recreation, aesthetic beauty, and stormwater management. Of course, a successful urban plan must also consider many elements and processes in addition to those involving nature. Depending on the planning context, this consideration may include transportation considerations, zoning and new affordable housing construction, water management, economic development, and energy use. A recent example of a multi-objective approach is the recently published draft action plan for European Union cities, Sustainable Use of Land and Nature-Based Solutions Partnership, which promotes a compact city model aimed at reducing urban sprawl while also incorporating nature into urban life and maintaining a healthy urban environment.

Important in any successful urban planning process, including greenprinting, is the inclusion of key stakeholders [6] to ensure that local knowledge from different groups is incorporated, and that plans reflect the values of the full range of stakeholders they will affect. Local stakeholder involvement is crucial to ensuring that the plan created will be politically viable and likely to be successfully implemented. Inclusion of a representative set of local stakeholders also helps to achieve a plan that equitably distributes the costs and benefits of urban planning decisions.

The livelihood and human wellbeing benefits provided from nature are often key to securing government and public support for any greenprinting plan. A case study of the mainstreaming of biodiversity into policy in South Africa found that messaging based around the avoidance of loss of habitat and biodiversity, though factually and scientifically accurate, was not successful in motivating support. More effective was messaging that quantifies the benefits of nature to people [134].

Many tools exist to help cities incorporate biodiversity and ecosystem service information in urban planning. For biodiversity information, many countries have available geospatial data on the spatial location of rare species or habitat types, which can be incorporated into plans as exclusion layers. For example, the NatureServe Explorer includes information on the distribution of more than 70,000 plants, animals, and ecological communities and systems in the United States and Canada. For ecosystem services, there are tools that can be used to measure the ecosystem service value of natural features. For instance, the ITree toolbox is widely used to quantify ecosystem services from urban trees, while the InVEST toolbox from the Nature Capital Project is often used to quantify services in more rural landscapes, such as services that contribute to water security and the mitigatoin of coastal hazards [135, 136]. Similarly, the TEEB Manual for Cities includes methods and models to estimate the value of ecosystem services provided by single green infrastructure elements [7]. Finally, in planning contexts where budget or other constraints require spatial optimization (e.g., selecting the most important patches of natural habitat to protect out of a large set of possible sites), tools like Marxan and Zonation are often used to construct optimal conservation plans [137].

Often during a planning process, whether at the metropolitan or national scale, it is helpful to develop multiple scenarios for the future [35]. The IPBES Expert Group on Scenarios and Models promotes the development of multiscale and cross-sectoral scenarios around positive visions of the relationship of people with nature, called Nature Future for Urban Systems [138]. These scenarios identify a range of preferences from different stakeholders for how to manage biodiversity and ecosystem services, and develop scenarios representing these preferences. These visions represent a diversity of preferences that include: valuing nature for itself [139], such as for its ecological integrity and biodiversity protection; valuing nature for the services it provides to people, such as climate regulation or food provisioning; and valuing an inseparable relationship between people and nature, such as that of cultural landscapes and local knowledge. Some of the visions foresee cities with more space for biodiversity and natural processes, with the rewilding of urban parks with native species and increased connectivity to the wider landscape. Others emphasize the availability of nature-based solutions, such as green infrastructure, green roofs, and artificial wetlands, and their potential to improve climate, air quality, water quality and physical and emotional wellbeing. Finally, others emphasize a cultural relationship with nature in cities, including the possibility of urban gardening and the historical heritage of city parks and botanical gardens. This participatory modeling framework can be used by cities to explore different planning options and assess how the different preferences result in different cityscapes.

Once a greenprint is complete, governments and stakeholders will need to move to implementation. This often requires the integration of actions across multiple levels of government. While municipal governments may control zoning, national government agencies may control major decisions about infrastructure spending, and other agencies may have responsibility for natural resource management [140]. Involving these various levels of government in the design of a greenprint is key to having enough buy-in to allow later implementation of the plan. Moreover, implementation takes time and resources from government agencies. In some cities in less developed countries, it can be challenging to fund the implementation of a greenprint, and supplemental sources of funding from national or international institutions may be needed.

We hope that the Nature in the Urban Century Assessment inspires the urban areas identified as priority places in this report to take action. We hope that there will be efforts to create collaborative, locally-led greenprints in some of these priority places, which will allow for growth while maintaining habitat that is key for biodiversity or climate-related ecosystem services. The greenprints must of course also be sensitive to local context, and to the needs and desires of city residents, in order to inspire support and catalyze implementation of the greenprinting plan.

Current Biodiversity Activities by Municipal Governments

Numerous cities around the world have already initiated activities to protect biodiversity. While these efforts may not be called "urban greenprints", the terminology used in this report, many of the goals of existing urban activities to protect biodiversity share the same general goal, to incorporate information on biodiversity and ecosystem services into urban planning, decision-making, and action.

In a recent effort to compile and understand current urban biodiversity activities, the Urban Biodiversity Hub (UBHub) has identified efforts undertaken by cities around the world, building off work by Pierce [141] and Nilon *et al*. [52]. The results to date are available at ubhub.org.

Urban Biodiversity Reports and Plans

At least 123 cities from 31 countries have produced a biodiversity report and/or a biodiversity plan (*Figure 28*). A biodiversity plan is defined here as an official government strategy or a document primarily dedicated to biodiversity or ecosystem health that describes goals related to biodiversity and the actions needed to meet those goals. Biodiversity plans cover a variety of topics, including education and communications campaigns about nature, efforts to increase direct access to nature, conservation planning, habitat restoration, green and blue infrastructure, species-specific strategies, regulations to improve development impacts, and broader sustainability initiatives that reduce the impact on local or global biodiversity. These plans often mimic the National Biodiversity Strategy and Action Plans and take on the name Local Biodiversity Strategy and Action Plans (LBSAP) or some similar derivative, such as LBAP or BAP. However, a municipality often chooses a different title that reflects its own approach, such as the Ecological Vision (Ecologische Visie) from Amsterdam (Netherlands). In all, there are 129 biodiversity plans from 108 municipal governments, primarily from the United Kingdom in Europe, North America, and Asia (*Figure 28*).

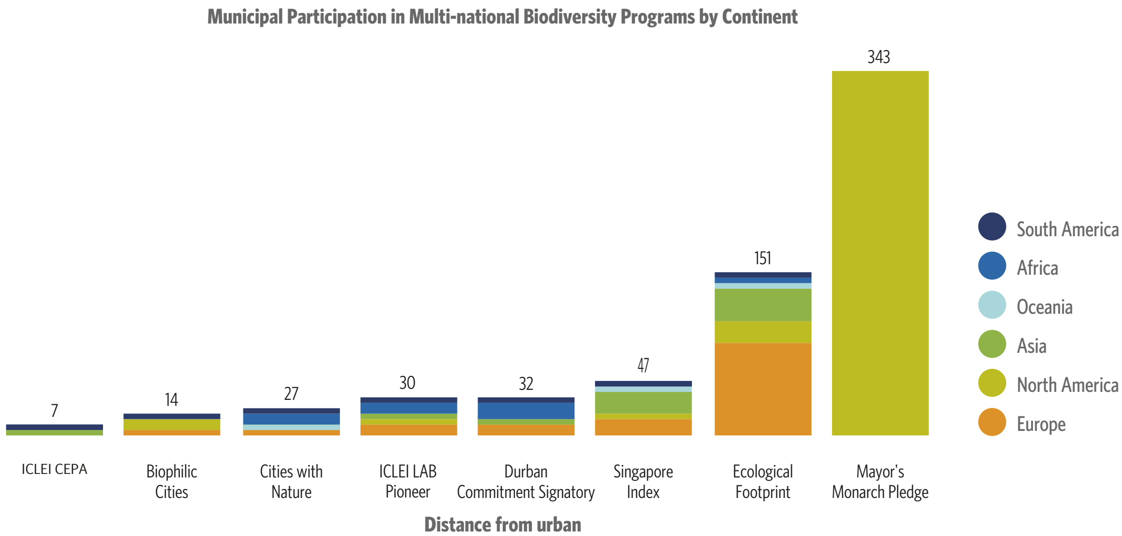


Figure 28: This graph compares municipal-level participation in some of the more popular urban biodiversity programs that span more than one country. ICLEI's programs include the Communication, Education, and Public Awareness (CEPA) program and the Local Action for Biodiversity (LAB) Pioneer program. Both the Singapore Index and Ecological Footprint data include both direct participation in the system by municipal governments themselves and assessments by other stakeholders, such as universities and NGOs.

