Managing for Urban Ecosystem Services:

The Yongding River Ecological Corridor

by

Christina P. Wong

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved November 2014 by the
Graduate Supervisory Committee:

Ann P. Kinzig, Chair
Kai N. Lee
Rachata Muneepeerakul
Zhiyun Ouyang
Enrique Vivoni

ARIZONA STATE UNIVERSITY

December 2014

ABSTRACT

Sustainability requires developing the capacity to manage difficult tradeoffs to advance human livelihoods now and in the future. Decision-makers are recognizing the ecosystem services approach as a useful framework for evaluating tradeoffs associated with environmental change to advance decision-making towards holistic solutions. In this dissertation I conduct an ecosystem services assessment on the Yongding River Ecological Corridor in Beijing, China. I developed a '10-step approach' to evaluate multiple ecosystem services for public policy. I use the 10-step approach to evaluate five ecosystem services for management from the Yongding Corridor. The Beijing government created lakes and wetlands for five services (human benefits): (1) water storage (groundwater recharge), (2) local climate regulation (cooling), (3) water purification (water quality), (4) dust control (air quality), and (5) landscape aesthetics (leisure, recreation, and economic development).

The Yongding Corridor is meeting the final ecosystem service levels for landscape aesthetics, but the new ecosystems are falling short on meeting final ecosystem service levels for water storage, local climate regulation, water purification, and dust control. I used biophysical models (process-based and empirically-based), field data (biophysical and visitor surveys), and government datasets to create ecological production functions (i.e., regression models). I used the ecological production functions to evaluate how marginal changes in the ecosystems could impact final ecosystem service outcomes. I evaluate potential tradeoffs considering stakeholder needs to recommend synergistic actions for addressing priorities while reducing service shortfalls.

To Dad, Mom, Melissa, Auntie Maya, and Mailei “Four Paws”.

Every pursuit is dedicated to you whose endless support gives me the courage to dream with passion and purpose, and whose love keeps me humble because few are granted this joy, selflessness, and wisdom.

To my fellow students who dare to dream, and are committed to making them a reality.

“We must be the change we wish to see in the world.” - Gandhi

ACKNOWLEDGEMENTS

I would like to acknowledge my committee for their comments on my proposal and dissertation: Dr. Ann P. Kinzig, Dr. Kai N. Lee, Dr. Rachata Muneepeerakul, Dr. Zhiyun Ouyang, and Dr. Enrique Vivoni. I thank Ann for her patience to work with me on navigating the complexity of my project. I thank Kai for his support, thoughtfulness, and wisdom. I am grateful for your willingness to learn with me, and for pushing me to learn from my experience. Thank you for sharing your knowledge before and during my dissertation, which were critical to my development. I thank Ouyang for taking a risk on a foreign student, who arrived at his doorstep naïve of the challenges awaiting her, but who saw my potential. I am grateful for your willingness to listen to my ideas, and your investments to make them a reality. Your decisions reinforce my faith in the importance of hard work, teamwork, and dedication.

I owe much of my work to the skills and effort of Jiang Bo. I want to thank Jiang Bo for many hours of endless discussion, so I could work through the conceptual challenges of my dissertation. Also the majority of my fieldwork, labwork, and administrative tasks were managed by Jiang Bo. My ambition at times can be frustrating, but Jiang Bo made sure all the work was completed. I could not have worked in China if it was not for you, and I am grateful for our friendship.

I could never have pursued this dissertation if it were not for the financial support of several United States and Chinese institutions. First I would like to thank the Ford Foundation Predoctoral Fellowship for its commitment to improving education by maximizing the diversity of our scholars. Second I would like to thank the US National

Science Foundation for three funding opportunities. The US National Science Foundation Graduate Research Fellowship (Grant No. NSF DGE-1311230), which is committed to enabling the innovations of young scholars. The US National Science Foundation East Asia and Pacific Summer Institutes (EAPSI) Fellowship (Grant No. NSF EAPSI 000553165) and International Supplemental, which support US graduate students to pursue international collaborations. Third I would like to thank the Philanthropic Educational Organization for granting me the Scholar Award, which celebrates the advancement of women to achieve their highest aspirations. Fourth I would like to thank the State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences for an open-fund grant to support my research in China (Grant No. SKLURE2012-2-3).

During my dissertation I worked across multiple institutions the: State Key Laboratory of Urban and Regional Ecology (SKLURE), University of Washington Land Surface Hydrology Research Group, and Beijing Water and Science Technology Institute (BWSTI). The work contained in this dissertation benefitted from a team of faculty, staff, and students at SKLURE. As a foreigner I relied heavily on the help of the 'big family' in China: Dr. Zheng Hua, Dr. Ren Yufen, Dr. Wang Xiaoke, Dr. Lu Fei, Dr. Xu Weihua, Dr. Zhou Weiqi, Chen Yuanyuan, He Chengwu, Zhang Qianqian, Wang Shiqi, Zhen Jia, Zhang Kai, Zhen Quan, Zhang Liyun, Wang Yaqing, Li Xiaoma, Jiang Jun, Chen Falin (my roommate), Yang Ning, Long Zhenwen, Liu Yayin, Zheng Mengmeng, Chen Xiaoshu, Qian Yuguo, Xiu Chen, and Beijing Forestry University students. I also would like to thank the skillful drivers, and the visitors who participated in my surveys. The modeling benefitted immensely from my time at the University of Washington where I received advice on the Variable Infiltration Capacity (VIC) model from: Dr. Dennis Lettenmaier, Dr. Bart Nijssen, and Dr. Ted Bohn. I must thank Ted for helping me think through the specifics of my project, and teaching me how to use VIC. Lastly, I would like to thank the BWSTI staff for their interest in my research because their expertise helped me understand the realities of managing the Yongding River. In particular, I need to thank Ma Dongchuan for inviting me to share my research with the BWSTI.

I also benefitted from my discussions with faculty and fellow students at Arizona State University. I would like to thank Dr. Joshua Abbott for teaching me about ecological production functions, Dr. Dan Childers for visiting my wetlands in China, Dr. Soe Myint for his advice on remote sensing, and Dr. Dave White for reviewing my social surveys. I would like to thank my fellow graduate students for spending many afternoons and late evenings discussing my work. For being the best audience: Dana Nakase, Kehinde Salau, Marie Fujitani, Nathan Rollins (teaching me Linux), and Wang Qiong. I also need to thank Dorothy Ibes for our weekly lunches where I could talk less about numbers and more about people's experiences of parks. I would like to thank Chuang Wenqing, Ouyang Yun, Du Songling, and Xie Liou for helping me translate many Chinese documents to English.

Lastly I would like to thank a group of individuals whose wisdom benefitted me throughout my dissertation. John and Laura Ellertson who helped me manage the logistical challenges of living in Arizona and China. Thank you for considering me a family member. Mario Neal whose constant support and enthusiasm for my PhD was tremendous during challenging times. The environmental community in the United States and China. Much of my work in China benefitted immensely from my time at the Wilderness Society who offered me a tremendous classroom with invaluable teachers. Thank you to my colleagues who listened to my Roll-calls on China, and whose practical advice, support, and interest have been significant in my journey. In particular I must recognize: Tom A. Barron, Brenda S. Davis, Caroline Getty, Flip Hagood, Jaime A. Pinkham, Heather Kendall-Miller, Marcia Kunstel, and Doug Walker.

TABLE OF CONTENTS

CHAPTER Page

CHAPTER Page

CHAPTER Page

CHAPTER Page

CHAPTER Page

CHAPTER Page

LIST OF TABLES

Table Page

Table Page

Table Page

Table Page

Table Page

LIST OF FIGURES

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

CHAPTER 1

INTRODUCTION

In this dissertation, I examine the application of the ecosystem services approach in advancing sustainability goals, exploring its use in improving decision-making with a focus on urban issues. For the past six and a half years, I dedicated myself to studying sustainability, which took me to the other side of the world. I found myself wandering through Beijing, a foreign land that slowly revealed more similarities than differences. However the differences are the cornerstone of my studies since they tested my assumptions helping me see core concerns and cultural frames. As a student in Beijing I experienced the concepts outlined in my textbooks where governments, nongovernmental organizations, scientists, businesses, and Chinese citizens are busily working to balance needs for environmental improvements, economic growth, and social equity. Through this dissertation I share my current thoughts on the environment, the relationship between knowledge and decision-making, and government actions towards sustainability.

In China the need for holistic thinking is urgent where the environment is an issue of national security, economic development is unprecedented, and basic human needs remain pressing in a sea of rapidly shifting demographic conditions. My hope is to weave a story that expands imaginations on possibilities of implementing holistic frameworks to manage intersecting social and environmental problems with Beijing as the backdrop of my narrative. My objective is to advance our understanding on the ecosystem services approach using the science of ecosystem services to bridge disciplinary and societal divides to advance decision-making on sustainability issues.

In this dissertation I develop a '10-step approach' to evaluate multiple ecosystem services for public policy then I use the framework to assess five services from the Yongding River Ecological Corridor in Beijing, China. Decision-makers need credible and legitimate measurements of ecosystem services to evaluate decisions for tradeoffs to make wise choices. However managers currently lack these measurements because of a data gap linking ecosystem characteristics (i.e., ecosystem structure, processes, and functions) to final ecosystem services (aspects of nature having direct value to society). First I explain the data gap limiting the application of the ecosystem services approach in decision-making then present a10-step approach on overcoming the data gap. Second I use the 10-step approach to design a framework to assess five ecosystem services from the Yongding Corridor. Third I present my methods and results for each ecosystem service. Lastly, I synthesize the results of all five services to assess potential synergies and tradeoffs to advise management on possible synergistic actions.

THE YONGIDNG RIVER ECOLOGICAL CORRIDOR

At the center of my analysis is the Yongding Corridor since it is one of few regional sustainable development projects in China where managers explicitly want multiple ecosystem services to advance social and economic conditions in Beijing. The Yongding River is 747 km long with a watershed area of 47,016 km^2, and is a major tributary of the Hai River Basin. The Yongding River starts in Shanxi Province flows through Inner Mongolia Autonomous Region and Hebei Province and terminates at Bohai Bay. The Yongding River is considered one of China's four priority flood control rivers, and is highly engineered to manage for large floods. The Yongding River is an important surface water source to Beijing since it supplies water to the Guanting Reservoir. Upstream of Beijing there is an estimated 267 reservoirs along the Yongding River. Water diversions and increased upstream water demands led to the drying of lower reaches on the Yongding River. Since 1980 mean annual streamflow on the Yongding River significantly declined, and in the last decade there has been near zero streamflow in Beijing (Jiang et al. 2014). Reduced streamflow and the loss of freshwater ecosystems increased desertification, and experts believe the Yongding River is the primary local contributor to Beijing's dust events. Furthermore the dry channels became dumping grounds for sewage and trash, and sites for sand mines and migrant settlements.

In 2009 the Beijing Municipal Government authorized the construction of the "Yongding River Green Ecological Corridor" with the aim of improving environmental conditions to advance urban livability in southwest Beijing (BWA 2009). Managers plan to add water and vegetation to the Yongding River making the Yongding Corridor 170 km long, covering an area of 1,500 km^2 at an estimated cost of 17 billion yuan ($2.7 billion USD). When complete the Yongding Corridor will extend across five southwest districts (Mentougou, Shijingshan, Fengtai, Daxing, and Fangshan) consisting of three sections: (1) mountainous (secondary forests), (2) urban (mix of factories and dense human settlements), and (3) outerurban (mix of suburban residences and rural villages). The Beijing Water Authority (BWA), the main government agency overseeing the project, expects full completion of the Yongding Corridor in 2014. The BWA completed construction of six lakes and wetlands in the urban section, and opened these parks to the public on September 29, 2011. In Beijing, the Yongding Corridor consists of: (1) 6 lakes, (2) streams, (3) wetlands, (4) greenbelt of trees and grasses, and (5) public parks. In this dissertation, I assess five ecosystem services (human benefits) from the Yongding Corridor selected by the BWA: (1) water storage (groundwater recharge), (2) local climate regulation (cooling), (3) water purification (water quality), (4) dust control (air quality), and (5) landscape aesthetics (leisure, recreation, and economic development) (BWA 2009).

DISSERTATION OBJECTIVES

The scientific objective of my dissertation is to contribute to the science of ecosystem services by unifying concepts, methods, and data from multiple disciplines to analyze ecosystem services. In Chapters 2-3, I present the 10-step approach and the specific conceptual framework for the Yongding Corridor. In Chapters 5-8, I present the empirical studies spanning: ecology, geography (i.e., remote sensing), hydrology, and recreation/leisure studies. From the empirical studies, I explore the utility of using ecosystem service indicators (ecosystem characteristics and final services) and ecological production functions to advance understanding on how to relate service outcomes to management goals, and causal mechanisms to management problems.

The management objective of my dissertation is to create useful information for managers of the Yongding Corridor in Beijing. For the majority of my dissertation I worked at the State Key Laboratory of Urban and Regional Ecology (SKLURE), Research Center for Eco-Environmental Sciences (RCEES), Chinese Academy of

Sciences (CAS) who provides scientific assistance to the BWA on the Yongding Corridor. The SKLURE works with the Beijing Water Science and Technology Institute (BWSTI), the BWA's principle scientific institution, who provides technical guidance to decision-makers on the Yongding Corridor. To understand management needs I studied BWA planning documents, discussed key components of my framework and methodology with SKLURE and BWSTI scientists and policy analysts, and conducted a questionnaire-based survey on BWSTI managers. In Chapters 2-3, I present the strategic components of the 10-step approach to meet management needs. In Chapter 9, I examine the potential of the ecosystem services approach in advancing the management of the Yongding Corridor.

Underpinning the overarching objectives are these specific objectives:

(1) To quantify the land use and land cover (LULC) changes on the Yongding River in Beijing from government efforts to promote regional sustainable development. Assess the importance of analyzing ecosystem services at different spatial scales (Chapter 4).

(2) To quantify water storage and local climate regulation by determining the potential impact of the new ecosystems on evapotranspiration (ET) rates interpreted in terms of water losses and local cooling effects on the Yongding Corridor (Chapter 5).

(3) To quantify water purification by determining the potential impacts of wetland nutrient retention and nutrient loading on lake water quality on the Yongding Corridor (Chapter 6).

(4) To quantify dust control by determining the potential impact of the new ecosystems on sand flux rates from the Yongding Corridor interpreted in terms of PM_{10} levels near the Yongding River (Chapter 7).

(5) To quantify the potential impact of perceived environmental quality on perceived landscape aesthetics on the Yongding Corridor using visitor surveys. Compare visitor priorities to management objectives on the Yongding Corridor by determining public preferences for different ecosystem services (Chapter 8).

DISSERTATION OUTLINE

In this dissertation, I draw from multiple disciplines (ecology, hydrology, economics, policy, etc.), thus I provide a brief summary of each chapter below. I present each chapter in the format of a scientific journal article (abstract, introduction, methods, results, discussion, and conclusion) to make it easier for the reader to move between sections. Due to the volume of material, detailed specifics of my methods are located in appendices: (A) remote sensing analyses, (B) Variable Infiltration Capacity (VIC) model, (C) ecological production functions (i.e., regression models), and (D) visitor survey questionnaire in English and Chinese.

Chapter 2 titled "Linking ecosystem characteristics to final ecosystem services," in this chapter I provide a brief background on ecosystem service concepts, summarize the current methods to measure ecosystem services, and present limitations of current methods in addressing the data gap. I present a 10-step approach to help guide decisions on measuring ecosystem services for public policy.

Chapter 3 titled "The Yongding River Ecological Corridor ecosystem services assessment framework," in this chapter I take the 10-step approach and create a conceptual framework to evaluate five ecosystem services from the Yongding Corridor. I present the main components of my assessment framework: (1) final ecosystem services, (2) final ecosystem service indicators, (3) ecosystem characteristics, (4) biophysical models, and (5) ecological production functions.

Chapter 4 titled "The new era of urbanization: land use and land cover change analysis," in this chapter I present the results of my land use and land cover change (LULC) analysis between pre-Corridor and post-Corridor conditions on the Yongding River in Beijing. First I present the use of eco-cities in China to advance sustainable development. Second I summarize current government and development actions to establish an eco-city on the Yongding River. Lastly, I use the LULC results to discuss the challenges of implementing sustainability at different spatial scales (i.e., urbanization, ecosystem restoration, water scarcity, etc.).

Chapter 5 titled "Water storage and local climate regulation," in this chapter I present the water storage and local climate regulation methods and results. First I calculate the estimated increase in ET from the new ecosystems relative to climate variation between pre- and post-Corridor periods. Second I evaluate the potential impact of fluctuations in surface water area: lake volume ratios at all lakes on water loss rates. Third I evaluate the potential impact of ET on air temperature and relative humidity to assess the local cooling effects of the new ecosystems on the number of sultry events (i.e., heat index).

Chapter 6 titled "Water purification," in this chapter I present the key components of my water purification analysis, which are the water quality, wetland nutrient retention, and nutrient loading results. First I calculate wetland nutrient retention and nutrient loading on the Yongding Corridor using field measurements on total nitrogen (TN) and total phosphorus (TP). Second I model denitrification rates using an empirical equation designed for constructed wetlands. Third I evaluate the potential impact of changes in wetland area on TP, and changes in nutrient loading on TN to meet water quality goals.

Chapter 7 titled "Dust control," in this chapter I present the key components of my dust control analysis, which are air quality and modeled sand flux rates for pre- and post-Corridor periods. First I model sand flux rates using empirical equations on wind erosion from different land covers on the Yongding River. Second I compare PM_{10} levels at varying distances from the Yongding Corridor. Third I evaluate the potential impact of changes in sand flux on PM_{10} from the new ecosystems on the Yongding Corridor.

Chapter 8 titled "Landscape aesthetics and visitor preferences," in this chapter I present the results of a visitor survey conducted to solicit information on perceived landscape aesthetics, perceived environmental quality, and preferences for different ecosystem services. First I evaluate park accessibility using the demographics of survey respondents, and distribution of visitors (i.e., residence). Second I assess the social legitimacy of management goals (i.e., endpoints) by summarizing the top services selected by respondents, and their top concerns about the future of the Yongding River. Third I evaluate the potential impact of changes in perceived environmental quality (air quality, water quality, and climate) on perceived landscape aesthetics.

Chapter 9 titled “Management,” in this chapter I synthesize the results from chapters 5-8 to evaluate the potential synergies and tradeoffs among ecosystem services. I present general conclusions on the use of the ecosystem services approach to improve the management of the Yongding River.