It is interesting to note that while Europe and North America have the majority of urban biodiversity plans, this assessment has shown that some of the most significant impacts on biodiversity from urban growth between 2000 and 2030 will be in Asia, Africa, and South America. This may simply be a reflection of that fact that it takes resources to develop an biodiversity report or plan, and cities in less developed countries may find it more challenging to find such resources. Other studies have identified this governance paradox. For instance, Huang *et al*. [142] found that the countries where urban growth is most likely to affect biodiversity are also, on average, countries with lower scores as measured by Worldwide Governance Indicators. Overall, the findings of our assessment emphasize the need for initiatives that can help cities in biodiverse regions craft urban biodiversity plans.

A biodiversity report is defined here as an assessment of current ecosystem health or biodiversity, commissioned or adopted by the government and summarized in a single public document primarily focused on this topic. The production of such a biodiversity report is a key element of biodiversity planning, as it contains the baseline data needed by a city to form a strategy for biodiversity. These documents are often entitled "Biodiversity Report," but other names are often adopted by cities, such as Naturbarometer from Berlin (Germany). There are forty-six municipalities that have produced such reports thus far, over half of which are located in Europe and North America. Many of these municipalities have updated their reports over time.

Urban Biodiversity Frameworks and Programs

The Urban Biodiversity Hub has identified twenty-two frameworks and programs that are specific to urban biodiversity and used in more than one country (*Figure 29*). Frameworks primarily guide cities on their biodiversity management by offering a standardized index or measurement system that they can use. These include indices such as the Singapore Index (also known as the City Biodiversity Index or Singapore Index on Cities' Biodiversity) and the Ecological Footprint, which result in a single score reflective of biodiversity status or planning efforts. Programs often ask cities to follow particular steps for biodiversity, such as creating biodiversity documents, piloting projects, making political commitments or joining particular networks. Several of these programs are offered by ICLEI - Local Governments for Sustainability, such as the Local Action for Biodiversity (LAB) program; the Communication, Education, and Public Awareness (CEPA) program; the LAB Wetlands program; the Integrated Action for Biodiversity Project (INTERACT-Bio), and the Urban Natural Assets (UNA) program. Other programs are offered by coalitions of NGOs, such as the newly-created CitiesWithNature program.

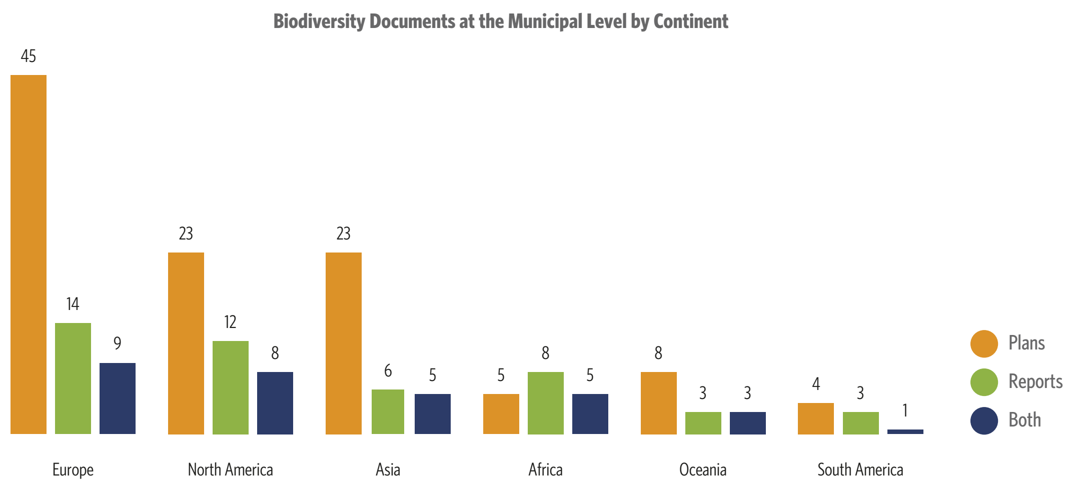


Figure 29: At least 108 cities have published biodiversity plans and at least 46 cities have published biodiversity reports. Of these cities, 31 have produced both. Most documents were produced by European cities, and most are from 34 cities in the United Kingdom. The next most common continent is North America, where most of the reports originate from 13 cities in the United States and 12 Canadian cities. Most of the documents published in Asia are from 19 Japanese cities.

The largest program, as measured by the number of participating municipalities, is the Mayor's Monarch Pledge by the National Wildlife Federation (USA), which awards points to participating cities for each action that a city takes for monarch butterflies from a predetermined list of twenty-four actions. Cities report their progress on an annual basis and earn a designation such as "Monarch Champion" or "leadership circle" for committing to a particular number of actions. Nearly all (330) of the participants in the program are in the United States, with the remainder (13) in Canada.

Managing urban protected areas

Multiple strategies can be used by cities seeking to plan for growth while protecting critical habitat for biodiversity and climate-related ecosystem services. For instance, as part of a greenprint, zoning and transportation decisions can be adjusted to reduce development pressure on critical habitat. The most common conservation tool to protect critical habitat; however, is land protection. Creating and managing protected areas has been a key strategy used by many countries to make progress toward Aichi Target 5 (limiting habitat loss) and Aichi Target 11 (increasing land protection). While they are often found in rural landscapes, many well-known and successful protected areas are in and near cities, such as Bukhansan National Park near Seoul (Korea) and Table Mountain National Park in Cape Town (South Africa).

There is a need for a new generation of urban protected areas, to address the massive urbanization of the 21st century. These protected areas would preserve habitat critical for protecting biodiversity or providing climate-related ecosystem services. Land protection would then be part of the implementation of an urban greenprint, which might include other important implementation steps (changes to transportation and zoning, for example). Research shows that, because of the spatial concentration of urbanization's biodiversity impacts of urbanization, a targeted increase in land protection could prevent extinctions of the majority of species at risk from urban growth [56]. Land protection remains the most permanent and effective way to safeguard biodiversity.

Protected areas also play an important role in maintaining ecosystem services crucial for human wellbeing. These can include the services related to climate change mitigation and adaptation that are considered in this report, but there are multiple other benefits from the proximity of people and nature. Protected areas are often used for recreation, improving physical and mental health and enhancing quality of life. Urban protected areas can be a key part of a city's economic development plans, becoming tourist attractions that give the city a worldwide reputation.

While urban protected areas supply multiple benefits, they also pose some management challenges (*see Figure 20*) [93]. Urban protected areas sustain more frequent resource harvesting and damage, such as illegal logging, firewood harvesting, poaching, and trampling of vegetation. The urban setting also often alters disturbance regimes, including the alteration of fire frequency in many landscapes and increases in the rate of establishment of non-native, invasive species. As urban protected areas are fragmented from other blocks of natural habitat, the lack of ecological connectivity can limit species migration while edge effects can degrade the quality of habitat in the protected area.

However, there are solutions to these management challenges. The IUCN WCPA Urban Conservation Strategies Specialist Group has been working since 2005 to bring together urban protected area managers and scientists. One useful report from this specialist group is Urban Protected Areas: Profiles and Best Practice Guidelines, which compiles case studies and suggests urban protected area management procedures [143]. Some of the guidelines focus on how to appropriately connect people with PAs, so that they fully benefit from proximity to the PA, while avoiding adverse impacts to the PA's natural systems. Another major focus of the guidelines is promoting collaboration among institutions, both across jurisdictions (many protected areas are in multiple jurisdictions) and across sectors (e.g., between natural resource managers and urban planners). In this urban century, governments at all levels will need to invest more money for adequate management of urban protected areas.

The IUCN is continuing to explore how it can best support urban protected areas. At the request of its members, it is creating a new IUCN Urban Alliance, which will provide a platform for debate and information-sharing among urban protected area managers. It will also catalyze new urban protected area creation and increased management. Efforts like this at institutions like IUCN, ICLEI, and The Nature Conservancy (TNC) can help support cities as a new generation of urban protected areas is created.

Integrating nature into cities

This report has focused on how urban growth can be harmonized with the preservation of existing natural habitat in and near cities. However, there are numerous other kinds of natural features that can be incorporated into urban areas, to the benefit of human wellbeing and biodiversity [6]. Urban parks often contain remnant forests and lawns that provide spaces for recreation, but also valuable habitat for some species. Street trees can shade roads, lowering the air temperature on hot days and filtering pollutants from car traffic. Constructed bioswales or wetlands can help manage stormwater. Green roofs and green walls can lower indoor temperatures during the summers and decrease the need for space heating in winter. Finally, urban gardens contribute to food production as well as being sites for environmental education.

These man-made natural features may not be as important for maintaining biodiversity as natural habitat for rare or sensitive species. But numerous studies show that cities can harbor significant biodiversity, and natural features can help make the urban landscape more hospitable for a larger variety of species. For instance, many species of migrating birds use parks, including New York City's Central Park, as temporary resting places while migrating. Some native species survive quite well in cities, such as eastern grey squirrels (*Sciurus carolinensis*) in the United States. Man-made natural features do provide important biodiversity benefits, and urban greenprints should try to plan to maximally incorporate these benefits.

Man-made natural features like parks can serve as important corridors and thus can help counteract fragmentation. Parks, even if they contain non-native habitat, can be important for wildlife movement or nesting. For instance, protected breeding birds like the European green woodpecker (*Picus viridis*) make use of park or backyard trees for feeding their offspring. Natural features can often serve as important corridors for human movement, too. Many cities strive to have "greenways" to increase walking and biking, and some cities are exploring the idea of strategically planting street trees to create "cool corridors" that allow for more comfortable movement during heat waves.

Man-made natural features are primarily designed to benefit humans, the urban residents who will interact with the natural features. The benefits that natural features provide, their ecosystem services, are often greater than the benefits provided by natural habitat, simply because the natural features are closer to where people live and work. Each ecosystem service needs to be generated within a certain distance around the people it is supposed to benefit [144]. The spatial scale at which natural features provide ecosystem services varies greatly, from the shade of a tree, which may extend up to tens of meters, to the carbon sequestration effects benefits of forests which have global impact on the atmospheric concentration of CO_2. Urban conservation and greenspace planners must balance two competing trends. Placing natural features closer to where people live increases ecosystem-service provision. However, the opportunity costs of using land for natural features is often greater near city centers, where there is so much competition from other land-uses.

This report has primarily presented urban spatial conservation planning (urban greenprinting) with regard to the preservation and maintenance of natural habitat. However, urban greenprinting can also focus on integrating man-made natural features into urban planning [6]. For instance, many cities conduct urban tree canopy assessments to map current tree cover and plan where additional trees should be planted, for maximal benefit. From a technical perspective, it can be challenging to plan for multiple types of natural features for multiple different ecosystem services. Nevertheless, there are several guidelines for how to successfully plan within this challenging urban context [7].

To aid cities in incorporating nature into their urban plans, ICLEI, in collaboration with TNC and the IUCN, has created CitiesWithNature, a global platform for cities and other subnational governments that recognizes and enhances the value of nature in and around cities. The platform builds on a decade of experience with ICLEI and the IUCN's international Local Action of Biodiversity (LAB) initiative and draws on lessons learned under the Cities' Biodiversity Index. CitiesWithNature provides an interactive, user-friendly, digital interface for cities, their communities and experts to connect, share, and learn from each other.

Through CitiesWithNature, participating cities and subnational governments can share their ambitions, policies, plans, actions and innovations and demonstrate their commitment to work, plan and live with nature; keep abreast of current global agreements and ambitions; and gain access to a wide variety of tools, projects, services and information offered by leading global organizations and city and subnational networks.

There are solutions for shaping urban growth while protecting biodiversity and climate-related ecosystem services.

Photo © Jacoblund

A call to action

Much of this assessment has focused on presenting the business-as-usual scenario, showing the negative impacts on biodiversity and climate-related ecosystem services if we continue on our current urban growth trajectory. We have tried to argue that there are solutions, ways to shape urban growth while protecting biodiversity and climate-related ecosystem services. In this last section, we list specific actions that can be taken to begin to achieve this more harmonious future. We, the individuals and institutions involved in writing this report, call on those reading this report to:

// Cities have the potential to be major catalysts of change.

1 Integrate local governments in national planning from the start

Countries use National Biodiversity Strategies and Action Plans (NBSAPs) to plan how they will achieve their commitments under the Convention on Biological Diversity. Aichi Target 17 calls for all Parties to the CBD to create NBSAPs, and since COP-10, 160 Parties have submitted such plans. Multiple documents provide guidance on how to write NBSAPs, as well as specific topics like agricultural biodiversity, gender issues, and unique issues of biodiversity for island states (https://www.cbd.int/nbsap/guidance.shtml). While there are guidance documents related to climate change and ecosystem services, two topics mentioned in this report, few are explicitly focused on urbanization or urban growth. However, decision X/22 of the CBD offered a plan of action for the engagement of subnational governments, cities and other local authorities in the work of the CBD. Furthermore, the Quintana Roo Communique on Mainstreaming Local and Subnational Biodiversity Action explicitly calls all levels of governments to action in this critical period of rapid urbanization.

There is an urgent need for many countries to more fully consider urban growth in the next iteration of NBSAPs. Currently, many NBSAPs make only slight mention of cities and urban growth. Better incorporation of urban issues into NBSAPs would allow countries to craft more efficient, effective plans to fulfill their commitments under the CBD. Many of the techniques of systematic conservation planning or *urban greenprinting* (see discussion above) can be useful during the preparation of an NBSAP.

National governments can work with their local government counterparts to incorporate urbanization and urban growth into the next iteration of the NBSAPs, and the support of cities and subnational governments allows countries to design more effective plans to fulfill their commitments under the CBD. The ICLEI Cities Biodiversity Center in collaboration with the SCBD and the Japan Biodiversity Fund, produced "Guidelines for an integrated approach in the development and implementation of national, subnational and local biodiversity strategies and action plans" [140]. These guidelines focus on vertical and horizontal integration and how the different levels of government can cooperate and coordinate their planning, actions and monitoring.

Governments will also have to set aside appropriate resources to implement the urban-focused components of their NBSAPs. The financial and resource commitments that countries make to urban conservation should match the scale of the challenge that poorly planned urban growth poses to the Aichi Targets and the goals of the CBD. If urban growth will cause 290,000 km^2 of habitat loss between 2000 and 2030, a significant portion of all habitat loss, then urban conservation work deserves a significant fraction of conservation dollars.

2 Empower cities to plan for a positive natural future

Cities have the potential to be major catalysts of change, because they can help to implement recent international agreements such as the Aichi Biodiversity Targets, the Paris Agreement, the 2030 Agenda for Sustainable Development, the New Urban Agenda, and the Sendai Framework for Disaster Risk Reduction. Actions by cities to address the implications of urban growth will make crucial contributions to the national efforts aimed at fulfilling international commitments. Empowering cities to take these actions will require planning and implementation among multiple actors, across various geographies and scales.

For instance, for urban greenprinting, much of the expertise for urban planning and zoning lies at the municipal level. However, national governments have a unique role in the CBD, being the entities that develop NBSAPs and funds their implementation. National agencies also often manage national parks and other protected areas, which may be crucial areas for biodiversity persistence in urban areas. This division of roles implies the need for greater coordination between municipal and national governments, which could work together to codesign and implement effective urban greenprints.

As important as cross-scale collaboration is the need for a change in mindset. Many urban planners still view conservation of natural resources as antithetical to planning for urban growth and economic development. A shift in perspective in urban planning is needed, toward planning for a positive natural future. Participatory methods can be used to identify such a future based on the preferences of different city stakeholders. Potential tactics to implement the vision of a positive natural future include ecological restoration and rewilding, integrated urban planning, technological solutions, nature-based solutions, and improved governance.

3 Leverage international institutions

International institutions have a key role in designing and building the cities of the future. The GEF has a role in funding projects that support achievement of the CBD and other international agreements. The GEF has a sustainable city program, and has recently broadened its focus to include conservation of urban biodiversity and ecosystem services. The Green Climate Fund and other mechanisms under the UNFCCC will finance climate mitigation and adaptation actions, which often will occur in and near cities. The World Bank and regional development banks will finance major development projects in cities, as will bilateral donors. These international institutions will collectively help shape the cities of the future.

We call for more extensive consideration of urban biodiversity impacts and ecosystem services in the funding decisions of major institutions, both multilateral and bilateral. Major international funders, such as the GEF and the Green Climate Fund, could direct appropriate funding to mitigate the impact of urban growth on biodiversity and ecosystem services, focusing especially on key priority areas where the return on investment is likely to be largest. Similarly, bilateral donors should increasingly fund projects that mitigate urban impacts on key priority areas.

4 Create a Convention on Biological Diversity for the urban century

In the past, discussion of urban growth and cities in the CBD decision-making process was relatively limited. Urban growth was often subsumed under the much broader discussion of the drivers of global habitat loss. Within that discussion, attention focused appropriately on conversion for agriculture and logging. In the next few decades, however, urban growth will be one of the major sources of habitat loss and in some countries, urban growth will be the largest driver of terrestrial habitat loss.

We call on all Parties to the CBD to ensure full integration of urban issues into the post-Aichi Targets. This could be through the creation of a new urban-focused target, in the same spirit as the current Aichi Target 7, which aims to foster agriculture-sector sustainability. Alternatively, urban issues could be considered through urban-related implementation metrics that would measure progress toward a broad goal, such as the current Aichi Target 5, which aims to halve the rate of habitat loss. Asking countries to track and report urban-related natural habitat loss could help ensure progress toward Aichi Target 5.