CHAPTER 2

LINKING ECOSYSTEM CHARACTERISTICS TO FINAL ECOSYSTEM SERVICES

ABSTRACT

Decision-makers need credible and legitimate measurements of ecosystem services to evaluate decisions for tradeoffs to make wise choices. Managers lack these measurements because of a data gap linking ecosystem characteristics to final ecosystem services. The dominant method to address the data gap is benefit transfer using ecological data from one location to estimate ecosystem services at other locations with similar land cover. However benefit transfer is only valid once the data gap is adequately resolved. Disciplinary frames separating ecology from economics and policy has resulted in confusion on concepts and methods preventing progress on the data gap. I present a 10-step approach to unify concepts, methods, and data from the disparate disciplines to offer guidance on overcoming the data gap. The approach suggests: (1) estimate ecosystem characteristics using biophysical models, (2) identify final ecosystem services using endpoints, and (3) connect them using ecological production functions to quantify biophysical tradeoffs. The guidance is strategic for public policy because analysts need to be: (1) realistic when setting priorities, (2) attentive to timelines to acquire relevant data, given resources, and (3) responsive to the needs of decision-makers.

INTRODUCTION

Ecosystem services provide a holistic framework for managing the interconnectivity between the natural environment and human welfare. Instead of viewing the environment separately as hazards, resource extraction, biodiversity, and wild landscapes – ecosystem services show how ecosystems support a diversity of human needs and wants. Traditionally environmental management has centered on a single sector or objective, however social and ecological problems are becoming increasingly complex and interrelated, requiring broader accounting of consequences from human actions (Baker et al. 2013). People have historically focused on maximizing market commodities like timber, oil, and agricultural crops without considering unintended losses in equally important, but less visible ecosystem services such as flood control, climate regulation, and water purification (MA 2005, TEEB 2010). Natural resource decisions driven by a few provisioning services (e.g., fuel, fiber, and food) can also undermine ecosystem integrity through regime shifts, which can threaten the production of all ecosystem services (MA 2005, Liu et al. 2013). Past development models are insufficient to meet the growing needs and interests of an increasing human population. Thus many nations are working to create more sustainable development trajectories (WCED 1987, US NRC 1999). Sustainability requires developing our capacity to manage difficult tradeoffs to advance human livelihoods now and in the future. An ecosystem services assessment (Fig. 1) is the process of evaluating social outcomes of ecosystem change to make tradeoffs among ecosystem services and other social goods explicit to determine superior management options (Carpenter et al. 2009).

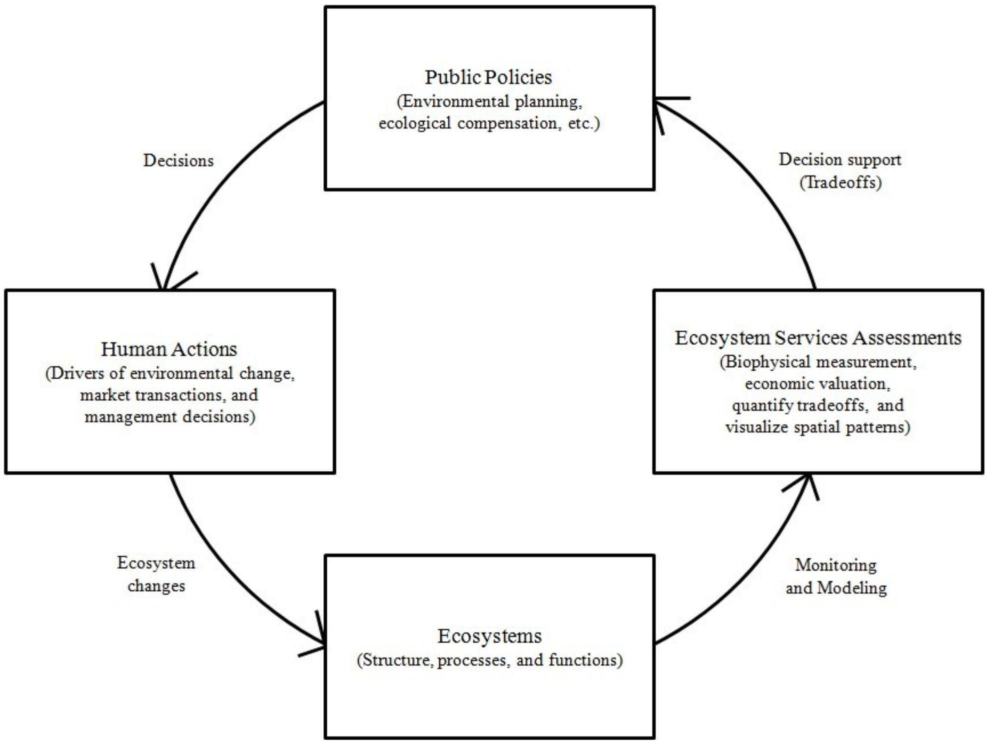


FIG.1. Ecosystem services assessments inform public policy choices by making tradeoffs on ecosystems explicit.

Ecosystem services is an interdisciplinary concept that links the ecological and social sciences by clarifying how ecosystems contribute to human well-being. The Millennium Ecosystem Assessment (MA) (2005) defines ecosystem services as the benefits people obtain from ecosystems, categorized as provisioning, regulating, cultural, and supporting services. The MA increased recognition of the importance of ecosystem change, but the successes remain primarily educational with few examples of how the ecosystem services approach can improve public policies (Burkhard et al. 2010). Several organizations proposed an operational definition to advance implementation, defining ecosystem services as the indirect or direct contributions of ecosystems to human well-being (Fisher et al. 2009, US EPA 2009, De Groot et al. 2010a, Tallis and Polasky 2011).

To operationalize this definition, however, requires consistent terms across the ecological and social sciences; consensus is growing on classifying contributions as intermediate or final ecosystem services (Fig. 2). Intermediate ecosystem services are ecosystem characteristics measured as ecosystem structure, processes, and functions that support final services. Final ecosystem services (now referred to as final services) are components of nature possessing an explicit connection to human well-being that have direct value to society (Boyd and Banzhaf 2007, Fisher et al. 2009, Ringold et al. 2013). Traditionally ecologists use ecosystem structure and processes to determine ecosystem functions while economists and policy makers use endpoints to determine human welfare outcomes from the environment (Boyd 2007). Ecosystem services bridge this divide by relating ecosystem characteristics as intermediate services to endpoints as final services. The MA (2005) categories of provisioning and cultural services are often final services while several regulating services (i.e., ecosystem functions) and most supporting services (i.e., ecosystem processes) are intermediate services (Polasky and Segerson 2009). Wetlands for example provide intermediate services of nutrient retention and erosion control to produce the final service of a clean water supply where consumption of safe (clean) drinking water is the benefit (Keeler et al. 2012).

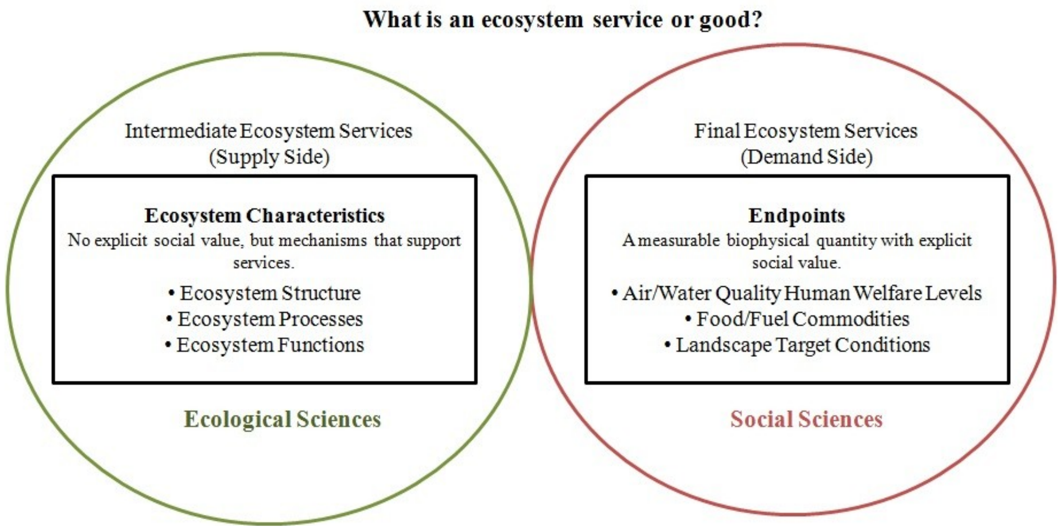


FIG. 2. The measurement of ecosystem services requires linking intermediate services to final services in an interpretable manner for management and the public.

Governments worldwide are increasingly recognizing ecosystem services as an approach to address sustainability challenges, however a data gap is limiting the use of the ecosystem services approach in public policy. The data gap is: a lack of biophysical measurements linking ecosystem characteristics to final services. In recent years the number of publications on ecosystem services grew exponentially (Fisher et al. 2009, Zhang et al. 2010, Seppelt et al. 2011), but progress on the data gap has been slow. Research has centered on management end products like economic values (Liu et al. 2010, Zhang et al. 2010) and service maps (Seppelt et al. 2011, Martínez-Harms and Balvanera 2012), which has advanced categorization, valuation, and mapping techniques (Ouyang et al. 2004, Troy and Wilson 2006, Polasky et al. 2008, Nelson et al. 2009, De Groot et al. 2010b, Tallis and Polasky 2011, Ruckelshaus et al. 2013). However there has been minimal improvement on understanding the relationships between ecological mechanisms and ecosystem services to create the realistic end products that managers need (Kremen 2005, Fisher et al. 2008, Bennett et al. 2009). The dominant method to address the data gap is benefit transfer using species (ecosystem function) values for a particular habitat in one location and land cover proxies to estimate ecosystem services at other locations (i.e., policy sites) with similar land cover (Seppelt et al. 2011, Mártinez-Harms and Balvanera 2012). The problem is current benefit transfer uses secondary data not based on causal relationships between ecosystem characteristics and final services. A valid ecosystem services approach requires adequate resolution of the data gap of which the majority of studies do not address. Second the information on ecosystem services must represent legitimate needs presented in terms of tradeoffs to aid decision-makers in determining courses of action on multiple services.

Ecological production functions address these weaknesses by calculating how marginal changes in ecosystem characteristics can lead to changes in final services, which are useful in determining biophysical tradeoffs among ecosystem services to select management actions (US NRC 2005, Daily et al. 2009, Polasky and Segerson 2009, US EPA 2009, TEEB 2010, Tallis and Polasky 2011). However ecologists currently are not creating ecological production functions using legitimate final services, which limit the application of the ecosystem services approach. Disciplinary frames separating ecology from economics and policy is a significant barrier causing confusion on concepts and methods. I created a 10-step approach to unify the concepts, methods, and data from the disparate disciplines. In this chapter I first present the biophysical measurements managers need to implement the ecosystem services approach. Second I summarize current biophysical methods and their limitations. I attempt to bridge disciplinary thinking to address limitations using: (1) biophysical models to estimate ecosystem characteristics, (2) endpoints to identify final services, and (3) ecological production functions to quantify biophysical tradeoffs. Lastly I present the 10-step approach to guide data and modeling choices when conducting ecosystem services assessments for public policy.

IMPLEMENTING THE ECOSYSTEM SERVICES APPROACH

For decision-makers to use the ecosystem services approach they need credible and legitimate measurements to evaluate potential tradeoffs among ecosystem services (Maes et al. 2012, Portman 2013). First are credible biophysical measurements linking ecosystem characteristics to final services. Second are legitimate final services represented as legal requirements and/or agreed upon targets (Cook and Spray 2012, Baker et al. 2013). Working with managers in China, three biophysical variables for management were identified: (1) ecosystem characteristic metrics, (2) final service indicators, and (3) final services (Fig. 3). Final services are the actual, desired values (i.e., required levels) while final service indicators are the measured, proxy values. Managers felt this distinction was significant because scientists often monitor final service indicators without referring to policy targets (i.e., final services). The difference between measured results (i.e., final service indicators) and required levels (i.e., final services) are service shortfalls. These variables are similar to those suggested by the U.S. Environmental Protection Agency's work on final services (Landers and Nahlik 2013) and the European Environment Agency's Common International Classification of Ecosystem Services (Haines-Young and Potschin 2013). Lastly ecosystem service values need to be presented as marginal changes to help managers determine potential tradeoffs among ecosystem services to select the best possible action(s) of reducing service shortfalls. Marginal changes clarify how (small) changes in a particular ecosystem characteristic from human actions may influence final service indicators (Fisher et al. 2008).

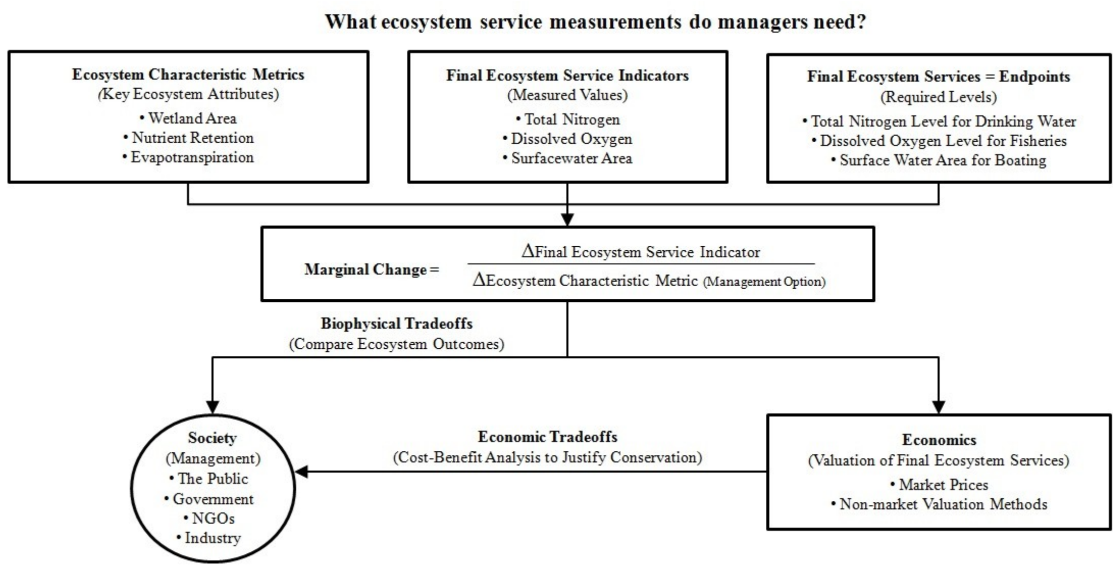


FIG. 3. To implement the ecosystem services approach mangers need: ecosystem characteristic metrics, final ecosystem service indicators, and final ecosystem services. Service shortfalls are the difference between measured values (i.e., final service indicators) and required levels (i.e., final services), which clarify the proximity of the system to policy targets. These variables allow scientists to calculate marginal changes using ecological production functions to help managers assess tradeoffs among goals and actions.

CURRENT CONCEPTUAL FRAMEWORKS

Several conceptual frameworks have been developed to measure ecosystem services, which I define as: (1) ecosystem service providers, (2) ecosystem functions, and (3) ecological production functions. The ecosystem service provider (ESP) or service providing unit (SPU) framework focuses on identifying and quantifying the organisms and traits providing services (Kremen 2005, Luck et al. 2009). The ESP-SPU framework suggests linking the most appropriate ecosystem level to a given service, such as species populations or functional groups to pollination, and habitat types to carbon storage (Luck et al. 2009). The ecosystem function framework measures ecosystem functions as the main ecosystem attributes responsible for providing services, resulting from one or multiple ecosystem processes (Lovett et al. 2005, Fu et al. 2013). When measuring ecosystem services it is helpful to separate the underlying structure and processes (e.g., primary productivity, denitrification, transpiration) from higher-level functions (e.g., net primary productivity, nutrient retention, evapotranspiration) (De Groot et al. 2010b). Human actions impact ecosystem structure, which influence ecosystem functions that support service delivery (Brauman et al. 2007, Bennett et al. 2009, Fu et al. 2013), thus understanding how ecosystem structure and processes support functions is important. However social scientists urge ecologists to move a step further relating ecosystem characteristics to final services.

Economists propose the ecological production function framework, which integrates ecology and economics to clearly estimate ecosystem contributions to service provision (US EPA 2009, Polasky and Segerson 2009, De Groot et al. 2010b). The Economics of Ecosystems and Biodiversity (TEEB) (2010) formalize ecosystem services as a 'production chain' using stepwise links to connect ecosystem characteristics and human well-being. Scientists can view research on ecosystem services as the science of understanding and articulating the production chain (Haines-Young and Potschin 2009). In economics a production function is used to determine contributions of multiple inputs like steel, energy, and labor to the creation of an output like an automobile. An ecological production function similarly links ecosystem characteristics to final services via marginal changes. The ESP-SPU and ecosystem function frameworks provide the means to measure key ecosystem characteristics (i.e., production inputs) while the ecological production function is the bridge between ecosystem characteristics and final services.

BIOPHYSICAL METHODS TO MEASURE ECOSYSTEM SERVICES

Scientists have developed several methods to advance the conceptual frameworks, which consist of four principle approaches: (1) metrics and indicators using primary data, (2) benefit transfer using secondary data and land cover proxies, (3) spatial mapping, and (4) modeling systems which combine all three approaches. The four approaches have limitations in addressing management needs, which are impacting the use of ecosystem service measurements in public policy.

Metrics and indicators using primary data

Scientists are developing indicators on ecosystem characteristics and final services, but there are no general criteria on selecting these variables. Ecologists possess extensive experience on measuring ecosystem characteristics, which scientists have extended to ecosystem services. The first step is selecting the desired ecosystem services then identifying key ecosystem characteristics known to support the selected services. Ecosystem characteristics and ecosystem service indicators have been categorized (Ouyang et al. 2004, De Groot 2006, Tallis et al. 2012, Van Oudenhoven et al. 2012), however studies often do not separate intermediate and final services (Boyd and Banzhaf 2007). Scientists use primary data to quantify metrics and indicators (Liss et al. 2013) and expert opinions to qualitatively connect ecosystem characteristics to ecosystem services (Burkhard et al. 2012, Maskell et al. 2013). To date no common set of ecosystem service indicators exist (Boyd and Banzhaf 2007, US EPA 2009, Reyers et al. 2013), which impacts the interpretation of ecosystem service results (Liss et al. 2013).

Ecological production functions offer the most promise in linking ecosystem characteristics and final services, however few studies employ the production function method because of data limitations and interdisciplinary challenges (MA 2005, US NRC 2005, Polasky and Segerson 2009, US EPA 2009, Liss et al. 2013). The classic ecological production function is the bioeconomic model for fisheries that relate habitat changes to fisheries production (Barbier 2007). They have also been developed to relate pollination to crop yields (Ricketts et al. 2004) and ecosystem conditions to air quality (Cooter et al. 2013). In ecology there is uncertainty on the term ecological production function since existing regression and process-based models are often incorrectly deemed ecological production functions. Ecologists have developed regression models mathematically resembling production functions, connecting ecosystem structure and processes to functions, such as biodiversity to pollen deposition (Kremen and Ostfeld 2005). However these regression models are not production functions because outputs are not final services. An important factor contributing to the slow progress on production functions in ecology is disciplinary differences leading to confusion on what are final services. There currently is a lack of consistent understanding on ecosystem characteristic metrics, final service indicators, and ecological production functions - a consequence is a data gap on ecosystem services.

Benefit transfer using secondary data and land cover proxies

Benefit transfer is a popular method to estimate ecosystem services at broad geographical scales because it is quick and less costly than primary data collection, but the data gap is impacting the credibility of this method. Benefit transfer is the application of measured values at one place and time (i.e., study site) to infer values at another place and time (i.e., policy site) (Plummer 2009). In theory scientists use ecosystem service coefficient values (i.e., marginal changes) and spatial variables to transfer values (Troy and Wilson 2006). However because ecological production functions are unavailable scientists use species (ecosystem function) values from past studies not intended for ecosystem services (Maes et al. 2012), and land cover as ecosystem characteristic proxies to estimate ecosystem services at policy sites with similar land cover to the study sites.

Decision-makers often want assessments on multiple services at regional or national scales, but obtaining primary data at these scales is often unfeasible, thus most ecosystem service studies use secondary data (Mártinez-Harms and Balvanera 2012). The problem is benefit transfer is only a valid method after the required empirical relationships between ecosystem characteristics and final services are established (Richardson et al. 2014).

For benefit transfer to effectively meet the salient needs of decision-makers, the basic requirements must be met, which means first creating a comprehensive database of primary data to derive "general" ecological production functions using meta-analysis. Many scientific and medical fields recognize meta-analysis as an important tool to "scale up" results (Rosenberger and Stanley 2006, Stewart 2010). Meta-analytic function transfer uses an ecological production function derived from the results of multiple primary studies (Brander et al. 2012). Economists found errors are reduced when transfers are conducted using functions that explicitly account for differences between sites (Rosenberger and Stanley 2006). The data gap undermines the utility of benefit transfer as a means of timely assessing ecosystem services at meaningful scales for policy makers.

Spatial mapping

Scientists have made significant progress on mapping techniques to evaluate the spatial distribution of ecosystem services (Chan et al. 2006, Egoh et al. 2008, Nelson et al. 2009, Raudsepp-Hearne et al. 2010, Burkhard et al. 2012, Haines-Young et al. 2012, La Notte et al. 2012, Crossman et al. 2013, Onaindia et al. 2013, Qiu and Turner 2013), however the data gap is impacting the use of spatially explicit results. Commonly spatial correlation is used to identify spatial patterns, service ranges, and hotspots (Egoh et al. 2008, Raudsepp-Hearne et al. 2010, Onaindia et al. 2013, Qiu and Turner 2013). The analyst then uses this information to determine potential synergies and tradeoffs as positive or negative associations among different services (Chan et al. 2006, Naidoo et al. 2008, Raudsepp-Hearne et al. 2010, Onaindia et al. 2013, Qiu and Turner 2013). Scientists assess how these synergies and tradeoffs may change under variable land covers across varying spatial or temporal scales (Burkhard et al. 2012). The tradeoffs are interpreted as relative changes in: the composition of service bundles per landscape configuration (Raudsepp-Hearne et al. 2010, Haines-Young et al. 2012, Qiu and Turner 2013) and services per land cover (Naidoo et al. 2008, Nelson et al. 2009). Spatially explicit results are helpful to assess the importance of heterogeneity on service flows and scale on service production relative to beneficiaries (Tallis and Polasky 2011). Despite advancements in spatial mapping, the data gap is impacting the application of spatially explicit results because service maps based only on land cover are vulnerable to considerable errors (Eigenbrod et al. 2010, Maes et al. 2012, Crossman et al. 2013).

Modeling systems

Ecosystem service modeling combines biophysical models with the above approaches to improve the measurement and mapping of ecosystem services (Chan et al. 2006, Nelson et. al. 2009, Logsdon and Chaubey 2013), however the problem facing modeling systems is the lack of explicit guidance on how to select legitimate final services. Current tools generate biophysical and economic values of multiple ecosystem services. Ecosystem service models combine biophysical models with the first and second approaches outlined above to quantify the biophysical supply of services (Chan et al. 2006, Nelson et. al. 2009, Logsdon and Chaubey 2013). Bagstad et al. (2013) identified 17 tools that quantify, model, and value ecosystem services. Three general and publicly available tools are: (1) InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs, (2) ARIES (ARtificial Intelligence of Ecosystem Services), and (3) MIMES (Multi-scale Integrated Models of Ecosystem Services) (Crossman et al. 2013). The best known tool for mapping and valuing services is InVEST, which uses ecological production functions and economic valuation methods to create spatially explicit values for 16 services (Tallis and Polasky 2011). All three modeling systems allow users to determine tradeoffs among services. The modeling systems are seen as part of the decision-making process where scientists work with stakeholders to tailor analyses to local needs (Ruckelshaus et al. 2013). However none of the current modeling systems provide explicit guidance on how to include institutional realities (e.g., regulations, policies) into ecosystem service values, which can limit management adoption (Scarlett and Boyd 2013).

DATA GAP: LIMITATIONS OF CURRENT METHODS

Scientists need to strategically address the data gap considering the needs and timelines of decision-makers while responsibly illustrating the causal links between ecosystem characteristics and final services. Two-thirds of published studies measured ecosystem services using secondary data and land cover with no validation techniques (Seppelt et al. 2011). Land cover proxies are useful for creating ecosystem service maps and economic values to build awareness, however this method is insufficient when trying to advise policy makers on complex problems. The data gap impacts decision-makers by limiting their ability to set clear goals on intersecting social and environmental problems (Reyers et al. 2013). The importance of setting clear and manageable goals to advance public policy is explained well by US President John F. Kennedy (1963) when he stated: "By defining our goal more clearly, by making it seem more manageable and less remote, we can help all peoples to see it, to draw hope from it, and to move irresistibly towards it."

Based on my review of current methods, I identified several problems limiting the credibility and legitimacy of current ecosystem service methods. First I found no general criteria on selecting ecosystem characteristic metrics and final service indicators. Second no clear technical explanation for ecologists on how to apply ecological production functions to determine changes in final services from marginal changes in ecosystem characteristics (i.e., marginality). Third I was unable to locate any clear steps on how to combine existing ecological methods with production functions to estimate ecosystem services at different spatial and temporal scales. Lastly most studies were unable to integrate the ecosystem services approach into policy frameworks.

LINKING ECOSYSTEM CHARACTERISTICS TO FINAL SERVICES

To address current problems I synthesized key concepts and methods across ecology, economics, and policy, and created a 10-step approach. Three key components underpin the approach: (1) use biophysical models to estimate ecosystem characteristics, (2) use endpoints to identify final services, and (3) create ecological production functions to quantify biophysical tradeoffs. Below I present each component, first I introduce its disciplinary origins then I explain how to use the component to advance the ecosystem services approach.

Biophysical models to estimate ecosystem characteristics

Ecologists estimate ecosystem characteristics either through direct measurements or biophysical models (empirically-based or process-based). Ecosystems are complex systems with multiple organizational levels, characterized by nonlinear behavior, feedback loops, time lags, and non-distinct spatial boundaries. Management options and monitoring data are commonly structural attributes because they are easily observable, physical components. Ecosystem structure (e.g., nutrient concentrations) and processes (e.g., denitrification and plant nutrient uptake rates) can be directly measured via repeated measurements to estimate ecosystem functions (e.g., nutrient retention). However direct measurements are expensive and time consuming when estimating ecosystem functions like evapotranspiration or sediment fluxes at regional and national scales. Ecologists use empirically-based or process-based models to estimate ecosystem services at broad geographical scales. Empirically-based models relate management and environmental factors to ecosystem functions through statistical relationships (e.g., Universal Soil Loss Equation, Penman Monteith Equation). Empirically-based models are useful for quick forecasting, but become problematic when investigating thresholds and extrapolating beyond known data and the original model context (Beldring 2002). In ecology a consensus is emerging that management decisions are best guided by process-based models rooted in causal mechanisms grounded in ecological theory (Cuddington et al. 2013). Process-based models are powerful tools to predict: (1) outcomes across a range of spatial and temporal scales, (2) threshold levels, and (3) changes in ecosystem functions under different management actions.

How can scientists use existing process-based models to measure ecosystem services? For complex systems like ecosystems, the ecological production function alone does not afford the same predictive power as process-based models. Yet existing process-based models are not framed around social variables, making it hard to interpret marginal service changes. I suggest scientists consider process-based models to estimate key ecosystem characteristics as inputs to ecological production functions. Combining modeling techniques allows scientists to simulate ecological changes across multiple scales, and a means to statistically interpret how those changes may impact social outcomes.

Endpoints to identify final ecosystem services

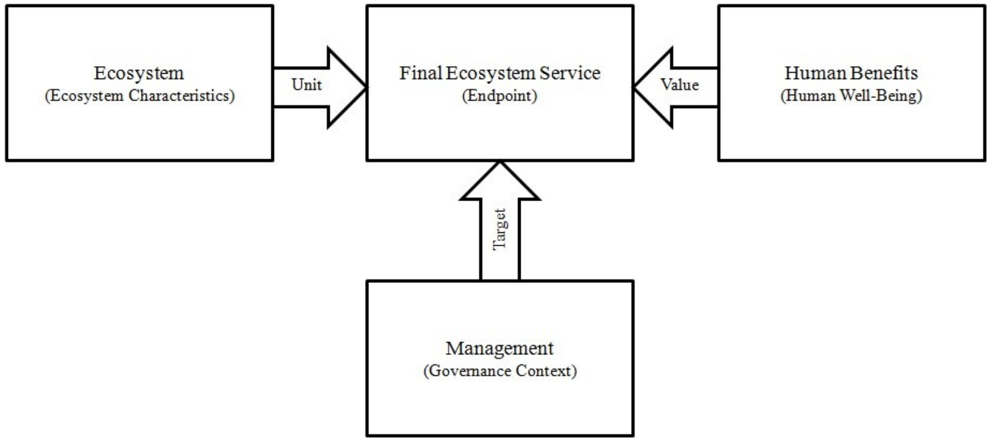


FIG. 4. Final ecosystem services known as endpoints are connected to ecology, economics, and policy. The final service is measured as an ecosystem result (biophysical unit), valued for human benefits (social value), and implemented as a management target (legal legitimacy).

The main challenge when conducting an ecosystem services assessment for public policy is selecting legitimate final services – the first step in an ecosystem services assessment. A final service is defined as a biophysical measurement with explicit social value. I propose three criteria to identify final services: (1) possess explicit social value, (2) direct relevance to management, and (3) be a measurable unit of an ecosystem (Fig.4). Final services guide scientists on what is worth measuring and how to measure services. The final service determines the final service indicator, and provides the biophysical unit to guide ecologists on measuring key ecosystem characteristics. To date we lack final services in public policy since policy makers and economists use endpoints. In theory endpoints are final services, which regulators define as measurable targets with specified spatial and temporal limits, explicitly expressing the actual environmental value to be protected (Suter 1990, US EPA, 1998, Boyd 2007). I suggest scientists use the above criteria to identify legitimate final services from existing endpoints.

The strength of endpoints as final services is legal legitimacy, which is a significant limitation preventing the use of the ecosystem services approach in public policy (Portman 2013). For several decades the endpoint has been used in environmental management in ecological risk and environmental impact assessments (Suter 1990, US EPA 1998, Suter 2008). Governments developed endpoints for a range of environmental issues: endangered species, commodities (e.g., crops, fisheries, timber), recreational quality, landscape aesthetics for heritage and cultural values, air and water quality, natural disasters (e.g., floods, droughts, fires) etc. Decision-makers use endpoints because they provide simple threshold values that are socially and ecologically significant (Suter 1990, Suter 2000). However endpoints alone are unable to incorporate ecosystem functioning into human choices. In practice two weaknesses limit endpoint effectiveness: (1) ecological endpoints with no human well-being components (e.g., ecosystem health indicators like indicator species) and (2) human health endpoints (e.g., environmental standards like drinking water quality) that ignore ecosystem functions. Ecological endpoints are often linked to statutory responsibilities, but are not tied to human well-being, thus are often unfamiliar to the public (US EPA 2009). In contrast human health endpoints are recognized by the public, but fail to incorporate ecosystem functions. Government reliance on strict numerical thresholds for contaminant concentrations has led to incomplete accounting of consequences from ecological degradation (Von Stackelberg 2013). The ecosystem services approach attempts to address the endpoint problem, however guidance is needed to identify appropriate endpoints as final services so managers can use ecosystem service values given current legal frameworks.

Existing endpoints provide a useful first step in selecting legitimate final services for ecosystem service assessments. Legal endpoints offer the most promise since many governments have regulatory frameworks for pollutant levels, biotic harvest rates, and species and landscape protections. For instance, China's Ministry of Environmental Protection uses different grades with concentration limits to regulate water quality; for example total nitrogen (i.e., final service indicator) has a drinking water endpoint of 0.5 mg/L (i.e., final service). In statutes biotic endpoints are final services when ecosystem characteristics have clear social importance, such as halibut population size for a commercial fishery or panda survival rates for heritage values. Management endpoints in environmental plans articulate final services when social objectives are defined in biophysical units, such as desired acreage of green space for urban recreation or required lake storage for drinking water supply. Scientists can also work with stakeholders to derive final services for specific ecosystems using pertinent ecological and social data (Ringold et al. 2013). For example, ecologists can work with social scientists to link algal biomass to beach closures or dust from wind erosion to landscape aesthetics. Scientists, however, should recognize the political challenges associated with final services. Multiple desired service levels likely exist for any given final service type (e.g., national and state air quality standards), thus scientists should always clearly define who selected the final services leading the given assessment.

Ecological production functions

Ecological production functions are regression models that measure the statistical influence of ecosystem characteristics (i.e., explanatory variables: vegetation area, wind speed, and sand flux) on final service indicators (i.e., response variables: PM_{10}) for a given place and time via marginal changes (i.e., regression coefficients) (Fig. 5). In theory scientists can use marginal changes to determine biophysical tradeoffs among services and management options (Polasky and Segerson 2009). For instance marginal changes could help scientists estimate how current wetland area is contributing to A water purification and B reed production to speculate how decreases in wetland area may lead to C changes in water purification and D changes in reed production.

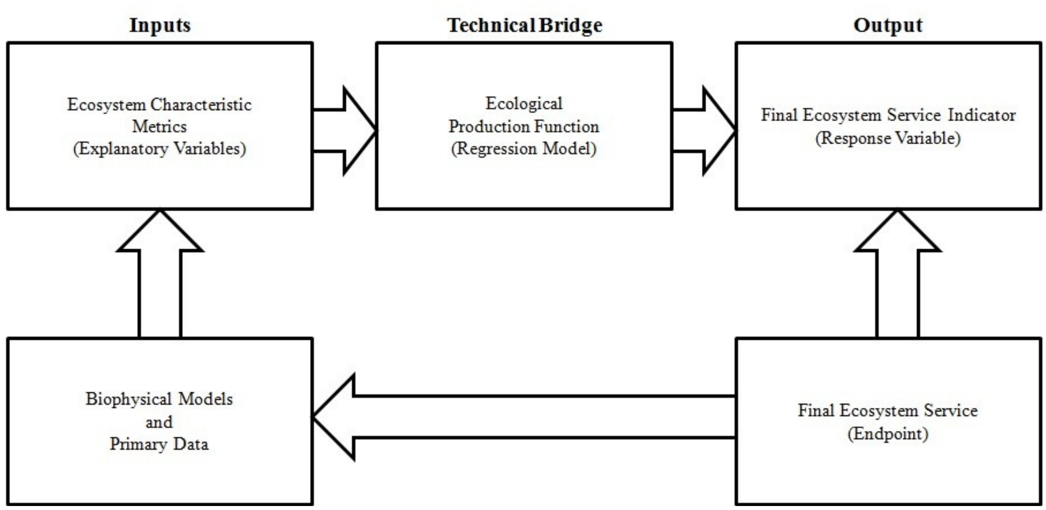


FIG. 5. Ecological production functions quantify the link between ecosystem characteristic metrics and final service indicators via marginal changes (i.e., regression coefficients). The final service informs the selection of the final service indicator and ecological methods to measure key ecosystem characteristics.

The ecological production function addresses two problems of economic valuation of ecosystem services, which are: (1) double counting and (2) valuation of ecosystem characteristics. In environmental valuation the ecological production function is considered a step in the economic valuation process (Wainger and Mazzotta 2011). I present the ecological production function as an ecological method to quantify the biophysical supply of ecosystem services, which can be combined with market and non-market valuation methods. The ecological production function classifies intermediate and final services, which is fundamental to welfare accounting. Ecological production functions clarify the economic value of ecosystem characteristics as contributions to final services, which otherwise would go unvalued. If the connections are not distinguished, the value of intermediate services is double counted when valued in addition to their respective final services (Boyd and Banzhaf 2007). The U.S. National Research Council (2005) stated “the grandest challenge for successful valuation of ecosystem services is to integrate studies of the ecological production function with studies of the economic valuation function.” Improving economic valuation is a high priority for policies on PES, mitigation banking, ecological compensation, etc. (Kinzig et al. 2011).

THE 10-STEP APPROACH

The 10-step approach unifies the above concepts, methods, and data from the disparate disciplines; presented in a stepwise form to clearly illustrate the technical integration of ideas (Fig. 6). Currently there exists little guidance on how to overcome the identified problems on ecosystem services. My intent is to offer an approach to guide choices on resource allocations for data collection and model selection, which vary depending on the study objectives and decision context (Table 1). The guidance is strategic for public policy because analysts need to be: (1) realistic when setting priorities, (2) attentive to timelines to acquire relevant data, given resources, and (3) responsive to the needs of decision-makers. The 10-step approach is about building craft not adherence to steps. Its effectiveness will depend on our ability to practice holistic and adaptive thinking (Lee 1993) centered on how ecosystems support human welfare. Below we summarize the steps in each phase.

Phase I: Identify metrics and indicators (steps 1-4)

Human benefits represented as final services should guide the measurement process. The final service criteria are used to identify legitimate final services using endpoints and/or agreed upon stakeholder targets. The analyst must clearly indicate who selected the final services and the spatial-temporal extent of the assessment. Final services most applicable to public policy, clearly describe their connections to human well-being as management metrics in the given governance context. The biophysical units of final services guide scientists on selecting final service indicators and ecosystem characteristic metrics. The ecosystem characteristic metrics should represent key ecosystem components and management options supporting the final services. The challenge is seeing the connections between social and ecological variables to link final services, final service indicators, and ecosystem characteristic metrics (e.g., water quality, total nitrogen, and nutrient retention) (Fig. 7).

Phase II. Biophysical measurement (steps 5-10)

From phase I, the selected final service indicators and ecosystem characteristic metrics are the output and input variables of the ecological production functions. Available data and field methods are selected to estimate final service indicators and ecosystem characteristic metrics. Depending on the study objectives and scale, scientists should consider biophysical models by identifying applicable process-based or empirically-based models. Biophysical models may be unnecessary if scientists can collect all the required primary data for ecological production functions at the scale of interest. If obstacles prevent primary data collection or the use of biophysical models then established proxies or secondary data are appropriate when available. Measurement and evaluation is an iterative process (steps 5-10), and every unique combination of ecosystem characteristic metrics and final service indicators results in new production functions. An uncertainty analysis should be conducted, and estimated errors and assumptions reported. Using ecological production functions to relate biophysical model results to final service indicators can help scientists and management interpret the potential causes driving final service outcomes. However when the analyst interprets marginality it is important to consider the ecosystem state because a small increase or decrease in structure or function could lead to large step changes depending on the system's proximity to a threshold.