We urge all Parties to the CBD to view the time between now and 2020 as a period to plan what urban conservation investments are needed to meet the challenge urbanization poses to the goals of the CBD. The 2020 COP of the CBD will be a major moment when new goals are set. The meeting will be held in China, in many ways the world center of urbanization. It is our hope that the next meeting of the CBD in 2020 will be a moment when Parties to the CBD can make meaningful commitments to protect biodiversity and human wellbeing in the urban century.

It is our hope that the next meeting of the CBD in 2020 will be a moment for making meaningful commitments to protect biodiversity and human wellbeing in the urban century.

Photo © DG Wildlife

Methods

Urban growth analysis

Two primary datasets were used to define the extent of urban land. Historical urban land was defined by the CCI Land Cover dataset [145] which provides an annual estimate of global land cover for the period 1992 – 2015 at 300m resolution. Future urban land projections were defined by urban land forecasts developed by Seto *et al*. [9]. The Seto *et al*. [9] forecasts identify the probability of land becoming urban by 2030 with 5 km resolution.

The Seto *et al*. [9] urban forecasts were downscaled to the same spatial resolution as the CCI Land Cover dataset (300 m), and small pixels along the coastline that were not assigned an urbanization probability in the Seto *et al*. [9] forecasts due to its coarser resolution were assigned the urbanization probability from neighboring cells. Regional and national boundaries used in the analysis are defined in the Natural Earth 1:10m cultural vector layer (Natural Earth 2018). For any calculation that required the accurate calculation of area, we used a Mollweide equal area projection.

Urban land over time

We analyzed the amount of global urban land over time. The total urban land area was extracted from the CCI Land Cover dataset by region for each year over the period 1992 – 2015. Urban land in 2030 is taken as the combined extent of the land in the Seto *et al*. [9] forecasts with 75% or greater probability of becoming urban, and the CCI Land Cover urban extent in 2015. This harmonized land cover assumes that any land identified as urban in 2015 will remain urban in 2030.

New urban land by country

New urban land between 2000 and 2030 was calculated as the difference in total urban area per country in 2000 and the total projected urban land per country in 2030. The extent of urban land in 2000 was defined as the combined extent of the CCI Land Cover urban extent in 2000, and the baseline extent of urban land for 2000 in the Seto *et al*. [9] urban land forecasts. The extent of urban land in 2030 is defined as the combined extent of the Seto *et al*. [9] baseline urban extent in 2000, the forecasted urban land with a 75% or greater probability of becoming urban by 2030, and the land identified as urban in the 2015 CCI Land Cover data. As per the analysis of regional urban land totals, this approach assumes that urban land in 2015 will remain urban by 2030.

Habitat loss analysis

Habitat loss calculation

We began by creating a raster of what areas were protected currently, assuming that future urban growth will not directly convert habitat within protected areas. We obtained the most recent World Database on Protected Area file (July 2018) [146]. The database contains both polygon features (for PAs with known boundaries) and point features (for PAs with unknown boundaries). For both types of features, we excluded exclusively marine preserves. For polygon features, we excluded PAs that have no IUCN category protection category and were not nationally designated. For those that are nationally designated but lack an IUCN protection category, we assume they are category VI. We also excluded polygon features that were EU Sites of Community Importance, because this regional designation does not necessarily translate to land protection against urbanization. For point features, we excluded those with no listed IUCN protection category, mostly UNESCO-MAB sites and Ramsar sites that do not have an accompanying nationally designated PA. Point features were buffered to be their reported size, in a Mollweide projection.

The next step was to create a raster of natural habitat that was not protected, and thus could be lost during urbanization. This involved integrating the protected area information from the WDPA with information from the CCI Land Cover grid [145]. For this analysis, we were principally interested in the land cover from 1992 (the first year available), 2000 (the base year of the Seto *et al*. [9] forecasts), and 2015 (the most current year available). CCI Land Cover was reclassified to a simple five-level classification scheme: Agriculture (codes 10-40 in the CCI data); Urban Settlement (code 190); Water (code 210); Permanent Ice/snow (code 220); and Natural habitat (all remaining codes).

Next, we wanted, for just unprotected natural habitat, to create a map of probability of habitat loss. The harmonized urban growth forecasts (see Urban Growth Analysis methods section) was used to estimate the probability of additional habitat loss (2000-2030). These probabilities are fundamentally based upon the Seto *et al*. [9] forecasts, which have a probabilistic estimate of the likelihood of urbanization occurring. Results for habitat loss were summarized by biome, using the WWF definition of biomes [147]. We also summarized habitat loss by country, using the high-resolution country shapefile available from the Natural Earth website (ne_10m_admin_0_countries). Finally, we mapped habitat loss with metrics of biodiversity importance, such as the Alliance for Zero Extinction [148], the Biodiversity Hotspots (25 April, 2016 edition; [149]), the Global 200 Ecoregions [81], and information on vertebrate endemism [56].

Key biodiversity areas

We focused special attention in our analysis on Key Biodiversity Areas (KBAs), where the is a global standard set by IUCN by which areas of biodiversity importance can be designated as a KBA. We obtained the most current KBA layer available (January 2018) [84, 150]. This was then intersected with our habitat loss probability layer, with pixels greater than 75% likely to be urbanized assumed "urban" for this calculation. In R, we statistically analyzed the fraction of KBAs that have different % losses of area due to urban (2000-2030). We mapped KBAs that are forecasted to lose more than 5% of their area (2000-2030) for graphing. For reporting, we calculated total area of KBAs using a Mollweide protection.

Imperilment analysis

In order to understand how urban growth and natural habitat loss affected the probability of imperilment, we obtained range maps for taxa from the IUCN [151]. We focused our analysis primarily on the terrestrial mammals and amphibians (Anura, Caudata, and Gymnophiona). In ArcGIS, we calculated the fraction of each species' range that was urbanized in 2000.

Protected area analysis

We began our analysis using the same selected features from the WDPA (see discussion in Habitat Loss Analysis methods section). We analyzed separately strictly protected PAs (IUCN protected area category I-IV) and loosely protected PAs (IUCN protected area category V-VI). We wanted to compare this to distance to urban area and population density. Our population density information came from the Gridded Population of the World (Version 4, Revision 10) [152]. This comes at a base resolution of 1 km, and except the calculations involving land cover (which we done at the resolution of the CCI Land Cover), all calculations described in this section were done at 1 km resolution using a Mollweide equal-area projection.

For every point on the earth's surface, we calculated the distance to the nearest urban area in 1992, 2000 and 2030. This distance to urban areas is important since it relates to the impact of cities on ecological structure and function in protected areas (see protected area analysis in main text for more detail). Specifically, we used the Euclidean Distance command in ArcGIS to calculate distance to urban areas as defined in the harmonized land cover (see Urban Growth Analysis methods section). We then calculated, for each time period, the fraction of PA area that is in different distance classes from urban areas (0-10 km, 10-20 km, 20-30 km, etc.).

We constructed 50 km buffer around the world's protected areas. Specifically, we used the WDPA features, processing strictly and loosely protected PAs separately, to define 50 km buffer zones around each PA. The 50 km threshold was used as it was the distance after which most urban impacts on protected areas ended (see protected area analysis in main text for more detail). We then clipped out the actual PA from this buffer area, since we want the buffer zone to be only what is in the buffer zone around PAs. We then used the Zonal Statistics command in ArcGIS to calculate the population density in each buffer zone.

Finally, we ran an additional GIS analysis to determine how much some iconic, big strictly protected areas are impacted by urbanization, now and in the future. For this exercise, we selected out strictly protected areas that were greater in area than 500 km^2. This threshold was chosen to pick large, named PAs. In the 50 km buffer around these PAs, we calculated the percent urban in 2000 and 2030 (projected). We then created two tables showing most "at-risk" PAs: biggest change in urban proportion of land (2000-2030) within 50 km of PA, and biggest amount of urban area (2000).

Carbon analysis

The analysis of carbon storage as a climate mitigation service is based on the Ruesch & Gibbs [97] carbon data for above- and below-ground biomass. To calculate the global amount of carbon stored in natural vegetation that could be lost to urban growth, we transformed the Ruesch & Gibbs [97] grid to match the resolution and projection of our habitat loss probability layer, and summed the total amount of carbon stored in biomass for the pixels that had a greater than or equal to 75% likelihood of being urbanized by 2030. For the country-level analyses, the same approach was followed, but the carbon figures were summed up for each country using zonal statistics. In addition, average carbon lost per hectare was calculated at the country level by dividing the total amount of carbon by the area lost to urban growth.

For the comparison between the Ruesch & Gibbs [97] data and the Baccini *et al*. [102] data, we obtained the Baccini *et al*. [102] dataset on pantropical aboveground woody biomass and resampled it to match the resolution and projection of our habitat loss probability layer. The data is originally expressed in biomass per hectare, which we converted to carbon per hectare using the 0.47 conversion factor from the IPCC. Average values of carbon stored per hectare were calculated for both the Ruesch & Gibbs [97] data and the Baccini *et al*. [102] data, using only pixels where i) the Baccini *et al*. [102] values were non-zero (i.e., they were forested pixels analyzed by Baccinni *et al*.), ii) both data sets overlapped in extent, and iii) natural habitat is projected to be lost to urban growth.