Marginal changes are used to calculate potential synergies and tradeoffs among services and management options. The service results are spatially evaluated using marginal changes and land cover to locate spatial patterns and determine potential beneficiaries. Scientists can use the tradeoff results, mapping results, and management input to select possible changes to management options to address service shortfalls. The selected changes inform model parameter alterations to run scenarios, and the production functions are used to forecast final service indicators under the scenario conditions.

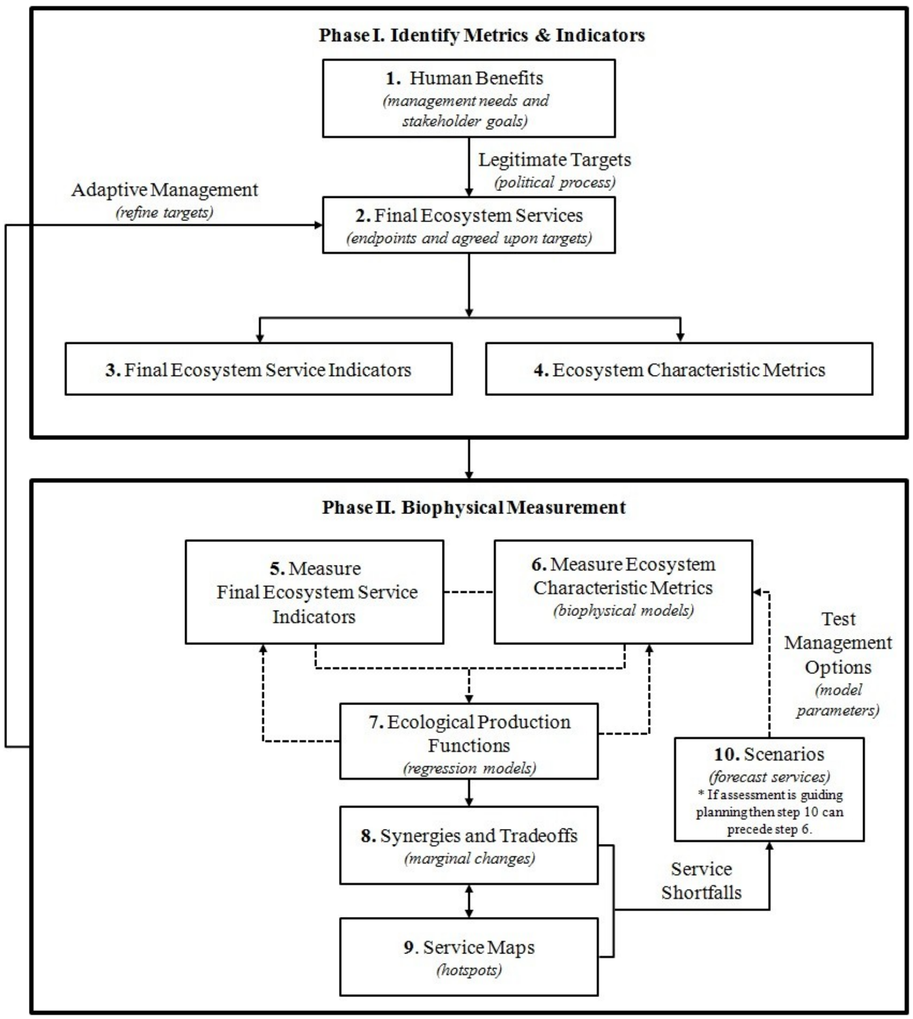


FIG.6. The 10-step approach. Phase I is identifying final services, final service indicators, and ecosystem characteristics metrics. Once these variables are selected then scientists can proceed to phase II to measure ecosystem services. Steps 5-7 are repeated until satisfactory ecological production functions are created. Steps 8 and 9 provide information on tradeoffs and spatial patterns to understand service shortfalls, which inform scenarios in step 10 that feed model alterations in step 6. The dashed lines are the main modeling steps in phase II.

TABLE 1. The 10-step approach to measure ecosystem services.

#	Step	Description
1	Human Benefits	Identify human benefits (damages) from the study ecosystem in relation to beneficiaries (individuals at risk). Determine the most relevant sources of human well-being connected to the ecosystem, such as aesthetic enjoyment, recreation, human health, physical damage avoidance, and consumed goods (Boyd and Banzhaf 2007). The human benefits are often articulated as management needs and stakeholder goals, which represent the desired environmental state.
2	Final Ecosystem Services	Select final services using endpoints from government standards and/or agreed upon stakeholder targets. Final services will likely change over time to meet changes in societal needs and scientific knowledge on service outcomes.
3	Final Ecosystem Service Indicators	Final services (step 2) inform the selection of final service indicators. Service shortfalls are the differences between final service indicators and final services.
4	Ecosystem Characteristic Metrics	Create a conceptual map of ecosystem connections to final services to identify the main ecosystem characteristics. Select the ecosystem characteristic metrics considering measurement feasibility, biological significance (i.e. causal mechanisms), and management options.
5	Measure Final Ecosystem Service Indicators	Collect data on the selected final service indicators chosen in step 3.
6	Measure Ecosystem Characteristic Metrics	Collect data and use process-based or empirically-based models to estimate the ecosystem characteristic metrics in step 4. If obstacles prevent primary data collection or the use of biophysical models then consider appropriate proxies and secondary data when available.
7	Ecological Production Functions	Create ecological production functions using regression models that relate ecosystem characteristic metrics (step 6) to final service indicators (step 5). Steps 5-7 are iterative where every unique combination of ecosystem characteristic metrics and final service indicators result in new production functions. An uncertainty analysis should be conducted, and estimated errors and assumptions reported.
8	Synergies and Tradeoffs	Use the marginal changes from ecological production functions to determine how changes in ecosystem characteristics could result in synergies and/or tradeoffs among ecosystem services.
9	Ecosystem Service Maps	Visualize service results using spatial mapping techniques to identify spatial patterns, hotspots, and potential beneficiaries.
10	Scenarios	Use tradeoff results, spatial results, and management input to understand service shortfalls to identify leverage points in management options. Generate management scenarios using biophysical models then forecast service outcomes using the ecological production functions (repeat steps 6-9).

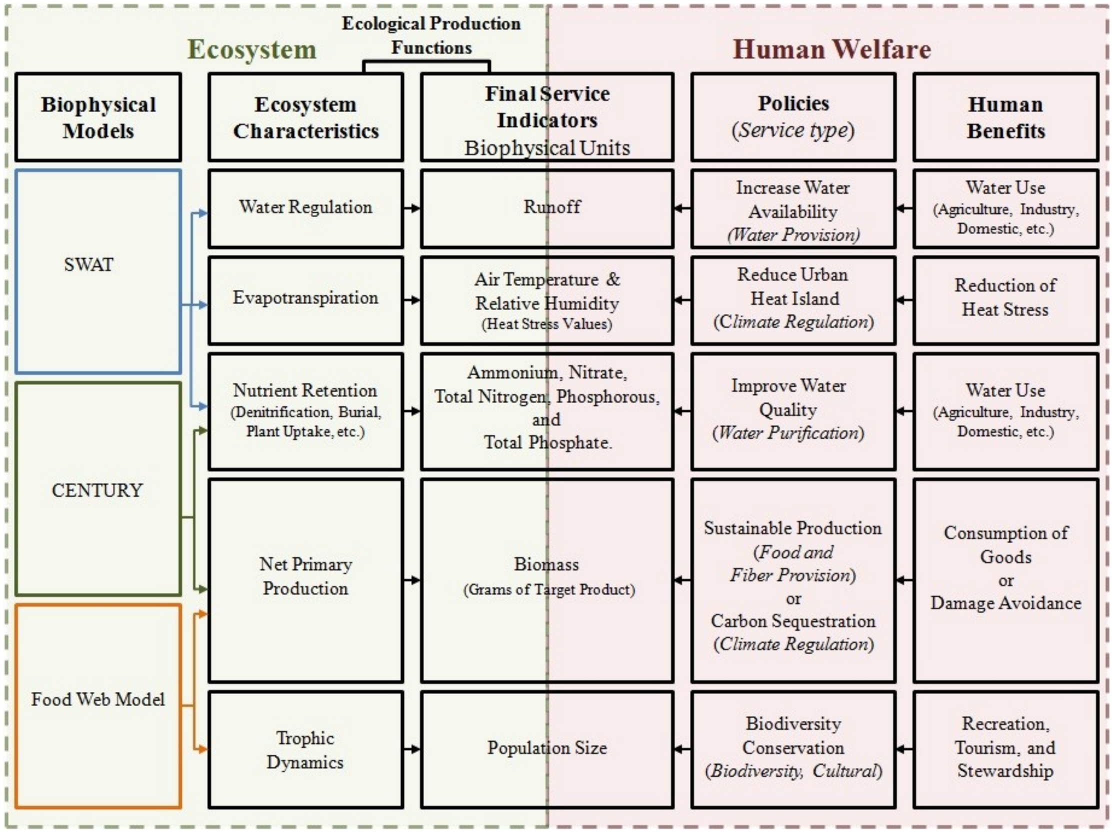


FIG. 7. Examples of how to use final service indicators to link biophysical models, ecosystem characteristics, policy targets, and human benefits.

CONCLUSION

A data gap separating ecosystem characteristic metrics and final service indicators is limiting the ecosystem services approach. Disciplinary frames separating ecology from economics and policy are preventing progress on the data gap. In the natural sciences, process-based models are considered powerful tools to advise management on ecosystem changes, but biophysical models lack outputs for final services (US EPA 2009). In environmental policy, endpoints are considered useful metrics, but current endpoints are unable to clarify connections between ecosystem functions and human well-being (Suter 2000). In economics, the production function mathematically describes how inputs relate to an output using marginality to evaluate tradeoffs; yet ecological production functions that account for ecosystem complexity remain elusive (US NRC 2005, US EPA 2009, Tallis and Polasky 2011). A transdisciplinary mindset is required to see the points of contact between disciplines to address the data gap.

A 10-step approach was designed to unify concepts, methods, and data from ecology, economics, and policy to help scientists overcome the data gap. I make three key suggestions: (1) estimate ecosystem characteristic metrics using biophysical models, (2) identify final services using endpoints, and (3) create ecological production functions to quantify biophysical tradeoffs. The guidance is strategic for public policy because analysts need to be: (1) realistic when setting priorities, (2) attentive to timelines to acquire relevant data, given resources, and (3) responsive to the needs of decision-makers. Policy targets, technical capacity, data availability, and decision settings will influence which steps are relevant for different contexts. When using the 10-step approach analysts need to relate assessment objectives to the specific decision-stage of the particular policy problem. Analysts need to make judgments relating the 10 steps to the specifics of the situations they face when designing an ecosystem services assessment for public policy.

CHAPTER 3

THE YONGDING RIVER ECOLOGICAL CORRIDOR ECOSYSTEM SERVICES ASSESSMENT FRAMEWORK

ABSTRACT

The Beijing Water Authority (BWA) asked the State Key Laboratory of Urban and Regional Ecology (SKLURE) to evaluate the ecosystem services from the Yongding River Ecological Corridor to assist managers in maintaining the new ecosystems for multiple services. I worked with SKLURE to evaluate five ecosystem services selected by management on the Yongding Corridor from 2012-2013. I took the 10-step approach presented in Chapter 2, and created a conceptual framework for the Yongding Corridor. In this chapter, I present the Yongding River Ecosystem Services Assessment Framework designed to evaluate five ecosystem services (management endpoints): (1) water storage (lake volumes, water area, and water loss), (2) local climate regulation (heat index values), (3) water purification (Grade III water quality standards), (4) dust control (PM_{10} air quality standard), and (5) aesthetics (visitor perceptions of scenic beauty). In an attempt to generate usable and credible information for managers, I created an assessment process consisting of three stages: (1) measurement, (2) evaluation, and (3) recommendations. In this chapter, I present the key components of each stage (i.e., indicators/metrics, data sources, and models) to provide an overview of my measurement methodology, and the key results I used in the evaluation stage that inform my management suggestions in the recommendation stage.

INTRODUCTION

The mission of the Yongding River Ecological Corridor is to ensure water ecosystem services to advance socioeconomic conditions and improve urban livability (BWA 2009). Managers have constructed six lakes and wetlands on the Yongding River in an attempt to reduce environmental damages from river drying in southwest Beijing. The managerial challenges include monitoring and operating the Yongding Corridor for final services (i.e., management endpoints). Managers want guidance on assessment methods to track their progress in obtaining multiple services from the Yongding River.

In this dissertation, my main objective is to create an assessment methodology to help managers evaluate five services from the Yongding River Ecological Corridor in Beijing, China. Managers are interested in five services (management endpoints): (1) water storage (lake volumes, water area, and water loss), (2) local climate regulation (heat index values), (3) water purification (Grade III water quality standards), (4) dust control (PM_{10} air quality standard), and (5) aesthetics (visitor perceptions of scenic beauty). The five services are management endpoints selected from official BWA planning documents and China's Ministry of Environmental Protection (MEP) and Beijing's Municipal environmental standards. The five final services withstood stakeholder evaluation determined from visitor surveys (presented in Chapter 8) and management surveys and discussions. My assessment framework consists of three stages (Fig. 8), first is *measurement* to determine the amount of each service provided by the new ecosystems on the Yongding Corridor. Second is *evaluation* to compare the measurement results of the five ecosystem services to identify potential synergies and tradeoffs among services, and summarize stakeholder needs and concerns. Third is *recommendations* to help translate results on tradeoffs and stakeholder needs to useful suggestions by presenting: a way to prioritize services, synergistic actions to address priorities while minimizing tradeoffs to other services, and practical steps to maintain the ecosystems. I present the conceptual framework in Fig. 8 and describe each step of the framework in Table 2.

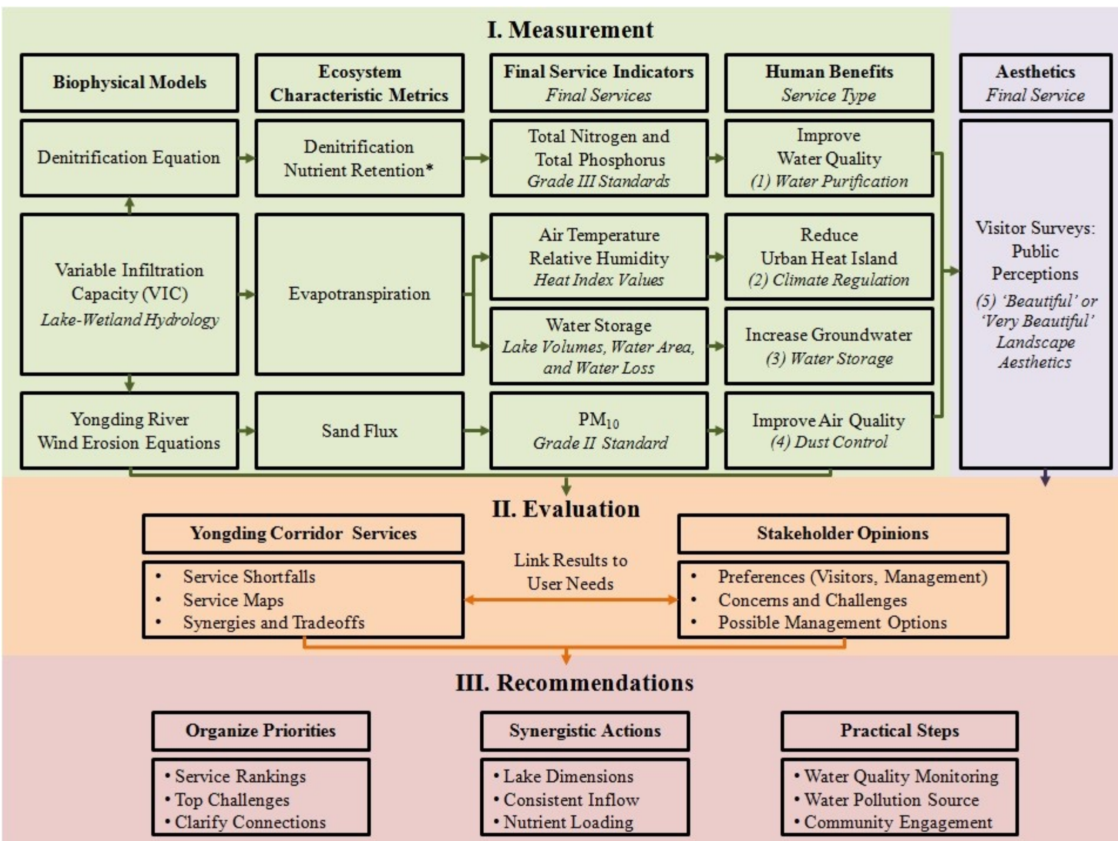


FIG. 8. Conceptual diagram of my Yongding River Ecological Corridor Ecosystem Services Assessment Framework. *Measurement* (Stage I) consists first of identifying the human benefits and final services to determine the final service indicators and ecosystem characteristic metrics. Next monitoring data is collected on the final service indicators and field methods and/or biophysical models are used to estimate the ecosystem characteristics at the appropriate temporal and spatial scales. The green box represents four regulating services (i.e., environmental quality) that require biophysical measurements, and the purple box is the cultural service that requires visitor surveys.

Simply the green box outlines the natural science methods and the purple box the social science methods. *Evaluation* (Stage II) consists first of presenting the ecosystem services results and relating them to stakeholder preferences and concerns. *Recommendations* (Stage III) consists of making management suggestions by: offering a way to organize priorities, presenting possible synergistic actions, and offering practical steps on management protocols. *The ecosystem characteristic metrics were estimated using biophysical models except nutrient retention, which was estimated using field data.

TABLE 2. Descriptions of the main steps presented in Fig. 8.

I. Measurement

#	Steps	Descriptions
1	Human Benefits and Final Ecosystem Services	Human benefits and final services guide the ecological and social analysis. Final services were selected using Beijing Water Authority management endpoints.
2	Final Ecosystem Service Indicators	Measurable indicators for each final service was selected. Data were collected from the field, government monitoring stations, and model simulations (only for water storage).
3	Ecosystem Characteristic Metrics	Key ecosystem characteristics supporting the final services were identified. Ecosystem characteristics were estimated using biophysical models and land cover data. Except nutrient retention and nutrient loading were calculated using field measurements.
4	Ecological Production Functions	Regression models were developed linking ecosystem characteristic metrics (i.e., explanatory variables) to final service indicators (i.e., response variables).

II. Evaluation : Assessment Results

#	Steps	Descriptions
5	Ecosystem Service Shortfalls	Ecosystem service shortfalls are reported as the difference between final service indicators (i.e., measured proxy values) and final service levels (i.e., required values).
6	Ecosystem Service Maps	Spatial distributions of the ecosystem services are illustrated using geographical maps.
7	Synergies and Tradeoffs	Potential synergies and tradeoffs are summarized using marginal service changes (i.e., regression coefficients).
8	Stakeholder Opinions	Stakeholder opinions are summarized as visitor and management preferences for different ecosystem services, concerns and identified problems, and possible management options.

III. Recommendations

#	Steps	Descriptions
9	Organize Priorities and Synergistic Actions	The results from the evaluation phase were synthesized and presented as management recommendations on priorities and synergistic actions to reduce service shortfalls.
10	Practical Steps	Using assessment results, specific suggestions are made on water quality monitoring, water pollution sources, and community engagement.

Next I will attempt to introduce the general organization of how I compose subsequent chapters to offer a simple explanation of the logic and reasoning behind my choices. To conduct my assessment I used both natural science and social science methods to create an interdisciplinary methodology, thus throughout this dissertation the methods and results are presented in an unconventional format for both natural and social scientists. First the novelty of my approach is that final services (i.e., stakeholder needs) drive the scientific analysis since stakeholder needs are often not considered or considered after the analysis is complete, which makes it difficult to create usable and relevant information for stakeholders (i.e., the users). However a significant problem for most scientists is identifying measurable final services (i.e., endpoints) that represent user needs to determine appropriate indicators and metrics for the scientific investigation. Furthermore, the primary type of information that mangers use to evaluate environmental conditions is basic monitoring data on environmental quality (i.e., final service indicators) to determine environmental trends and proximity of the system to their targets (i.e., shortfalls). However often managers are unable to link causes to shortfalls to identify appropriate actions for reducing shortfalls because this requires scientific understanding on how ecosystem changes impact final services (i.e., ecological production functions). Scientific research is the primary means in which society generates knowledge to understand how changes in mechanisms lead to problems. The difficulty is creating scientific investigations that: (1) consider user needs at the outset, (2) advance knowledge relating ecological mechanisms to social problems, and (3) present results in a useful format for management.

In the subsequent chapters, I first present the *measurement* methods and results in Chapters 4-8, and the *evaluation* results and management *recommendations* in Chapter 9. To assess each ecosystem service, I developed a simple logic framework outlined in Fig. 9, which maps the general progression of my research questions. I used this roadmap to guide my methodological choices and formatting choices when presenting my results. I organize the material in this manner to offer examples of how to organize scientific analyses to address the science policy problems summarized in the previous paragraph. For Chapters 5-8, I generally present the methods and results in this order: (1) the final services and how I evaluated their legitimacy; (2) final service indicator datasets, final service trends, and service shortfalls; (3) biophysical models, datasets to parameterize the models, and estimates of ecosystem characteristics; (4) ecological production functions using regression models, and how marginal changes in ecosystem characteristics may alter final service indicators; (5) the use of ArcGIS to present spatially explicit results.

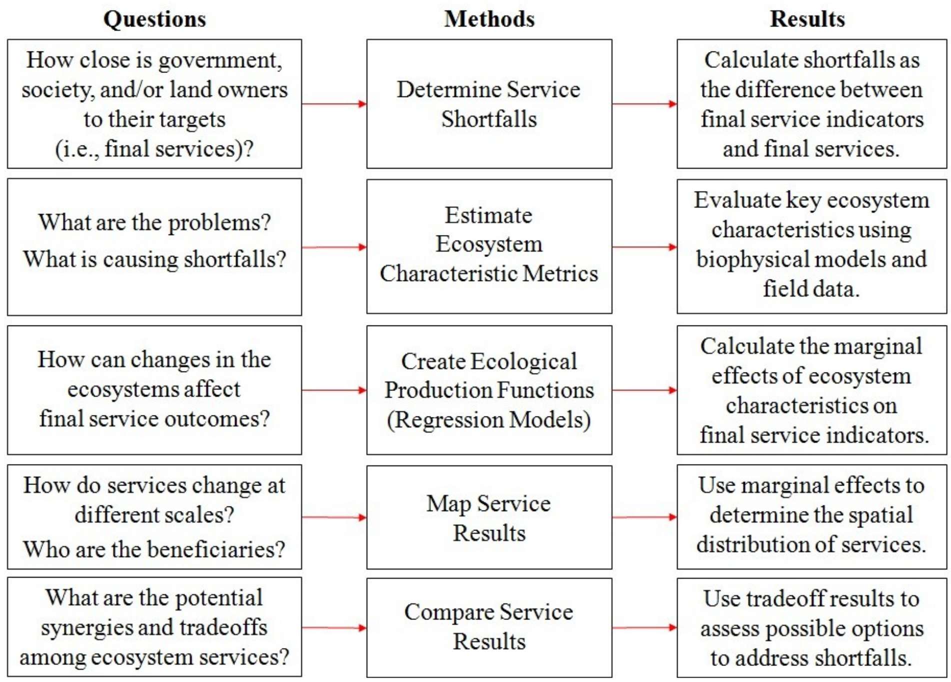


FIG.9. Conceptual roadmap outlining the progression of my research questions and respective methods and results. In chapters 5-8, I present my methods and results in this general order: final services, service shortfalls, estimates of ecosystem characteristics, ecological production functions, and service maps.

STAGE I: MEASUREMENT

Final ecosystem services

I used official BWA planning documents to identify final services, however locating tangible quantities for all services was challenging since BWA goals were a mix of qualitative and quantitative statements. The BWA had explicit targets for water storage and water purification. For water storage, I used BWA targets for lake volumes, water area, and water loss. For water purification, the BWA wants the wetlands to improve total nitrogen (TN) and total phosphorus (TP) levels from a Grade IV (i.e., industrial and recreational use) to Grade III (i.e., drinking water quality) using the MEP standards (GB3838-2002). For local climate regulation, I used the Beijing Meteorological Bureau's official heat index (HI) endpoint for sultry events. HI values are calculated using a simple human comfort equation to predict sultry events using outdoor air temperature and relative humidity. For dust control, I delved into the literature where I discovered several studies on Yongding River wind erosion. Chinese scientists created empirical equations to predict sand flux from the Yongding River, which is considered an important contributor to high PM_{10} levels in Beijing during dust events. For dust control, I selected the MEP daily PM_{10} endpoint for Grade II (GB 3095-1996), which is the legal limit for urban residents in China. For landscape aesthetics, I discussed with economists and recreation scientists to determine how to evaluate the scenic beauty from the Yongding Corridor. They helped me recognize that my four regulating services (i.e., water storage, local climate regulation, water purification, and dust control) were essentially different aspects of environmental quality. Social scientists often evaluate landscape aesthetics using a questionnaire-based survey to solicit information on public perceptions by asking visitors to score environmental quality and landscape aesthetics using a scoring system. Based on sample questionnaires of fellow social scientists, I created a scoring system for landscape aesthetics presented to visitors as: ‘very unattractive’ (1), ‘unattractive’ (2), ‘okay’ (3), ‘beautiful’ (4) and ‘very beautiful’ (5). For landscape aesthetics, I selected the final service levels as ‘beautiful’ (4) or ‘very beautiful’ (5). Lastly, I surveyed managers and visitors to evaluate the legitimacy of all five final services. The use of endpoints and their associated human benefits significantly increased the legitimacy of my assessment, which has led to management consideration of my results.

Datasets for final ecosystem service indicators

I measured the final service indicators mainly using field data and monitoring data from government stations, however water storage indicators (lake volume, water area, and water loss) were estimated using the Variable Infiltration Capacity (VIC) model. In Table 3 I present the final services, final service indicators, and methods used to collect data on the final service indicators. Data on the final service indicators for local climate regulation, water purification, and landscape aesthetics were collected in the field from 2012-2013. Data on the final service indicator for dust control was obtained from the Beijing Environmental Protection Bureau (BEP) stations reported as Air Pollution Index (API) or Air Quality Index (AQI) values from 2009-2010 and 2012-2013, which were converted to daily mean PM_{10} using the MEP equation. Data on the final service indicators for water storage were estimated using the VIC model from 2012-2013. I first parameterized the VIC model using engineering values then calibrated the model to represent observed seasonal fluctuations in lake and wetland hydrology based on monthly field observations. I present the temporal and spatial scales of each service in Fig. 10.

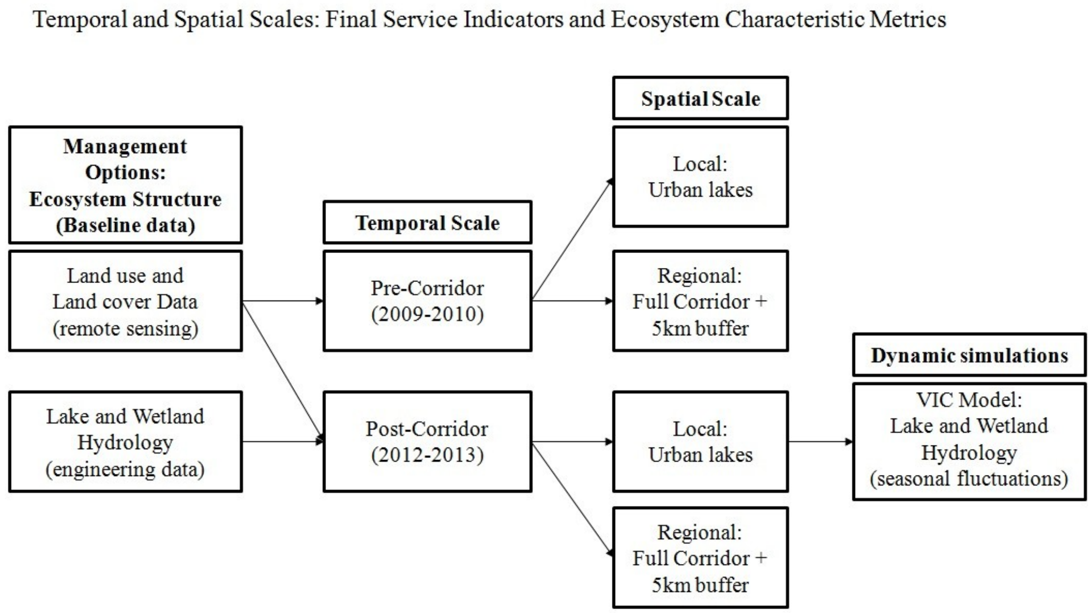
TABLE 3. Final ecosystem services, final ecosystem service indicators, and the methods used to obtain data on final ecosystem service indicators.

No.	ES Types	Final Services (Endpoints)	Final Service Indicators	Methods
1	Water storage	(1) Lake volume (m^3)* = 12.05 million (2) Water area (ha) = 651 (3) Evapotranspiration (m^3) = 200. 48 million	Lake volume (m^3) Surface water area (ha) Evapotranspiration (m^3)	Daily water volume simulated using the VIC model.
2	Local climate regulation	Heat index values† Sultry = 27-28	(1) Air temperature (°C) (2) Relative Humidity (%)	Hourly air temperature and humidity collected using data loggers.
3	Water purification	Drinking water quality (mgL^{-1})* (1) Total Nitrogen = 1.0 (2) Total Phosphorus = 0.2	(1) Total Nitrogen (mgL^{-1}) (2) Total Phosphorus (mgL^{-1})	Monthly water quality data collected in the field.
4	Dust control	PM_{10} ($\mu g\ m^{-3}$)* Good air quality = 150	PM_{10} ($\mu g\ m^{-3}$)	Daily PM_{10} data from government monitoring stations.
5	Aesthetics	Visitor preferences‡ (1) Very Beautiful (2) Beautiful	Landscape aesthetic scores	Monthly visitor surveys conducted in the field.

* Beijing Water Authority and Ministry of Environmental Protection Water and Air Quality Standards.

† Beijing Meteorological Bureau Physical Comfort Index, final services are below sultry endpoint; physical comfort equation requires air temperature and relative humidity.

‡ Visitor survey rankings, final services are 'beautiful' and 'very beautiful'.



1. Water storage: calculated for post-Corridor period at local and regional scales.
2. Local climate regulation: calculated for pre- and post-Corridor periods at local and regional scales.
3. Water purification: calculated for post-Corridor period at local scale.
4. Dust control: calculated for pre- and post-Corridor periods at local and regional scales.

FIG. 10. The temporal and spatial scales used to calculate each ecosystem service. The land use and land cover data and engineering data on lake/wetland hydrology were used to parameterize the biophysical models to estimate the ecosystem characteristic metrics.

Biophysical models to estimate ecosystem characteristics

I estimated the majority of the ecosystem characteristic metrics using biophysical models except nutrient retention and perceived environmental quality, which I measured using field data. Managers are altering the ecosystem structure of the Yongding River adding lakes, wetlands, and shoreline vegetation to alter ecosystem functions to enhance services. Therefore the land use and land cover (LULC) changes before and after the Yongding Corridor represent the ecological changes (direct = lakes/wetlands; indirect = urbanization), which influence the ecosystem functions that impact final services. To estimate the ecosystem characteristic metrics, the first step in my methodology is to determine the LULC for the pre- and post-Corridor periods using remote sensing and engineering data. I determined the LULC on the Yongding River at two spatial scales: (1) lakes in the urban section (i.e., local scale), and (2) full Corridor spanning the 170 km of the Yongding River in Beijing with a 5 km buffer (i.e., regional scale) (Fig. 10). The second step is to simulate the lakes/wetlands hydrology using the VIC model, a process-based hydrological model, because the addition of water is the main management alteration to the Yongding River. The hydrology of the lakes/wetlands regulates the delivery of all five ecosystem services. I selected five key VIC model outputs: (1) lake volume, (2) evapotranspiration, (3) sensible heat flux, (4) flow rate, and (5) wetland + lake area. These VIC model outputs were either: (1) key ecosystem characteristics (i.e., response variables for ecological production functions) or (2) model parameters for the denitrification equation and Yongding River wind erosion equations (Fig. 11). I conducted a sensitivity analysis on how a 20% change in VIC model parameters may alter VIC outputs. The third step is to model denitrification and sand flux using empirical equations. I modeled denitrification using a common empirical equation for constructed wetlands, and modeled sand flux using empirical equations for the Yongding River.

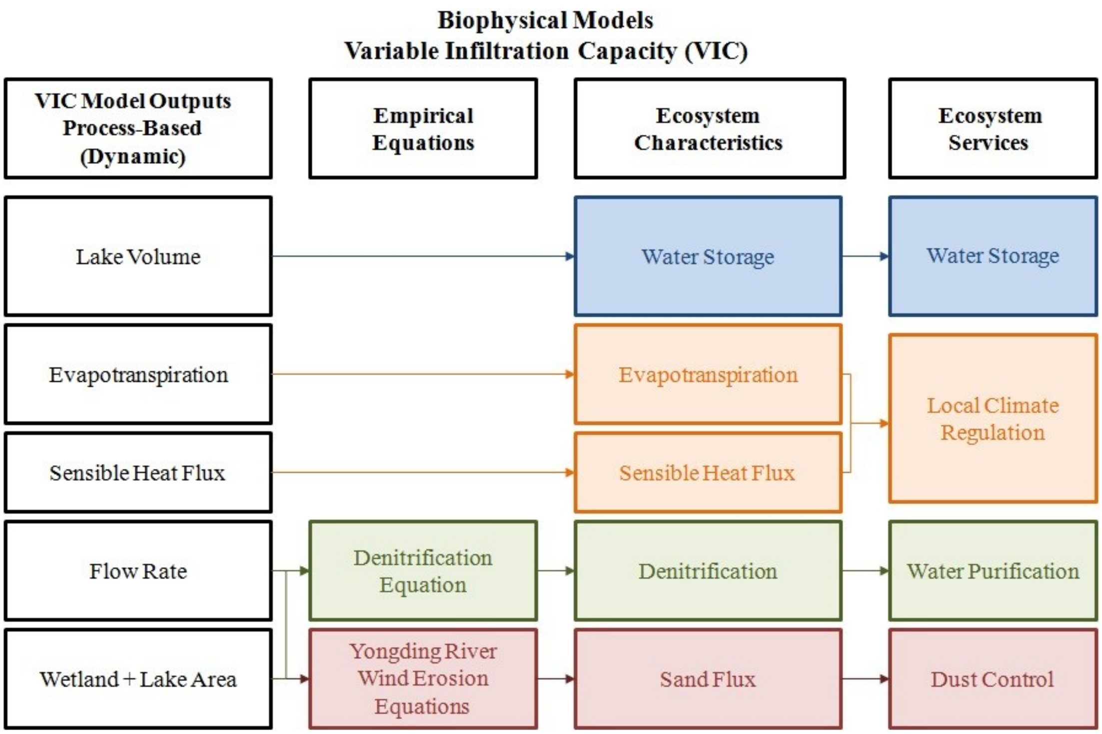


FIG.11. Summary of connections between biophysical models to estimate key ecosystem characteristic metrics for each ecosystem service.

Datasets to parameterize biophysical models to model ecosystem characteristics

I used biophysical models to estimate the key ecosystem characteristic metrics, and to parameterize the models I used a mixture of datasets: field data, government monitoring data, engineering data, and literature values. In Table 4, I present the datasets I used to parameterize each biophysical model for different ecosystem characteristic metrics. The VIC model had the most data requirements, but the most important are the LULC data and climate data. The Beijing government has a climate station near the Yongding Corridor, and I obtained daily average values for precipitation, wind speed, relative humidity, and daily max and min air temperature for pre- and post-Corridor periods. In addition to the daily climate data, I used Hobo data loggers to obtain hourly air temperature and relative humidity at each lake/wetlands site in the post-Corridor period. The VIC model provides global datasets for vegetation and soil parameters, and I supplemented these datasets with literature values for *Phragmites* wetlands and an urban land use class. Lastly, I used engineering data to parameterize lake bathymetries and flow rates. To parameterize the denitrification equation, I collected monthly water samples that were analyzed for nitrate+nitrite and took in-situ water temperature measurements. Lastly, I used the modeled monthly flow rates and wetland areas from the VIC model to estimate hydrologic residence times. To parameterize the Yongding River wind erosion equations, I used the LULC data and government monitoring data on daily average wind speed.

TABLE 4. Summary of data and methods used to parameterize biophysical models.