Coastal analysis

The analyses for the case study of coastal resilience were mainly based on the InVEST Coastal Vulnerability model developed by The Natural Capital Project (www.naturalcapitalproject.org) [116, 136]. This model produces a qualitative, relative index of coastal exposure to erosion and inundation, taking into account the following bio-geophysical variables: sea level change, wind exposure, wave exposure, relief, geomorphology (shelf only, since there are no global datasets for shoreline type), surge potential depth contour, and natural habitats. The climate change adaptation service provided by natural coastal habitats (such as coral reefs, mangroves, seagrass, and salt marshes) is calculated as the difference in exposure with and without that habitat. The model was run globally, and provided service values for points spaced 1 km apart along the major coastlines of the world. These service values were classified into 5 quantiles, ranging from very low to very high, and converted into a raster. All rasters used or created in this section were projected and resampled to match our habitat probability layer.

To display population density along the coast, we downloaded the Gridded Population of the World, Version 4 (GPWv4) [152] Population Density Adjusted to Match UN WPP Country Totals, Revision 10 [153], and assigned population density values from the grid to the points from the coastal vulnerability model.

Euclidean allocation was used to extend the classified service raster out in to the low-elevation coastal zone (LECZ). A LECZ layer representing areas along the coast with elevations of 10m and lower was provided by the Center for International Earth Science Information Network [154], and overlaid with the extended classified service layer. All following calculations were limited to those areas within the LECZ where service values were medium, high, or very high.

The amount of urban area in the LECZ was calculated for 2000 and 2030, based on the Seto *et al*. [9] 2000 baseline land cover data and the 2030 urban forecasts. For the population estimates within the LECZ, we used the 1 km resolution GPWv4 data for 2000 and for 2020 (the farthest available population forecast). For areas within the LECZ that had medium to very high service values, we calculated the average population density and converted that to number of people based on the number of pixels in those areas.

Tables

Table 1. Project habitat loss for the world's biome types, 2000-2030. Data is shown for area lost 2000-2030 (square kilometers), as well as the proportion of the biome's total area that will be converted. Note that as the total area of biomes varies widely, these two quantities differ. The Mangrove biome is projected to lose around 10,000 km^2 of habitat, which amounts to 3% of the total biome area. A similar amount of habitat in Temperate Coniferous Forests will be lost to urbanization 2000-2030, but as this is a much larger biome, this urbanization amount to only 0.15% of the total biome area.

Biome Name	Urban-caused habitat loss, 2000-2030 (km2)	Urban-caused habitat loss, 2000-2030 (% of biome area)
Boreal Forests/Taiga	1,430	0.01%
Deserts	38,206	0.14%
Flooded Grasslands	3,289	0.30%
Mangroves	10,091	2.90%
Mediteranean Habitat	20,515	0.64%
Montane Grasslands	8,036	0.15%
Temperate Broadleaf Forests	78,430	0.61%
Temperate Coniferous Forests	11,135	0.27%
Temperate Grasslands	15,156	0.15%
Tropical Coniferous Forests	3,356	0.47%
Tropical Dry Forests	7,573	0.25%
Tropical Grasslands	26,636	0.13%
Tropical Moist Forests	63,439	0.32%
Tundra	72	0.00%

Table 2. Amphibians and mammals listed as threatened on the IUCN Red list that have more than 20% of their range converted to urban area. The IUCN codes species as Critically Endangered (CR), Endangered (EN), or Vulnerable (VU). Species are sorted by their Latin binomial name.

Amphibians:

Latin name	Common name	Country	IUCN category
Allobates juanii	None	Colombia	CR
Ambystoma flavipiperatum	Yellow-peppered Salamander	Mexico	EN
Dryophytes suweonensis	Suweon tree frog	South Korea	EN
Eleutherodactylus grandis	Great Peeping Frog	Mexico	CR
Eleutherodactylus lentus	Yellow Mottled Coqui	U.S. Virgin Islands	EN
Eurycea sosorum	Barton Springs Salamander	United States	VU
Eurycea tonkawae	Jollyville Plateau Salamander	United States	EN
Eurycea waterlooensis	Austin Blind Salamander	United States	VU
Heleophryne rosei	Table Mountain Ghost Frog	South Africa	CR
Hyalinobatrachium guairarepanense	None	Venezuela	EN
Hyla heinzsteinitzi	None	Israel; Palestinian Territory	CR
Hynobius tokyoensis	Tokyo Salamander	Japan	VU
Hynobius yangi	Kori Salamander	South Korea	EN
Hypsiboas cymbalum	Campo Grande tree frog	Brazil	CR

Mammals:

Latin name	Common name	Country	IUCN category
Crocidura wimmeri	Wimmer's shrew	Côte d'Ivoire	CR
Dipodomys stephensi	Stephen's kangaroo rat	United States	EN
Eumops floridanus	Florida bonneted bat	United States	VU

Table 3. Selected protected areas currently with a lot of urban area within 50 km. Protected areas near urban areas can be impacted ecologically unless properly managed, although this proximity also benefits urban dwellers by allowing greater interaction with nature. This list was created by measuring urban area in the year 2000 in the 50 km buffer around strictly (IUCN category I-IV) protected areas greater than 500 km^2 in area. This list is sorted by country name and then by the name of the protected area.

Name	
Cordon del Plata Provincial Park	Argentina
Blue Mountains National Park	Australia
Neusiedler See und Umgebung landscape protection area	Austria
Parque Estadual Da Serra Do Mar Park	Brazil
Parque Nacional Da Serra Do Itajai Park	Brazil
Golden ears park A - Park	Canada
Calanques National Park - Core Area	France
Kiskunsagi National Park	Hungary
Gunung Halimun - Salak National Park	Indonesia
Parco dell' Etna Regional/Provincial Nature Park	Italy
Parco nazionale del Gran Paradiso National Park	Italy
Parco nazionale dell'Alta Murgia National Park	Italy
Biwako Prefectural Wildlife Protection Area	Japan
Hallyeohaesang National Park	Korea, Republic of
Veluwe Nature Conservation Act	Netherlands
Ingushsky Zakaznik (Federal)	Russian Federation
Ci-lan Major Wildlife Habitat	Taiwan
Shei-pa National Park	Taiwan
Alpine Lakes Wilderness	United States of America
Merritt Island National Wildlife Refuge	United States of America
Mount Rainier National Park	United States of America
Rocky Mountain National Park	United States of America
Sespe Wilderness	United States of America

Table 4. Selected protected areas with substantial urban growth in their surroundings. This list was created by measuring urban growth (2000-2030) in the 50 km buffer around large strictly (IUCN category I-IV) protected areas greater than 500 km^2 in area. All these protected areas were forecast to have more than a 5% increase in the nearby urban area. This list is sorted by country name and then by the name of the protected area.

Name	Country
Parc national du Ruvubu National Park	Burundi
Parque Estadual Da Serra Do Mar Park	Brazil
Parque Nacional Da Serra Do Itajai Park	Brazil
Golden ears park A - Park	Canada
Mont Cameroun National Park	Cameroon
Virunga National Park	Congo (DRC)
Chingaza Natural National Park	Colombia
Farallones de Cali Natural National Park	Colombia
Las Hermosas Natural National Park	Colombia
Los Nevados Natural National Park	Colombia
Cuenca del Lago Atitlan Multiple Use Area	Guatemala
Bromo Tengger Semeru National Park	Indonesia
Gunung Halimun - Salak National Park	Indonesia
Kolleru Sanctuary	India
Sundarban National Park	India
Kolahghazi Wildlife Refuge	Iran
Biwako Prefectural Wildlife Protection Area	Japan
Aberdare National Park	Kenya
Meru National Park	Kenya
Mt. Kenya National Park	Kenya
Maduru Oya National Park	Sri Lanka
Ifrane National Park National Park	Morocco
Majete Wildlife Reserve Wildlife Reserve	Malawi
Falgore (Kogin Kano) Game Reserve	Nigeria
Okomu Forest Reserve	Nigeria
Veluwe Nature Conservation Act	Netherlands
Parsa Wildlife Reserve	Nepal
Kirthar National Park	Pakistan
Nyungwe National Park	Rwanda
Ci-lan Major Wildlife Habitat	Taiwan
Shei-pa National Park	Taiwan
Kilimanjaro National Park National Park	Tanzania
Mount Elgon National Park	Uganda
Queen Elizabeth National Park	Uganda
Sespe Wilderness	United States of America
Ugam-Chatkal National Park	Uzbekistan
Cerro Saroche National Park	Venezuela