Data to Parameterize Biophysical Models to Model Ecosystem Characteristic Metrics					
Ecosystem Service	Ecosystem Characteristic Metrics	Biophysical Model	Data Collection Method	Field Sites (#)	Dates
Water Storage	Lake Volumes Water Area Water Loss	Variable Infiltration Capacity model (process-based)	(1) LULC data (2) Engineering data (3) Government climate data: precipitation, wind speed, daily max and min air temperature, and relative humidity	7	June 2012 - June 2013
Local Climate Regulation	Evapotranspiration Sensible Heat Flux		(4) Field data: hourly air temperature and relative humidity from Hobo data loggers (5) VIC vegetation and soil texture datasets with literature values.		June 2009 - June 2010; June 2012 - June 2013
Water Purification	Denitrification	Denitrification equation (empirical)	(1) VIC model outputs: flow rate and wetland area (2) Field data: nitrate+nitrite and water temperature	20	March 2013 - August 2013
Dust Control	Sand Flux	Yongding River Wind Erosion equations (empirical)	(1) LULC data (2) VIC model outputs: lakes/wetlands area (3) Government climate data: wind speed	N/A	June 2009 - June 2010; June 2012 - June 2013

Datasets to measure ecosystem characteristics

I measured nutrient retention and visitor perceptions of environmental quality using data collected in the field. Only these two ecosystem characteristic metrics were measured using field data presented in Table 5. I measured wetland nutrient retention taking monthly water samples at 20 sites on the Yongding Corridor, and analyzing them for TN and TP. The majority of the nutrient loading occurred in the wetlands, thus there was a substantial difference in nutrient concentrations above the wetlands (i.e., upstream), in the wetlands, and below the wetlands (i.e., Lianshi Lake). Nutrient retention was measured as the difference in average TN and TP concentrations between the wetlands and Lianshi Lake. I created a questionnaire-based survey to solicit information on visitor perceptions of: air quality, water quality, and climate.

TABLE 5. Field data and methods to measure ecosystem characteristic metrics.

Data to Measure Ecosystem Characteristic Metrics				
Ecosystem Service	Ecosystem Characteristic Metrics	Data Collection Method	Field Sites (#)	Dates
Water Purification	Wetland Nutrient Retention	Monthly water samples were taken, and analyzed for TN and TP.	20	March 2013 - August 2013
Aesthetics	Visitor Perceptions of Environmental Quality	Monthly visitor surveys were conducted.	2	April 2013 - September 2013

Ecological production functions: Regression models

The final step of the measurement phase is creating ecological production functions to link the ecosystem characteristic metrics to the final service indicators using regression models. I created six ecological production functions to estimate the potential influence of the ecosystem characteristics on final services shown in Fig. 12. The objective is to calculate the regression coefficients also known as marginal effects, which are the ecosystem service metrics. I use the regression coefficients to interpret how marginal changes in the ecosystem characteristic variables could potentially change the final service indicators. Therefore in Chapters 5-8, I present the ecosystem service results using common practices and the language of economics interpreting regression coefficients in terms of marginality.

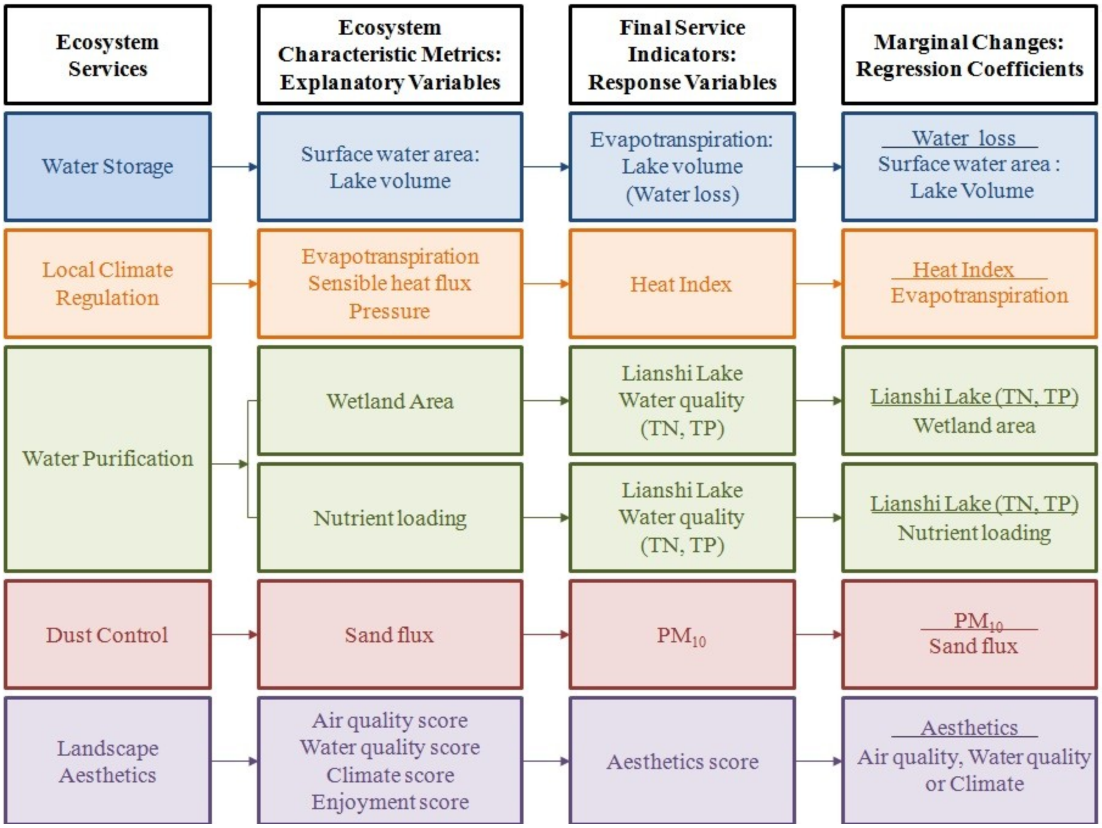


FIG.12. Six ecological production functions (i.e., regression models) to link the ecosystem characteristic metrics and final service indicators.

STAGE II: EVALUATION

Ecosystem service results

For each ecosystem service, I present the ecosystem service results in three ways: (1) service shortfalls, (2) service maps, and (3) marginal service changes. In Chapters 5-8, I first present the service shortfalls because managers typically want to know the general trends of the indicators of interest to assess the proximity of the system to their targets. The shortfalls are useful because they help management and scientists gauge the current distance to their targets similar to financial managers who use deficits to determine fiscal health. Also they are informative in helping scientists assess the potential magnitudes of the problems. Next I present the service maps to illustrate the spatial distribution of each ecosystem service in relation to individual districts in Beijing to evaluate the potential beneficiaries. Lastly, I present the marginal effects of ecosystem characteristic metrics on final service indicators to assess the potential contributions of the ecosystems to social outcomes. The marginal effects are useful because they can help scientists and managers estimate the potential changes in ecosystem characteristics needed to address shortfalls to obtain final service levels.

In Chapter 9, I synthesize the results from Chapters 5-8 to determine potential tradeoffs and synergies among the ecosystem services, which I then compare to stakeholder needs to prioritize actions. I use the marginal changes to identify potential synergies and tradeoffs among the five services from changes in BWA management options like lake and wetland dimensions. Information on potential tradeoffs can help managers address priorities in a manner that minimizes losses to other services. The novelty of Chapter 9 is relating the ecosystem service results to the needs of stakeholders to assess tradeoffs in terms of social priorities and ecological connections.

STAGE III: RECOMMENDATIONS

Based on the *measurement* and *evaluation* stages, I make three general types of *recommendations* for management to address service shortfalls on the Yongding Corridor: (1) a way to organize priorities, (2) possible synergistic actions to address priorities while minimizing tradeoffs to other services, and (3) practical steps. The *recommendations* are presented in Chapter 9.

CHAPTER 4

THE NEW ERA OF URBANIZATION:

LAND USE AND LAND COVER CHANGE ANALYSIS

ABSTRACT

The eco-city is central to China's vision of sustainability, and a critical component of eco-cities is green infrastructure to incorporate ecosystem services into urban design. The Yongding River Ecological Corridor in Beijing is one of the first development projects to implement eco-city concepts at a regional scale. I conducted a land use and land cover (LULC) analysis of the Yongding Corridor before (2009) and after (2013) construction of lakes and wetlands at a local scale (i.e., lakes/wetlands in the urban section) and regional scale (i.e., full Corridor + 5 km buffer). Managers are attempting to create multifunctional lake and wetland ecosystems for regional ecosystem services. From 2009 to 2013, bare soil area declined from 21.6% to 4.9% of total local area, but only went from 4.9% to 4.0% of total regional area. In the four-year period, the largest regional change was a 52% increase in urban area representing an increase of 93 km^2, mainly from the conversion of cropland and grass. The largest local changes were the expansion of water area by 935% and deciduous trees area by 322%, mainly from the conversion of grass and bare soil. Despite the dramatic local change in water area, the water class made up less than 1% of total regional area in 2013 while the urban class was 23% of total regional area. The LULC results illustrate the importance of evaluating how local ecosystem changes may scale regionally, and monitoring surrounding land uses to manage ecosystem service flows under rapidly changing conditions.

INTRODUCTION

Cities in developing countries are emerging in an era of high-technology, globalization, public-private partnerships, and complex environmental problems. Today more than 50% of the world's population live in cities, and continued urban growth is occurring mainly in developing countries like China and India where the majority of their populations are expected to be urban by 2050 (UN-Habitat 2008). China is currently driving this global surge towards urbanization with rapid urban growth rates because urbanization is considered the means to economic development (Hald 2009). Past models informed by the Western experience are likely insufficient to understand the development trajectories of emerging economies like China (Jaques 2009). New modes of thinking are required to understand the changing conditions of urbanization (Bai 2003).

Scholars are constructing new theories on urban-environmental problems that build upon the environmental Kuznets curve (EKC).The EKC states countries follow a development path of an inverted-U function of environmental degradation across an income spectrum from low to high. It suggests cities will experience rising environmental degradation until a critical income-level is reached that allows a municipality to invest in technology to minimize environmental problems. However the EKC cannot explain the diversity of environmental burdens and technological leaps occurring in developing countries at lower income levels than developed nations during their industrialization. The time-space telescoping theory suggests that developing countries are experiencing local, regional, and global environmental problems at lower income levels with faster growth, in a more simultaneous fashion than developed countries (Marcotullio et al.

2005). This theory suggests cities in developing nations have compressed development pathways where sanitation and access to water problems (local), industrial pollution (local to regional), and water scarcity and climate change (regional to global) are occurring earlier with less capital than the past (Bai 2007, Marcotullio 2007). The management implication is that developing countries will likely need synergistic solutions in a quicker fashion than past development schemes focused on individual social and environmental problems (Marcotullio et al. 2005).

Countries are addressing current urban complexities using approaches like eco-cities to advance sustainability (UN-Habitat 2009). In 2013 over 20 new eco-cities were launched (Cugurullo 2013), such as Masdar in Abu Dhabi (Cugurullo 2013), Tianjin Eco-City in China (Caprotti 2014), and Songdo Eco-City in South Korea (Kim 2010). An eco-city is a city managed as an ecosystem, designed to enhance the self-resilience and functioning of the city (Yip 2008). China is leading the eco-city movement with more than 100 planned eco-cities (Caprotti 2014). According to Wu (2012) China is experiencing an "eco-revolution" because many of its eco-cities are built from scratch at large-scales at a pace faster than any other human developments on Earth. Driving the eco-city movement in China is the environmental targets set by the central government. However because the road to sustainability is unknown, the central government is encouraging local governments to carry out experiments to find a pathway forward using "exemplar" developments as models. Eco-cities are not state-funded projects rather they are built as real estate developments in cooperation with local governments. Exemplar status is a major achievement because with notoriety comes a bundle of supporting policies from the central government. Chinese eco-cities are usually new towns in the suburbs of large municipalities often known as low-carbon communities (Wu 2012). A distinctive element of an eco-city is green infrastructure defined as natural or semi-natural networks of green (soil-covered or vegetated) and blue (water-covered) spaces and corridors that maintain and enhance ecosystem services (Naumann et al. 2011). Chinese urban planners are experimenting with ecological corridors using large-scale green infrastructure to enhance ecosystem services to improve the quality of life for residents (Yu et al. 2011).

A project representing this new approach to urban design is the Yongding River Ecological Corridor in Beijing, which attempts to address multiple environmental and social problems while advancing economic development. The Yongding River is commonly known as Beijing's "Mother River," however in the past 30 years the Yongding River became perennially dry in Beijing (Jiang et al. 2014). Beijing officials believe the poor environmental quality on the Yongding River is preventing economic development in the southwest, which makes up 30% of Beijing's land area but only contributed 12% to GDP in 2009 (BWA 2009). The Beijing government is creating new lakes and wetlands on the Yongding River known as the Yongding Corridor to improve ecosystem services to advance socioeconomic conditions (BWA 2009). The Yongding Corridor is the foundation for a new eco-city, Changxindian (Yip 2008), which represents a large-scale experiment on the application of eco-city concepts in Beijing (Shi 2013).

Regional development along the Yongding River is an important component of Beijing's Master Plan (2004-2020) to move towards a service economy while creating a "green city" through ecological improvements (Gu et al. 2010). Since 2010 over 290 billion yuan ($47.3 billion USD) has been invested in the southwest districts (Shi 2013). The focus of the Yongding Corridor is planning for sustainability by attempting to translate performance-based indicators into zoning and regulatory standards, focused on renewable energy, water efficiency, affordability, public transportation, and green space (Yip 2008). The government's goal is to transition the region from industry and agriculture to high-technology by creating a new central business district in southwest Beijing. The eco-city Changxindian will be the heart of the new central business district consisting of new residential neighborhoods and businesses on the banks of the Yongding Corridor. New transportation networks are being constructed to reduce future congestion as subway lines, roads, high-speed rail, and an international airport. Beyond the river banks, however, there has been a simultaneous surge in suburban neighborhoods similar to the planned tracked homes in the United States. Advertised as European villas or Southern California homes, but unlike the dense high-rise, apartments characterizing the urban core of Beijing these are large square-footage homes. Adjacent to these suburban neighborhoods are an increasing number of golf courses. The leisure industry is important to advancing district-level economies by providing recreational opportunities to urban residents. The concern among environmentalists and academics is that government officials are not managing the Yongding Corridor with consideration of the implications of more development on Beijing's limited water resources.

Beijing is a mega-city situated in a water scarce region, and its' most severe water shortages have occurred in the past decade because of growing regional water consumption and pollution, and a drier climate. Water shortage is the main limiting factor affecting the development of the city (Wei 2005). Per capita water availability declined from 1,000 m^3 in 1949 to less than 230 m^3 in 2007 (Probe 2010). The United Nations defines water scarcity as an annual water availability of less than 1,000 m^3 per capita, and absolute water scarcity as less than 500 m^3 (WWAP 2012). Today the majority of Beijing's rivers are dry, making surface water an unreliable water source. More than two-thirds of the city's water comes from limited groundwater supplies. Further exacerbating Beijing's water scarcity is climate change and water pollution. Since 1999 Beijing has been in a state of prolonged climatic drought with a 28% decline in mean annual rainfall compared to the historic average (Probe 2010). Lastly Beijing's remaining freshwater ecosystems are threatened by untreated pollution from upstream industrial factories and agricultural production and local stormwater and sewage. Government officials approved several water transfer projects like the South-North Water Transfer Project (SNWT) to get new water supplies to Beijing. The SNWT will transport water over 1,000 km from the Yangtze River, providing over 14 billion m^3yr^{-1} of water to Beijing by 2030 (Stone and Jia 2006). However experts and government officials note that even the world's largest water transfer project will be insufficient to meet future water demands. The key to addressing Beijing's water crisis is effective governance to generate regulations and economic incentives to promote more sustainable water use (Probe 2010).

The management challenges of the Yongding Corridor illustrate the opportunities and difficulties of balancing social, economic, and environmental needs of cities at different scales. Managers of the Yongding Corridor created the new ecosystems to increase water storage, reduce urban heat island effects, improve water quality, reduce dust events, and enhance landscape aesthetics across the region. A significant challenge for managers is managing the Yongding Corridor considering the surrounding land use and land cover (LULC) changes, which can impact the functionality of the new ecosystems. The land use heterogeneity of cities makes spatial organization extremely important to maintain the multifunctionality (ecological, economic, and social) of green infrastructure (Andersson et al. 2014). However urban planners typically do not routinely use LULC data to evaluate how changes in surrounding areas may impact ecological corridors (Wickham et al. 2010). For instance managers of the Yongding Corridor are focused on the LULC in the engineered boundaries of the Yongding Corridor. No general analysis has been conducted on how local ecosystem changes on the Yongding Corridor may scale up regionally, and adjacent land uses may impact ecosystem services.

In this chapter I estimate the LULC changes of the Yongding River in Beijing before (2009) and after (2013) the construction of the Yongding Corridor. To my knowledge this is the first LULC analysis to estimate the changes in water area, vegetation area, and urbanization on the Yongding River from government efforts for regional sustainable development. Also I present the LULC methods and results separately from the ecosystem service analyses because the LULC changes drive the alterations in ecosystem functions, which impact the ecosystem services. The LULC data is also an important parameter in the biophysical models, which I use to estimate the ecosystem characteristics in the following chapters. Chapter objectives are to quantify: (1) the spatial extent of ecosystem changes on the Yongding Corridor, and (2) the surrounding land use changes that may impact ecosystem services. The purpose of this chapter is to use LULC data to identify important scale considerations when designing multifunctional landscapes in cities.

METHODS

Study area

My study area is the Yongding Corridor covering the section of the Yongding River in Beijing stretching between longitudes 115°70′- 116°44′E and latitudes 40°13′ - 39°39′N (Fig. 13). The Yongding Corridor is 170 km long and spans an area of 1,188 km^2. The Yongding Corridor has three sections: (1) mountainous, (2) urban, and (3) outerurban (Figs. 13-14). The mountainous section is mainly secondary forests of deciduous broad-leaf trees extending from Youzhou Township to Sanjiadian (92 km long). The urban section is factories and residential homes starting below Sanjiadian dam to the southern portion of the Sixth Ring Road (37 km long). The outerurban section is a mixture of suburban homes and rural villages consisting mainly of agriculture, grass, and bare soil running from the Sixth Ring Road to Liangge Zhuang (41 km long). From 2011-2014, the government constructed six new lakes and wetlands in the urban section. The plan is to create streams and wetlands in the mountainous and outerurban sections as well, but as of this study construction had not started on these additional ecosystems.