Works Cited

1. MEA, *Millennium Ecosystem Assessment Synthesis Report*. 2005, Washington, D.C.: Island Press.
2. UNPD, *World Urbanization Prospects: The 2018 Revision*. 2018, New York: United Nations Population Division.
3. Glaeser, E., *Triumph of the City: How our Greatest Invention Makes Us Richer, Smarter, Greener, Healthier, and Happier*. 2012, New York: Penguin Books.
4. Elmqvist, T., et al., *Urbanization, biodiversity, and ecosystem services: Challenges and opportunities, a global assessment*. 2013, New York: Springer.
5. Seto, K.C., et al., *Urban land teleconnections and sustainability*. Proceedings of the National Academy of Sciences of the United States of America, 2012. **109**(20): p. 7687-7692.
6. McDonald, R.I., *Conservation for cities: How to plan & build natural infrastructure*. 2015, Washington, DC: Island Press.
7. TEEB, *TEEB Manual for Cities: Ecosystem Services in Urban Management*. 2011, www.teebweb.org: The Economics of Ecosystems and Biodiversity.
8. Schneider, A., M.A. Friedl, and D. Potere, *A new map of global urban extent from MODIS satellite data*. Environment Res. Lett., 2009. **4**: p. 0044003.
9. Seto, K., B. Guneralp, and L. Hutyra, *Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools*. Proceedings of the National Academy of Science, 2012. **109**(40): p. 16083-16088.
10. Glaeser, E., *Cities, productivity, and quality of life*. Science, 2011. **333**(6042): p. 592-594.
11. Liu, J., et al., *Effects of household dynamics on resource consumption and biodiversity*. Nature, 2003. **421**: p. 530-533.
12. Jedwab, R., L. Christiaensen, and M. Gindelsky, *Demography, urbanization and development: Rural push, urban pull and ... urban push?* . Journal of Urban Economics, 2017. **98**: p. 1339-1351.
13. Martine, G., J.E. Alves, and S. Cavenaghi, *Urbanization and fertility decline: cashing in on structural change*. 2013: IIED.
14. Montgomery, M., et al., *Cities transformed: demographic change and its implications in the developing world*. 2003, Washington, DC: National Academies Press.
15. Cronon, W., *Nature's metropolis: Chicago and the Great West*. 2009: WW Norton & Company.
16. Jackson, K., *Crabgrass Frontier*. 1985, New York: Oxford University Press.
17. Leamer, E.E. and M. Storper, *The economic geography of the internet age, in Location of International Business Activities*. 2014, Springer. p. 63-93.
18. Banister, D., et al., *Transportation and the environment*. Annual Review of Environment and Resources, 2011. **36**: p. 247-270.
19. Haase, D., N. Kabisch, and A. Haase, *Endless urban growth? On the mismatch of population, household and urban land area growth and its effects on the urban debate*. PLoS One, 2013. **8**(6): p. e66531.
20. Wang, Y.P., Y. Wang, and J. Wu, *Urbanization and informal development in China: urban villages in Shenzhen*. International Journal of Urban and Regional Research, 2009. **33**(4): p. 957-973.
21. Loftus-Farren, Z., *Tent cities: An interim solution to homelessness and affordable housing shortages in the United States. California Law Review*, 2011: p. 1037-1081.
22. de Oliveira, J.P., et al., *Cities, biodiversity and governance: perspectives and governance challenges for the convention on biological diversity at the city level*. Biological Conservation, 2011. **144**(5): p. 1302-1313.
23. Chang, G.H. and J.C. Brada, *The paradox of China's growing under-urbanization*. Economic Systems, 2006. **30**(1): p. 24-40.
24. Deng, X. and X. Bai, *Sustainable urbanization in western China*. Environment: Science and Policy for Sustainable Development, 2014. **56**(3): p. 12-24.
25. Teaford, J.C., *The American suburb: the basics*. 2008: Routledge.

26. Pesaresi, M., et al., *Operating procedure for the production of the Global Human Settlement Layer from Landsat data of the epochs 1975, 1990, 2000, and 2014*. Publications Office of the European Union, 2016.

27. Seto, K.C., et al., *A meta-analysis of global urban land expansion*. PLoS ONE, 2011. **6**(8): p. e23777.

28. Batty, M., *Fifty years of urban modeling: Macro-statics to micro-dynamics*, in *The dynamics of complex urban systems*. 2008, Springer. p. 1-20.

29. Güneralp, B. and K. Seto, *Futures of global urban expansion: uncertainties and implications for biodiversity conservation*. Environmental Research Letters, 2013. **8**(1): p. 014025.

30. Pimm, S.L., et al., *The biodiversity of species and their rates of extinction, distribution, and protection*. Science, 2014. **344**(6187): p. 1246752.

31. He, F. and S.P. Hubbell, *Species–area relationships always overestimate extinction rates from habitat loss*. Nature, 2011. **473**(7347): p. 368.

32. Dirzo, R. and P.H. Raven, *Global state of biodiversity and loss*. Annual Review of Environment and Resources, 2003. **28**(1): p. 137-167.

33. Myers, R.A. and B. Worm, *Rapid worldwide depletion of predatory fish communities*. Nature, 2003. **423**(6937): p. 280.

34. Jackson, J.B. and K.G. Johnson, *Measuring past biodiversity*. Science, 2001. **293**(5539): p. 2401-2404.

35. Pereira, H.M., et al., *Scenarios for global biodiversity in the 21st century*. Science, 2010: p. 1196624.

36. Ceballos, G., et al., *Accelerated modern human–induced species losses: Entering the sixth mass extinction*. Science advances, 2015. **1**(5): p. e1400253.

37. Pautasso, M., *Scale dependence of the correlation between human population presence and vertebrate and plant species richness*. Ecology Letters, 2007. **10**(1): p. 16-24.

38. Aronson, M.F., et al., *A global analysis of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers*. Proc. R. Soc. B, 2014. **281**(1780): p. 20133330.

39. Murphy, G.E. and T.N. Romanuk, *A meta-analysis of declines in local species richness from human disturbances*. Ecology and evolution, 2014. **4**(1): p. 91-103.

40. Newbold, T., et al., *Global effects of land use on local terrestrial biodiversity*. Nature, 2015. **520**(7545): p. 45.

41. Vellend, M., et al., *Global meta-analysis reveals no net change in local-scale plant biodiversity over time*. Proceedings of the National Academy of Sciences, 2013: p. 201312779.

42. Dornelas, M., et al., *Assemblage time series reveal biodiversity change but not systematic loss*. Science, 2014. **344**(6181): p. 296-299.

43. Supp, S.R. and S.M. Ernest, *Species-level and community-level responses to disturbance: a cross-community analysis*. Ecology, 2014. **95**(7): p. 1717-1723.

44. Elahi, R., et al., *Recent trends in local-scale marine biodiversity reflect community structure and human impacts*. Current Biology, 2015. **25**(14): p. 1938-1943.

45. Gonzalez, A., et al., *Estimating local biodiversity change: a critique of papers claiming no net loss of local diversity*. Ecology, 2016. **97**(8): p. 1949-1960.

46. Sax, D.F. and S.D. Gaines, *Species diversity: from global decreases to local increases.* Trends in Ecology & Evolution, 2003. **18**(11): p. 561-566.

47. Stohlgren, T.J., et al., *Exotic plant species invade hot spots of native plant diversity*. Ecol. Modelling, 1999. **69**(1): p. 23-40.

48. CBD, *Global biodiversity outlook 3*. 2010, Secretariat of the Convention on Biological Diversity: Montréal, Canada.

49. Ziter, C., *The biodiversity–ecosystem service relationship in urban areas: a quantitative review*. Oikos, 2016. **125**(6): p. 761-768.

50. Schwarz, N., et al., *Understanding biodiversity-ecosystem service relationships in urban areas: A comprehensive literature review*. Ecosystem services, 2017. **27**: p. 161-171.

51. Hall, D.M., et al., *The city as a refuge for insect pollinators*. Conservation Biology, 2017. **31**(1): p. 24-29.

52. Nilon, C.H., et al., *Planning for the future of urban biodiversity: a global review of city-scale initiatives*. BioScience, 2017. **67**(4): p. 332-342.

53. Beninde, J., M. Veith, and A. Hochkirch, *Biodiversity in cities needs space: a meta-analysis of factors determining intra-urban biodiversity variation*. Ecology letters, 2015. **18**(6): p. 581-592.

54. Goddard, M.A., A.J. Dougill, and T.G. Benton, *Scaling up from gardens: biodiversity conservation in urban environments*. Trends in ecology & evolution, 2010. **25**(2): p. 90-98.

55. Lepczyk, C.A., et al., *Biodiversity in the city: fundamental questions for understanding the ecology of urban green spaces for biodiversity conservation*. BioScience, 2017. **67**(9): p. 799-807.

56. McDonald, R.I., et al., *Conservation priorities to protect vertebrate endemics from global urban expansion*. Biological Conservation, 2018. **224**: p. 290-299.

57. Fahrig, L., *Effects of Habitat Fragmentation on Biodiversity*. Annual Review of Ecology, Evolution, and Systematics, 2003. **34**(1): p. 487-515.

58. Haddad, N.M., et al., *Habitat fragmentation and its lasting impact on Earth's ecosystems*. Science Advances, 2015. **1**(2): p. e1500052.

59. Franklin, A.B., B.R. Noon, and T.L. George, *What is habitat fragmentation?* Studies in avian biology, 2002. **25**: p. 20-29.

60. Riitters, K., et al., *Global-scale patterns of forest fragmentation*. Conservation Ecology, 2000. **4**(2): p. 3. [online].

61. Etter, A., et al., *Characterizing a tropical deforestation wave: a dynamic spatial analysis of a deforestation hotspot in the Colombian Amazon*. Global Change Biology, 2006. **12**(8): p. 1409-1420.

62. Gonzalez, A., N. Mouquet, and M. Loreau, *Biodiversity as spatial insurance: the effects of habitat fragmentation and dispersal on ecosystem functioning*. Biodiversity, ecosystem functioning and ecosystem services, 2009: p. 134-146.

63. Pereira, H.M., L.M. Navarro, and I.S. Martins, *Global Biodiversity Change: The Bad, the Good, and the Unknown*. Annual Review of Environment and Resources, 2012. **37**(1): p. 25-50.

64. McKinney, M.L., *Urbanization as a major cause of biotic homogenization*. Biological Conservation, 2006. **127**(3): p. 247-260.

65. Beninde, J., M. Veith, and A. Hochkirch, *Biodiversity in cities needs space: a meta-analysis of factors determining intra-urban biodiversity variation*. Ecology Letters, 2015. **18**(6): p. 581-592.

66. Fahrig, L. and G. Merriam, *Conservation of Fragmented Populations*. Conservation Biology, 1994. **8**(1): p. 50-59.

67. Pereira, H.M., G.C. Daily, and J. Roughgarden, *A Framework for Assessing the Relative Vulnerability of Species to Land-Use Change*. Ecological Applications, 2004. **14**(3): p. 730-742.

68. Gonzalez, A., B. Rayfield, and Z. Lindo, *The disentangled bank: How loss of habitat fragments and disassembles ecological networks*. American Journal of Botany, 2011. **98**(3): p. 503-516.

69. Liu, Z., C. He, and J. Wu, *The Relationship between Habitat Loss and Fragmentation during Urbanization: An Empirical Evaluation from 16 World Cities*. PLoS ONE, 2016. **11**(4).

70. Angel, S., J. Parent, and D.L. Civco, *The fragmentation of urban landscapes: global evidence of a key attribute of the spatial structure of cities, 1990–2000*. Environment and Urbanization, 2012. **24**(1): p. 249-283.

71. He, C., et al., *Urban expansion dynamics and natural habitat loss in China: a multiscale landscape perspective*. Global Change Biology, 2014. **20**(9): p. 2886-2902.

72. Li, T., et al., *Fragmentation of China's landscape by roads and urban areas*. Landscape Ecology, 2010. **25**(6): p. 839-853.

73. Gao, B., et al., *How does sprawl differ across cities in China? A multi-scale investigation using nighttime light and census data*. Landscape and Urban Planning, 2016. **148**: p. 89-98.

74. Baxter-Gilbert, J.H., et al., *Road mortality potentially responsible for billions of pollinating insect deaths annually*. Journal of Insect Conservation, 2015. **19**(5): p. 1029-1035.

75. Gibb, H. and D.F. Hochuli, *Habitat fragmentation in an urban environment: large and small fragments support different arthropod assemblages*. Biological Conservation, 2002. **106**: p. 91-100.

76. Beaudry, F., P.G. Demaynadier, and M.L. Hunter, *Identifying Hot Moments in Road-Mortality Risk for Freshwater Turtles*. Journal of Wildlife Management, 2009. **74**(1): p. 152-159.

77. Borda-de-Água, L., C. Grilo, and H.M. Pereira, *Modeling the impact of road mortality on barn owl (Tyto alba) populations using age-structured models*. Ecological Modeling, 2014. **276**: p. 29-37.

78. Ascensão, F., et al., *Spatial patterns of road mortality of medium–large mammals in Mato Grosso do Sul, Brazil*. Wildlife Research, 2017. **44**(2): p. 135-146.

79. Baillie, J.E.M., et al., *Evolution Lost Status & Trends of the World's Vertebrates*. 2010, United Kingdom. https://portals.iucn.org/library/sites/library/files/documents/2010-057.pdf: Zoological Society of London.

80. Olson, D.M. and E. Dinerstein, The global 200: *A representation approach to conserving the Earth's most biologically valuable ecoregions*. Conservation Biology, 1998. **12**(3): p. 502-515.

81. Olson, D.M. and E. Dinerstein, *The Global 200: Priority ecoregions for global conservation*. Annals of the Missouri Botanical Garden, 2002. **89**(2): p. 199-224.

82. Brooks, T.M., et al., *Habitat loss and extinction in the hotspots of biodiversity*. Conservation Biology, 2002. **16**(4): p. 909-923.

83. Ricketts, T.H., et al., *Pinpointing and preventing imminent extinctions*. Proceedings of the National Academy of Sciences, 2005. **51**: p. 18497-18501.

84. International, B., *World Database of Key Biodiversity Areas*, I.U.f.t.C.o.N. Developed by the KBA Partnership: BirdLife International, Amphibian Survival Alliance, Conservation International, Critical Ecosystem Partnership Fund, Global Environment Facility, Global Wildlife Conservation, NatureServe, Rainforest Trust, Royal Society for the Protection of Birds, Wildlife Conservation Society and World Wildlife Fund, Editor. 2018: Available at www.keybiodiversityareas.org.

85. Eken, G., et al., *Key biodiversity areas as site conservation targets*. AIBS Bulletin, 2004. **54**(12): p. 1110-1118.

86. Weller, R., C. Hoch, and C. Huang, *Atlas for the End of the World*. 2017: http://atlas-for-the-end-of-the-world.com.

87. Abell, R., et al., *Freshwater ecoregions of the world: A new map of biogeographic units for freshwater biodiversity conservation*. Bioscience, 2008. **58**(5): p. 403-414.

88. McDonald, R.I., et al., *Urban growth, climate change, and freshwater availability*. Proceedings of the National Academy of Sciences, 2011. **108**(15): p. 6312-6317.

89. Abell, R., et al., *Beyond the source: The environmental, economic, and community benefits of source water protection*. 2017, The Nature Conservancy.: Washington, DC.

90. McDonald, R.I. and D. Shemie, *Urban water blueprint: Mapping conservation solutions to the global water challenge*. 2014, The Nature Conservancy. : Washington, DC. Available online at: nature.org/waterblueprint.

91. Beck, M.W., et al., *The global flood protection savings provided by coral reefs*. Nature communications, 2018. **9**(1): p. 2186.

92. UNEP-WCMC and IUCN, *Protected Planet Report*. 2016, UNEP World Conservation Monitoring Centre: Cambridge, UK.

93. McDonald, R.I., et al., *Urban effects, distance, and protected areas in an urbanizing world*. Landscape and Urban Planning, 2009. **93**: p. 63-75.

94. Pachauri, R.K., et al., *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. 2014, Geneva, Switzerland: IPCC.

95. IPCC, *Climate change 2014: Mitigation of climate change*. Vol. 3. 2014: Cambridge University Press.

96. Le Quéré, C., et al., *Global carbon budget 2017*. Earth System Science Data Discussions, 2017: p. 1-79.

97. Ruesch, A. and H. Gibbs, *Global biomass carbon stock map based on IPCC Tier-1 Methodology*. 2008, Oak Ridge National Laboratory's Carbon Dioxide Information Analysis Center: Oak Ridge, TN.

98. EPA. *Greenhouse Gas Equivalencies Calculator*. 2018.

99. Nordhaus, W.D., *Revisiting the social cost of carbon*. Proceedings of the National Academy of Sciences, 2017: p. 201609244.

100. EPA, *Technical update on the social cost of carbon for regulatory impact analysis-under executive order 12866, in Interagency Working Group on Social Cost of Carbon, United States Government*. 2016, US Environmental Protection Agency: Washington, DC.

101. Hamrick, K. and M. Gallant, *Unlocking potential: State of the voluntary carbon markets 2017*. Forest Trends' Ecosystem Marketplace, 2017.

102. Baccini, A., et al., *Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps*. Nature climate change, 2012. **2**(3): p. 182.