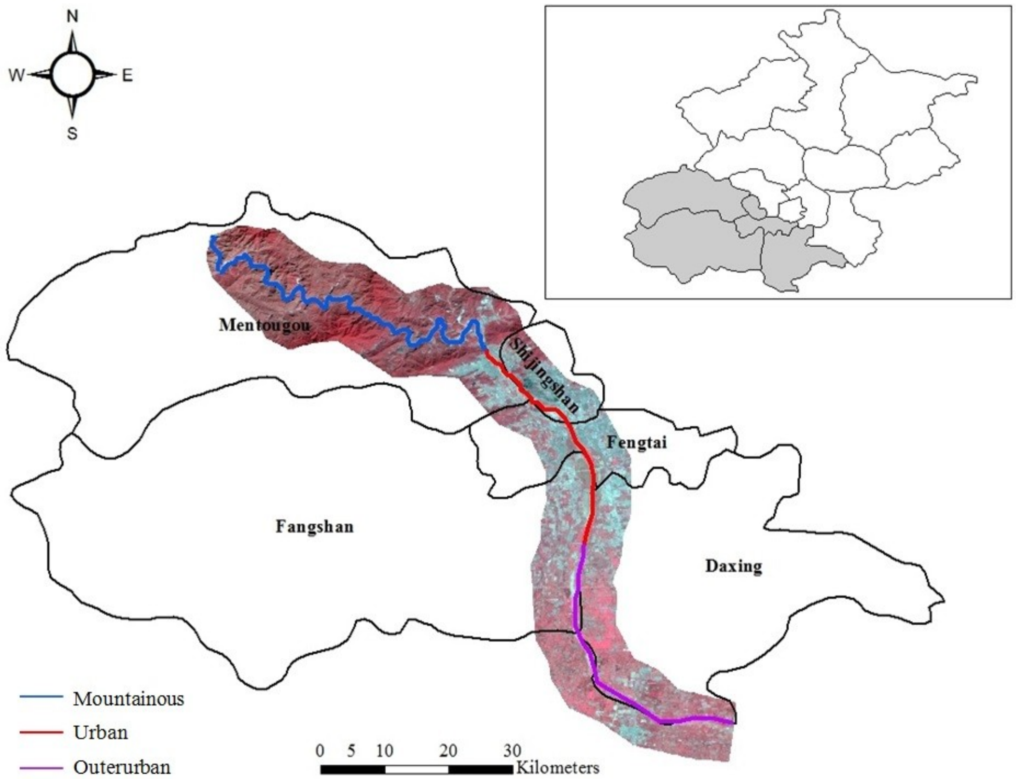


FIG. 13. Study area, the Yongding River in Beijing. Three sections of the Yongding River Ecological Corridor: (1) mountainous, (2) urban, and (3) outerurban.

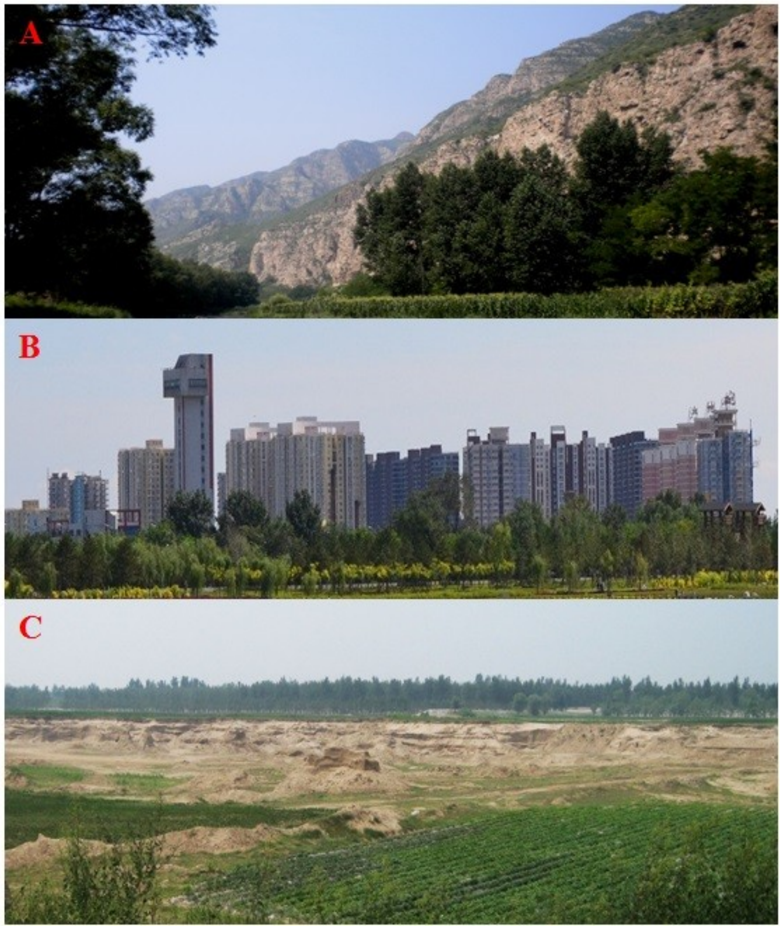


FIG. 14. Photos of the (A) mountainous, (B) urban, and (C) outeruban sections of the Yongding Corridor in 2010. The mountainous was mainly Poplar trees and outerurban were corn fields, orchards, and sand dunes.

Beijing has a seasonal temperate and semiarid continental monsoonal climate. The average annual precipitation spans 550 to 660 mm, and roughly 85% of the rainfall occurs from June to September. Beijing is located in a water scarce region and water shortages are a serious problem (Wei 2005). For the past 30 years, there has been near zero-streamflow at Sanjiadian and the downstream reaches in the urban and outerurban sections. Hence the majority of water for the Yongding Corridor is recycled water from wastewater treatment plants in Beijing.

Characterization and classification of land use and land cover

Image preprocessing, classification, and classification accuracy assessment were performed using ArcGIS 10.1 (ESRI, Inc.) and ERDAS IMAGINE 9.3 (Leica, Inc.). Satellite images for two time periods where used to compare pre-Corridor (2009) and post-Corridor (2013) conditions (Appendix A). Medium resolution remote sensing images (i.e., 30m for multispectral bands) from the U.S. Landsat (4-5; 8) satellites were downloaded, which are commonly used for regional classification to determine general LULC classes (Xie et al. 2008). I downloaded two Landsat images: (1) 9/22/2009 (pre-Corridor) and (2) 9/1/2013 (post-Corridor) (Table 6). These images were selected for better land cover detection because they had the lowest percentage of cloud cover and were within the peak vegetation growth season in Beijing.

TABLE 6. General information on downloaded Landsat satellite images.

Image Category	Date	Landsat Satellite	Cloud Cover
Pre-Corridor	9/22/2009	5 TM	0%
Post-Corridor	9/1/2013	8	2% (north of study site)

Image preprocessing of satellite images is important to remove noise and increase interpretability of image data. The preprocessing steps consisted of geometric correction, mosaic (two images for each date to cover study area), image cutting, and band combination. For 2009 and 2013, two images were clipped at two scales defined as: (1) lakes in the urban section (i.e., local scale), and (2) full Corridor spanning the 170 km of the Yongding River in Beijing with a 5 km buffer (i.e., regional scale). I chose to analyze LULC at these two scales to examine how local ecosystem changes may scale to the region, and how adjacent land use changes within a 5 km buffer may impact the new ecosystems. In total I used four images: (1) lakes 2009, (2) lakes 2013 (3) full Corridor 2009, and (4) full Corridor 2013.

Classification is the process of determining LULC classes from raw remotely sensed satellite data. A hybrid unsupervised and supervised approach was performed on the four images to classify the LULC into seven categories: (1) deciduous trees, (2) water, (3) grass, (4) wetland, (5) cropland, (6) urban, and (7) bare soil (Table 7). Unsupervised classification purely relies on spectrally pixel-based statistics to create classes, thus no a priori knowledge of known features is used. Alternatively supervised classification is when the analyst assigns spectral attributes to classes via a training dataset, which the computer software utilizes to assign each pixel in the image dataset to a land cover class it most closely resembles. The hybrid approach first uses unsupervised classification to delineate general spectral classes. Next the spectral classes are differentiated via supervised maximum likelihood classification using known information of the study area (Lillesand et al. 2008). After completing the classification, I used a 7x7 majority filter to smooth the classes to improve LULC interpretations. I quantified the area for each LULC class to determine the difference in total area and percent area between both time periods.

TABLE 7. Land use and land cover classification scheme.

LULC Class	Description
Water	Lakes, ponds, streams, and reservoirs
Deciduous trees	Deciduous broadleaf trees
Grass	Grassland, shrubland, and golf courses
Wetland	Non-forested wetland
Cropland	Agricultural fields
Urban	Residential, commercial, industrial or other built-up land
Bare soil	Non-vegetated soils, mainly sand

Uncertainty of LULC classifications are commonly expressed as accuracy reports via error matrices. Image classification is an important error source where misidentification of LULC classes can impact LULC estimates (Ayanu et al. 2012). Error matrices compare on a class-by-class basis, the relationship between reference data and the corresponding results of the software classification. I used the following two methods: (1) field verification using GPS points matching the randomly generated reference points and (2) high-resolution images on Google Earth and Baidu. The stratified random sample strategy was used to select 100 points per image. A change detection matrix for the time period between 2009 and 2013 was produced using the pixel by pixel method.

The results of the accuracy assessments are reported in Table 8, which include the overall, producer's and user's accuracies, and Kappa statistics. The accuracy of the classifications is satisfactory for both the lakes and full Corridor maps. For the lakes maps, the estimated overall accuracies were 90% (2009) and 92% (2013), and Kappa statistics of 0.83 (2009) and 0.90 (2013). For the 2009 lakes map, the urban class had a producer's accuracy of 57.14% and the bare soil class had a user's accuracy of 61.90%. For the 2013 lakes map, the bare soil class had a user's accuracy of 50%. The overall accuracies of the full Corridor maps were 94% (2009) and 96% (2013), and Kappa statistics of 0.91 (2009) and 0.94 (2013). The LULC class with the greatest potential error was bare soil with a user's accuracy of only 66.7% (2009) and 75% (2013). Overall the urban and bare soil classes had the greatest potential errors because of their spectral similarity.

TABLE 8. Accuracy assessment of classified images for 2009 and 2013.

	Pre-Corridor				Post-Corridor			
	2009 (Lakes)		2009 (Full Corridor)		2013 (Lakes)		2013 (Full Corridor)	
Class	P (%)	U (%)	P (%)	U (%)	P (%)	U (%)	P (%)	U (%)
Water	100.00	100.00	---	---	93.75	96.77	---	---
Deciduous trees	100.00	100.00	100.00	95.56	94.74	100.00	100.00	93.88
Grass	93.55	96.67	92.86	81.25	87.50	84.00	60.00	100.00
Wetland	---	---	---	---	100.00	100.00	100.00	100.00
Cropland	---	---	92.31	97.30	---	---	89.66	100.00
Urban	57.14	100.00	81.25	100.00	88.24	93.75	97.73	100.00
Bare soil	100.00	61.90	100.00	66.67	100.00	50.00	100.00	75.00
Overall accuracy	90.00		94.29		92.00		96.00	
Kappa statistic	0.83		0.91		0.90		0.94	

RESULTS

Four classification maps were generated: (1) 2009 lakes, (2) 2013 lakes, (3) 2009 full Corridor, and (4) 2013 full Corridor (Figs. 15-16), and the individual class area and change statistics are summarized in Table 9. For the lakes from 2009 to 2013 water area increased by 5.33 km^2 (935%), deciduous trees area increased by 3.12 km^2 (322%), and urban area increased by 0.63 km^2 (33%). Grass area decreased by 6.40 km^2 (54%) and bare soil area decreased by 3.28 km^2 (78%). For the full Corridor from 2009 to 2013 urban area increased by 93.2 km^2 (52%), deciduous trees area increased by 52.85 km^2 (9%), and water area increased by 6.53 km^2 (328%). Cropland area decreased by 71.73 km^2 (29%), grass area decreased by 71.27 km^2 (68%), and bare soil area decreased by 9.80 km^2 (17%).

The change detection matrices are presented in Table 10, in the table unchanged classes are located along the major diagonal of the matrices in bold. For the full Corridor, the increase in urban area mainly came from conversion of cropland (32.34 km^2) and grass (30.91 km^2) during the four-year period. Of the 93.02 km^2 of total growth in urban land use, 31% was converted from cropland and 32% from grass. The urban growth was located mainly in the outeruban section of the Yongding River in Fangshan and Daxing districts (Fig. 17). Bare soil area changed to these three classes: urban (29.77 km^2), deciduous trees (9.66 km^2), and cropland (4.70 km^2). For the lakes, the increase in water area mainly came from the conversion of grass (4.07 km^2) and bare soil (1.23 km^2). Of the 5.33 km^2 of total growth in water area, 76% was converted from grass and 23% from bare soil. The increases in water area and wetland area occurred in the urban section in Mentougou, Shijingshan, and Fengtai districts (Fig. 18).

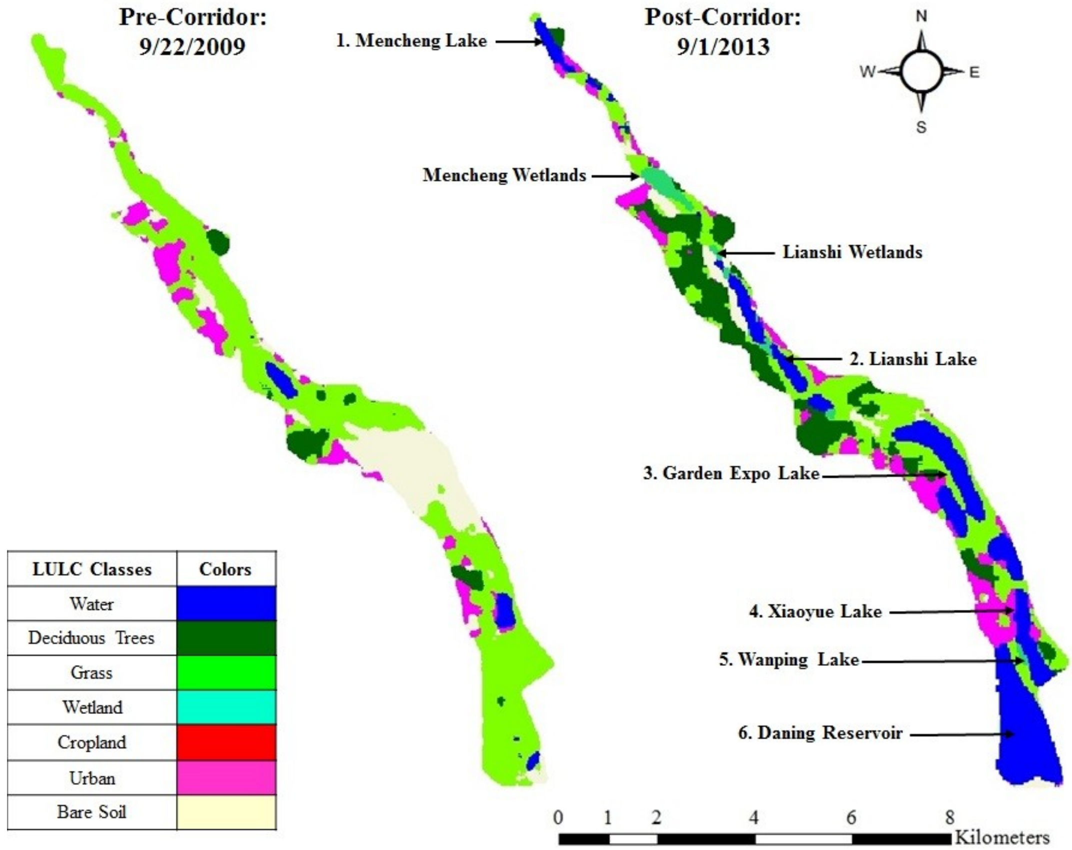


FIG. 15. Land use and land cover maps of the lakes; for post-Corridor the six lakes and wetlands are labeled.

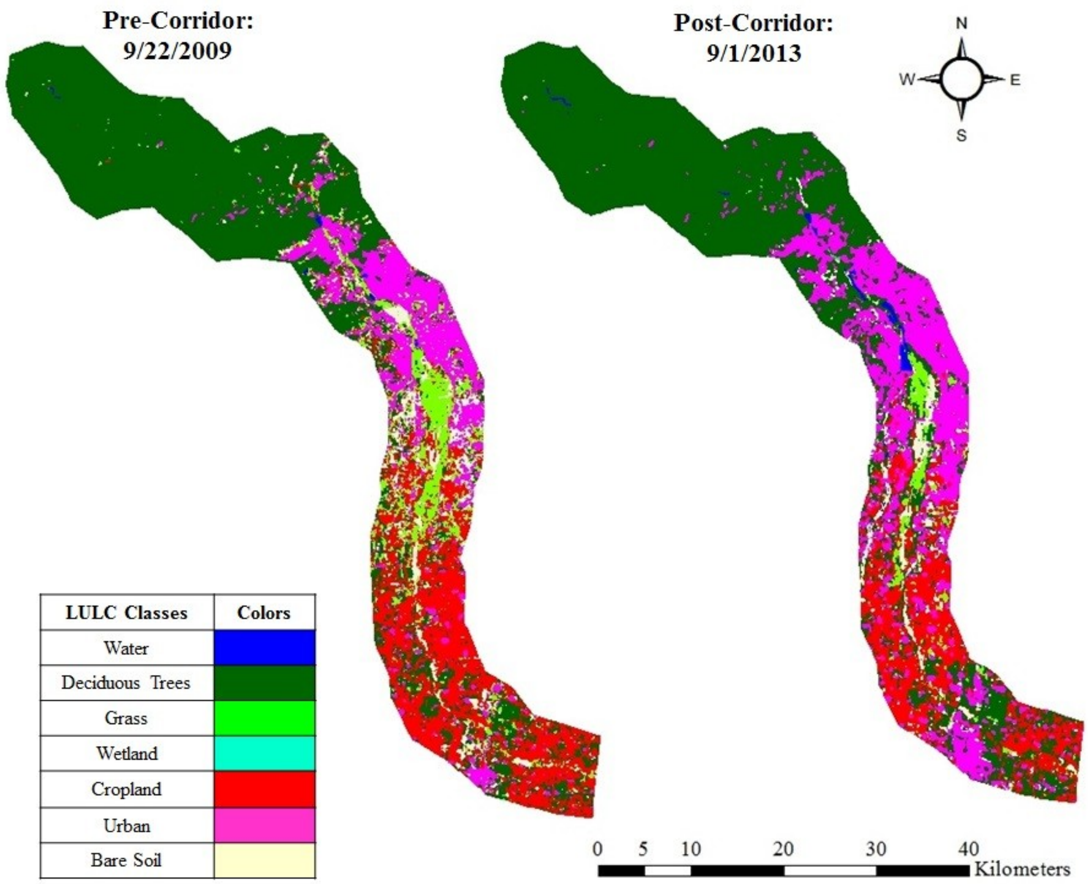


FIG. 16. Land use and land cover maps of the full Corridor + 5km buffer.

TABLE 9. Summary of Landsat classification area statistics for 2009 and 2013.

Lakes						
Class	Area (km^2)		Percent Area (%)		LULC Change	
	2009	2013	2009	2013	Area (km^2)	Percent (%)
Water	0.57	5.90	3.0	30.4	5.33	935.4
Deciduous trees	0.97	4.09	4.9	20.8	3.12	321.6
Grass	11.86	5.46	60.6	27.6	-6.40	-54.0
Wetland	0.00	0.62	0.0	3.2	---	---
Cropland	0.00	0.00	0.0	0.0	---	---
Urban	1.93	2.56	9.9	13.2	0.63	32.6
Bare soil	4.23	0.95	21.6	4.9	-3.28	-77.5

Full Corridor						
Class	Area (km^2)		Percent Area (%)		LULC Change	
	2009	2013	2009	2013	Area (km^2)	Percent (%)
Water	1.99	8.52	0.2	0.7	6.53	327.6
Deciduous trees	593.07	645.92	49.9	54.3	52.85	8.9
Grass	105.52	34.25	8.9	2.9	-71.27	-67.5
Wetland	0.00	0.40	0.0	0.0	---	---
Cropland	251.44	179.71	21.2	15.1	-71.73	-28.5
Urban	178.55	271.57	15.0	22.9	93.02	52.1
Bare soil	57.88	48.08	4.9	4.0	-9.80	-16.9

TABLE 10. Change detection matrices of land use and land cover (km^2).