103. Tyukavina, A., et al., *Aboveground carbon loss in natural and managed tropical forests from 2000 to 2012*. Environmental Research Letters, 2015. **10**(7): p. 074002.

104. Liu, Y.Y., et al., *Recent reversal in loss of global terrestrial biomass*. Nature Climate Change, 2015. **5**(5): p. 470.

105. UN Habitat, *Cities and climate change: Global report on human settlements 2011*. 2011, London: Earthscan.

106. Moran, D., et al., *Carbon footprints of 13 000 cities*. Environmental Research Letters, 2018. **13**(6): p. 064041.

107. Wackernagel, M., et al., *The ecological footprint of cities and regions: comparing resource availability with resource demand*. Environment and Urbanization, 2006. **18**(1): p. 103-112.

108. Calcott, A. and J. Bull, *Ecological footprint of British city residents: what we can do to reduce ours*. 2007, WWF: Surrey.

109. Barros, V., et al., *Climate change 2014: impacts, adaptation, and vulnerability-Part B: regional aspects-Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. 2014.

110. Hanson, S., et al., *A global ranking of port cities with high exposure to climate extremes*. Climatic change, 2011. **104**(1): p. 89-111.

111. Hallegatte, S., et al., *Future flood losses in major coastal cities*. Nature climate change, 2013. **3**(9): p. 802.

112. Gedan, K.B., et al., *The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm*. Climatic Change, 2011. **106**(1): p. 7-29.

113. Shepard, C.C., C.M. Crain, and M.W. Beck, *The protective role of coastal marshes: a systematic review and meta-analysis*. PloS one, 2011. **6**(11): p. e27374.

114. Ferrario, F., et al., *The effectiveness of coral reefs for coastal hazard risk reduction and adaptation*. Nature communications, 2014. **5**: p. 3794.

115. Narayan, S., et al., *The value of coastal wetlands for flood damage reduction in the northeastern USA*. Scientific reports, 2017. **7**(1): p. 9463.

116. Arkema, K.K., et al., *Coastal habitats shield people and property from sea-level rise and storms*. Nature Climate Change, 2013. **3**(10): p. 913.

117. McGranahan, G., D. Balk, and B. Anderson, *The rising risks of climate change: Urban population distribution and characteristics in low elevation coastal zones*. Environment and Urbanization, 2007. **19**(1): p. 17-37.

118. Cutter, S.L. and C.T. Emrich, *Moral hazard, social catastrophe: The changing face of vulnerability along the hurricane coasts*. The Annals of the American Academy of Political and Social Science, 2006. **604**(1): p. 102-112.

119. Masozera, M., M. Bailey, and C. Kerchner, *Distribution of impacts of natural disasters across income groups: A case study of New Orleans*. Ecological Economics, 2007. **63**(2-3): p. 299-306.

120. Bathi, J.R. and H.S. Das, *Vulnerability of coastal communities from storm surge and flood disasters*. International journal of environmental research and public health, 2016. **13**(2): p. 239.

121. Ruckelshaus, M.H., et al., *Evaluating the benefits of green infrastructure for coastal areas: Location, location, location*. Coastal Management, 2016. **44**(5): p. 504-516.

122. Phelan, P.E., et al., *Urban heat island: mechanisms, implications, and possible remedies*. Annual Review of Environment and Resources, 2015. **40**: p. 285-307.

123. Koomen, E. and V. Diogo, *Assessing potential future urban heat island patterns following climate scenarios, socio-economic developments and spatial planning strategies*. Mitigation and Adaptation Strategies for Global Change, 2017. **22**(2): p. 287-306.

124. Robine, J., et al., *Death toll exceeded 70,000 in Europe during the summer of 2003*. Comptes Rendus Biologies, 2008. **331**(2): p. 171-178.

125. Azhar, G.S., et al., *Heat-related mortality in India: Excess all-cause mortality associated with the 2010 Ahmedabad heat wave*. PLoS One, 2014. **9**(3): p. e91831.

126. Bowler, D.E., et al., *Urban greening to cool towns and cities: A systematic review of the empirical evidence*. Landscape and urban planning, 2010. **97**(3): p. 147-155.

127. Zhang, B., J.-x. Gao, and Y. Yang, *The cooling effect of urban green spaces as a contribution to energy-saving and emission-reduction: A case study in Beijing, China*. Building and environment, 2014. **76**: p. 37-43.

128. Kong, F., et al., *Energy saving potential of fragmented green spaces due to their temperature regulating ecosystem services in the summer*. Applied energy, 2016. **183**: p. 1428-1440.

129. Mishra, V., et al., *Changes in observed climate extremes in global urban areas*. Environmental Research Letters, 2015. **10**(2): p. 024005.

130. Miller, J.D. and M. Hutchins, *The impacts of urbanization and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom*. Journal of Hydrology: Regional Studies, 2017. **12**: p. 345-362.

131. Zimmermann, E., et al., *Urban flood risk reduction by increasing green areas for adaptation to climate change*. Procedia Eng, 2016. **161**: p. 2241-2246.

132. Janhäll, S., *Review on urban vegetation and particle air pollution–Deposition and dispersion*. Atmospheric Environment, 2015. **105**: p. 130-137.

133. Johnson, H.D., *Green plans: Greenprint for sustainability*. Vol. 7. 1997, Lincoln, Nebraska: U of Nebraska Press.

134. Manuel, J., et al., *Key Ingredients, Challenges and Lessons from Biodiversity Mainstreaming in South Africa*. 2016, https://doi.org/10.1787/19970900: OECD Environment Working Papers.

135. Tallis, H., *Natural capital: theory and practice of mapping ecosystem services*. 2011: Oxford University Press.

136. Tallis, H.T., et al., *InVEST 2.5.6 User's Guide*. 2013, Stanford, CA: The Natural Capital Project.

137. Ball, I.R., H.P. Possingham, and M. Watts, *Marxan and relatives: software for spatial conservation prioritisation*. Spatial conservation prioritisation: Quantitative methods and computational tools, 2009: p. 185-195.

138. Rosa, I.M., et al., *Multiscale scenarios for nature futures*. Nature ecology & evolution, 2017. **1**(10): p. 1416.

139. Lundquist, C. and H. Pereira, *Visions for nature and nature's contributions to people for the 21st century*. 2017, New Zealand: NIWA Science and Technology Series.

140. ICLEI, CBD, and Japan Biodiversity Fund, *Guidelines for an integrated approach in the development and implementation of national, subnational and local biodiversity strategies and action plans*. 2017, Montreal, Canada: Secretariat of the Convention on Biological Diversity.

141. Pierce, J.R., *Planning for Urban Biodiversity in a Divided World*. 2014, Cornell University: Ithaca, NY.

142. Huang, C.-W., R.I. McDonald, and K. Seto, *The importance of land governance for biodiversity conservation in an era of global urban expansion*. Landscape and Urban Planning, 2018. **173**: p. 44-50.

143. Trzyna, T., *Urban Protected Areas: Profiles and best practice guidelines*. Best practice protected area guidelines series. 2014, Gland, Switzerland: IUCN. 39.

144. McDonald, R.I., *Ecosystem service demand and supply along the urban-to-rural gradient*. Journal of Conservation Planning, 2009. **5**: p. 1-14.

145. European Space Agency, *Land Cover CCI Product User Guide Version 2.0*. 2017, European Space Agency: Online at www.esa-landcover-cci.org.

146. WDPA Consortium, *World Database on Protected Areas*. 2018, Cambridge, UK: World Conservation Monitoring Centre.

147. Olson, D.M., et al., *Terrestrial ecoregions of the worlds: A new map of life on Earth*. Bioscience, 2001. **51**(11): p. 933-938.

148. Alliance for Zero Extinction, *2010 AZE Update*. 2010, Alliance for Zero Extinction: www.zeroextinction.org.

149. Myers, N., et al., *Biodiversity hotspots for conservation priorities*. Nature, 2000. **403**(6772): p. 853-858.

150. Eken, G., et al., *Key biodiversity areas as site conservation targets*. Bioscience, 2004. **54**(12): p. 1110-1118.

151. NatureServe and IUCN, *The IUCN Red List of Threatened Species*. 2018, International Union for Conservation of Nature: http://www.iucnredlist.org.

152. Doxsey-Whitfield, E., et al., *Taking Advantage of the Improved Availability of Census Data: A First Look at the Gridded Population of the World, Version 4*. Papers in Applied Geography, 2015. 1(3): p. 226-234.

153. CIESIN, *Documentation for the Gridded Population of the World, Version 4 (GPWv4), Revision 10 Data Sets*. 2017, NASA Socioeconomic Data and Applications Center (SEDAC): Palisades, NY.

154. CIESIN, *Low Elevation Coastal Zone (LECZ) Urban-Rural Population and Land Area Estimates, Version 2.* . 2013, NASA Socioeconomic Data and Applications Center (SEDAC): Palisades, NY.

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