	Lakes								
	2009	Water	Deciduous	Grass	Wetland	Cropland	Urban	Bare soil	2013 Total
2013	Water	**0.515**	0.026	4.073	---	---	0.046	1.230	5.890
	Deciduous	0.000	**0.829**	2.072	---	---	0.584	0.601	4.086
	Grass	0.028	0.083	**3.521**	**---**	**---**	0.484	1.341	5.457
	Wetland	0.000	0.000	0.617	**---**	---	0.000	0.001	0.618
	Cropland	0.000	0.000	0.000	---	**---**	0.000	0.000	0.000
	Urban	0.027	0.032	0.907	---	---	**0.752**	0.841	2.559
	Bare soil	0.000	0.000	0.671	---	---	0.067	**0.212**	0.950
	2009 Total	0.570	0.970	11.861	---	---	1.933	4.226	19.560
	Full Corridor								
	2009	Water	Deciduous	Grass	Wetland	Cropland	Urban	Bare soil	2013 Total
2013	Water	**1.492**	1.355	3.984	---	0.115	0.343	1.235	8.524
	Deciduous	0.381	**527.727**	31.416	---	56.860	19.883	9.654	645.921
	Grass	0.005	3.947	**18.044**	**---**	9.827	0.806	1.618	34.247
	Wetland	0.004	0.049	0.323	---	0.008	0.002	0.018	0.404
	Cropland	0.001	25.358	10.914	---	**135.230**	3.511	4.699	179.713
	Urban	0.095	27.563	30.911	---	32.342	**150.890**	29.766	271.567
	Bare soil	0.016	7.070	9.930	---	17.059	3.111	**10.894**	48.080
	2009 Total	1.994	593.068	105.522	---	251.441	178.547	57.884	1188.456

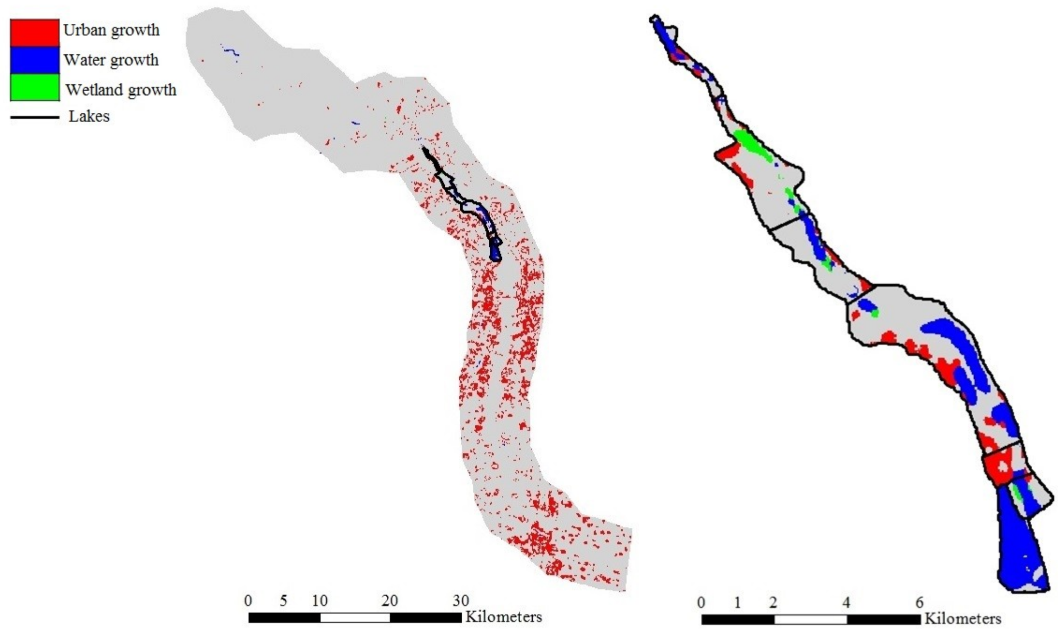


FIG.17. Urban, water, and wetland growth for the full Corridor and lakes from 2009 to 2013.

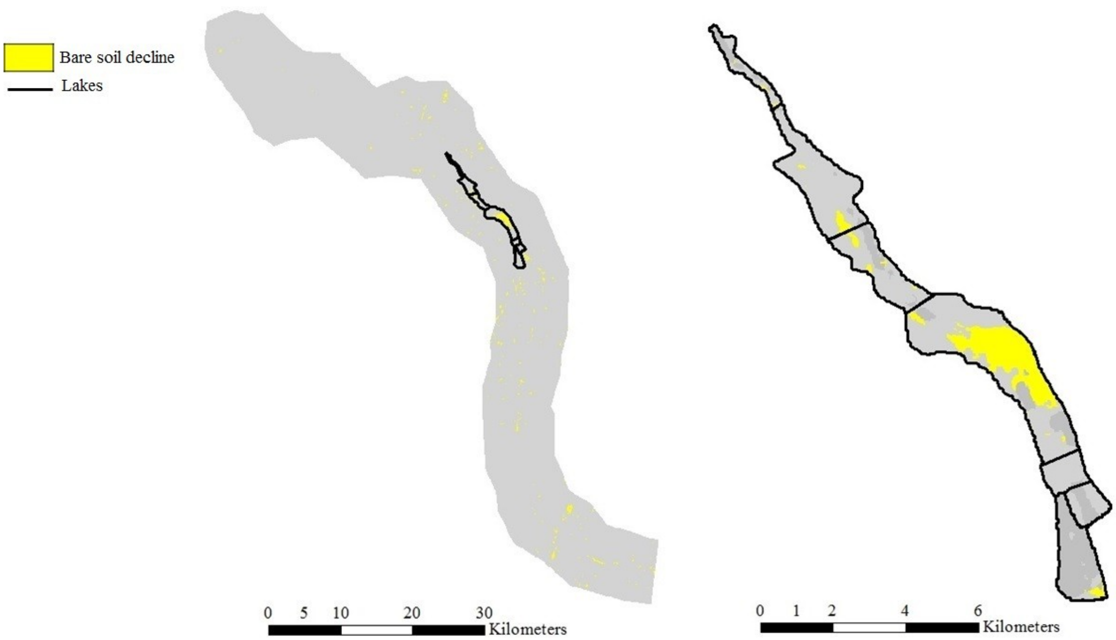


FIG.18. Bare soil decline for the full Corridor and lakes from 2009 to 2013.

DISCUSSION

For the lakes, the largest LULC change was the near 10-fold increase in water area over the four-year period. In 2009 the main LULC classes were grass and bare soil because in the 2000s the government's "greening" program was planting grass to reduce dust from the barren channels in Beijing (China Daily 2005, Fig. 19). From 2009 to 2013, the growth in water area was mainly due to the conversion of grass and bare soil, which was the design plan. In the four-year period, water area increased from 0.57km^2 to 5.90 km^2 because of the new lakes and wetlands. Deciduous trees area increased by 321% while grass area declined by 54% and bare soil area decreased by 78%. Planners believe the combination of increased water area and deciduous trees will bring more dust reductions, cooling benefits, and landscape aesthetic improvements (Figs.19-20).

For the full Corridor urban growth was the largest change between 2009 and 2013. Deciduous trees was the dominant land cover in both 2009 and 2013 because of government afforestation efforts in the mountainous section to reduce sedimentation in the upper watershed (Wang et al. 2009). From 2009 to 2013 urban area increased by 93 km^2 while cropland area declined by 72 km^2 and grass area declined by 71 km^2. Also water area increased by 7 km^2 and bare soil area decreased by 10 km^2. In the four-year period, urban area increased by 52%, mainly from the conversion of cropland and grass areas in the outerurban sections.

FIG.19. Pre-Corridor photos of the urban section of the Yongding Corridor: (A) grass and remnant gravel pits (photo taken in 2010), and (B) trash mounds ranging from 15 to 30 m (photo taken in 2010).

FIG. 20. Post-Corridor photos of the urban section of the Yongding Corridor: (A) landfills and gravel pits were transformed into parks like the Garden Expo's Splendid Valley, (B) central business district, and (C) new apartments and commercial buildings along the banks of the Yongding Corridor (all photos take in 2013).

The water and vegetation additions comprised a large percentage of the total area at the local scale, but small percentage of the total area at the regional scale highlighting the importance of assessing LULC outside engineered boundaries. I plan to present the urban growth and bare soil decline maps from 2009 to 2013 (Figs. 17-18) to management to illustrate the importance of scale. The government wants the Yongding Corridor to provide: water storage to recharge groundwater supplies, climate cooling to reduce heat stress from the urban heat island, water purification to reduce water pollution, dust control to reduce PM_{10} levels, and parks for recreation (BWA 2009). However in 2013 the lakes and wetlands made up less than 1% of total regional area while the urban class was 23% of total regional area. Understanding the possible spatial extent of ecosystem services from the lakes/wetlands can help managers improve future plans on green infrastructure considering the region. Also knowing where and how much regional urbanization is occurring is important. If not managed properly fast urban growth could threaten the functioning of the new ecosystems from increased air and water pollution, impervious surfaces, and recreational use. Managers of the Yongding Corridor have to balance the pressing need to determine feasible and desirable interventions while trying to avoid undertaking what may seem like sensible short-term actions that ultimately result in little benefits or adverse outcomes.

CONCLUSION

The Yongding Corridor is being designed for ecosystem services, however ongoing urbanization could rapidly change functionality if not properly managed. Recent water additions and bare soil reductions are small at the scale of the region because the majority of bare soil area is in the outerurban section not the urban section. Furthermore if not managed properly the rapid urbanization surrounding the Yongding Corridor could threaten the functioning of the lakes because of increased air and water pollution, impervious surfaces, and recreational use. Managers need to develop a monitoring scheme to strategically design the Yongding Corridor considering regional LULC (Sun 2011).

Cities in developing countries are emerging in an era of globalization and high-technology while confronting a range of complex environmental problems. The shifting dynamics of urbanization is creating new opportunities, but pressing urgencies for synergistic solutions. Cities are experimenting with new approaches like the Yongding Corridor, and there is a growing need to study changing urban-environmental relationships worldwide to guide decision-making in this new era of urbanization (Bai 2003, Marcotullio et al. 2005).

The key findings from the LULC analysis in this chapter are:

- From 2009 to 2013, bare soil area declined from 21.6% to 4.9% of total local area, but only went from 4.9% to 4.0% of total regional area.
- In the four-year period the largest regional change was a 52% increase in urban area representing an increase of 93 km^2, mainly from the conversion of cropland and grass.
- The largest local changes were the expansion of water area by 935% and deciduous trees area by 322%, mainly from the conversion of grass and bare soil.
- In 2013 the water class made up less than 1% of total regional area while the urban class was 23% of total regional area.

CHAPTER 5

WATER STORAGE AND LOCAL CLIMATE REGULATION

ABSTRACT

Beijing officials are creating the Yongding River Ecological Corridor to enhance water storage and local climate regulation to improve water availability and reduce urban heat island effects. Evapotranspiration (ET) links these services contributing to both water loss and cooling of warm microclimates. In this chapter, I evaluate these two services by estimating how the new ecosystems on the Yongding Corridor are altering ET, and ET's contribution to final services of concern to management. I used the Variable Infiltration Capacity (VIC) model to compare ET rates between the pre- and post-Corridor periods. I estimated that the new ecosystems increased local ET by 0.01 mm hr^{-1} (105 mm yr^{-1}), which was smaller than the estimated increase in ET of 0.04 mm hr^{-1} (344 mm yr^{-1}) from climate variation between the pre- and post-Corridor periods. This result suggests the new ecosystems increased ET on the Yongding Corridor, however the climate differences between both periods led to a larger increase in ET than the land cover changes.

I used the VIC model to estimate water storage shortfalls by taking the difference between modeled results and management targets. The model results suggest there were shortfalls for all three water storage targets: (1) lower mean lake water volumes, (2) lower mean surface water area, and (3) higher total annual water loss (i.e., higher ET values than engineers expected). I created a water storage production function relating the surface water area: lake volume ratio to water loss. I found on average a 1% increase in

surface water area: lake volume would likely result in an estimated 3% increase in water loss. This result suggests an 18% reduction in total surface water area: lake volume would likely be needed to reach the desired water storage to prevent lake drying on the Yongding Corridor.

Local climate regulation shortfalls were determined as the number of sultry events (heat index (HI) >26): Wanping Lake (98 events)> Xiaoyue Lake (72 events)>Mencheng Lake (69 events)>Lianshi Lake (59 events)>Wetlands (51 events). I created local climate regulation production functions relating summer daytime and nighttime ET to air temperature and HI. It was estimated an hourly increase of 0.01 mm hr^{-1} of summer daytime ET would likely result in an air temperature decrease of 0.01-0.08 °C, and a HI decrease of 0.01-0.06. Also it was estimated an hourly increase of 0.01 mm hr^{-1} of summer nighttime ET would likely result in a decrease of air temperature by 0.05-0.16 °C, and a decrease of HI by 0.01-0.05. These results suggest the lakes/wetlands are providing a cooling effect, however a 100-fold increase in the ET rate would likely be needed to have any impact on reducing the number of sultry events in the summer. Overall the model results suggest the new ecosystems increased ET on the Yongding Corridor, but the current design of the lakes/wetlands is likely resulting in poor water efficiency, causing water storage shortfalls while having a small estimated cooling effect on reducing human comfort shortfalls.

INTRODUCTION

Two important ecosystem services of concern to cities are water storage and local climate regulation, which are linked by evapotranspiration (ET). Water storage is regulated by the hydrological cycle via the regulation of the water balance (TEEB 2010). Local climate regulation is the influence of ecosystems on microclimates by affecting temperature, humidity, and precipitation. The microclimate people experience is the net result of the energy balance, which scientists evaluate by estimating: latent heat, ground heat, and sensible heat. Latent heat is the heat required in the vaporization of water otherwise known as ET, which people directly experience as humidity. Ground heat is heat exchange in and out of the soil. Sensible heat is the transfer of energy from the surface to the atmosphere through conduction and convection, which people directly experience as temperature. ET can increase latent heat and reduce sensible heat at the surface, which can provide cooling benefits to improve human comfort under high air temperatures. ET links water and climate regulation as an ecosystem function that contributes to both water loss (undesired effect in this system) and the cooling of microclimates (desired effect in this system).

Land use and land cover (LULC) changes associated with urbanization can alter water and energy balances in turn changing water storage and local climate regulation. High water demands of cities and the elimination of channel networks for development commonly lead to losses in freshwater ecosystems in urban areas (Steele et al. 2014). Impervious surfaces create higher peak flows and increased surface runoff in cities. An impervious surface cover of 75-100% can result in more than a five-fold increase in runoff compared to forested catchments (Paul and Meyer 2001). Increased runoff and low infiltration rates of urban surfaces impact aquifers by reducing groundwater recharge rates. Cities are often characterized with fewer surface water bodies and lower groundwater tables, yet increased flood risks compared to non-urban areas.

Surface water and vegetation reductions and impervious surfaces in cities alter microclimates, causing urban areas to experience higher air temperatures relative to nonurban areas - known as the urban heat island effect (UHI) (Unger 2004). Urban materials trap heat during the day resulting in increased heat storage, which is slowly released in the evening causing higher nighttime temperatures relative to non-urban areas. Losses in vegetation and surface water alter ET rates in cities, which impacts the dissipation of heat and the amount of water vapor in the air. The annual mean air temperature of a city with one million or more people can be 1 to 3 °C warmer than its surroundings, and on a clear, calm night this temperature difference can be as much as 12 °C (US EPA 2008).

The UHI affects human health by contributing to heat-related illnesses, which governments monitor using heat indexes. A public health concern is that the UHI will increase the intensity and frequency of heat waves, which have been linked to heat stroke, heat exhaustion, heat cramps, and increased mortality (Patz et al. 2005, Kovats and Hajat 2008). Government weather agencies developed heat indexes to predict climate impacts on human comfort, such as the U.S. National Oceanic and Atmospheric Administration’s National Weather Service Heat Index and the Beijing Meteorological Bureau’s Heat Index. Heat indexes define threshold levels of heat stress sensations (e.g., fatigue, heat exhaustion) that humans are likely to experience under various air temperature and humidity conditions. High air temperature and relative humidity can cause heat gain to exceed a level the body can remove because high humidity slows evaporation (i.e., sweating). This can then lead to a rise in the temperature of the body's inner core, which can cause heat-related illnesses.

In Beijing, government officials are working to address the hydrologic and climate changes associated with urbanization. First a major concern is increasing local water storage because the majority of Beijing's rivers are dry, and current groundwater supplies are over-drafted. Excessive pumping and slow recharge rates due to impervious surfaces have dramatically reduced groundwater levels. In the late 1980s access to the groundwater table was at a mean depth of 5 m and in 2008 it was 23 m. The depletion of aquifers is also a safety hazard due to land subsidence, which has destroyed factories, buildings, and underground pipelines. Second is increased flood risk from large precipitation events during the summer monsoons. In the July 21, 2012 flash flood, Beijing received 170 mm a month's worth of rainfall in a day, marking the heaviest rainfall event in 60 years. The channel networks and stormwater systems were unable to handle the water load resulting in massive flooding, costing the city an estimated $1.6 billion U.S. dollars in damages and affecting more than 1.6 million people. Third is human discomfort and heat-related illnesses from high air temperatures during the summer because of the UHI. Since the 1980s Beijing has experienced an increase in the number of summer sultry events because of increased air temperatures (Wang et al. 2010). Liu et al. (2008) compared urban and rural areas in Beijing, and found a mean annual temperature and humidity difference of 1.7 °C and -6.3%, respectively (Liu et al. 2009).

The Beijing government is constructing new lake and wetland ecosystems known as the Yongding River Ecological Corridor to help regulate the water cycle and microclimates on the Yongding River. The Beijing Water Authority (BWA) is adding 130 million m^3 of water to the once parched Yongding River landscape. The water sources are reclaimed water from wastewater treatment plants (128 million m^3), upstream water from Guanting Reservoir (10-30 million m^3), and local runoff (2 million m^3) (BWA 2009). Managers want to increase water storage for groundwater recharge and flood control. Managers also want to enhance human comfort by reducing UHI effects. Several studies have shown that air temperatures can decrease with increased vegetation because of increased ET and shading (Huang et al. 2009, Gober et al. 2010).

However the challenge is managing the hydrology of the lakes/wetlands to prevent water losses to maintain lake volumes and local cooling effects overtime (Fig. 21). From 2012-2013, the lakes/wetlands experienced drying because of inflow problems creating shallower lakes (Gao 2012) likely increasing ET, which impacted their water regulation capacity. Furthermore managers want to improve the climate regulation capacity of the ecosystems because local cooling is a concern among visitors. However managers are currently unaware of the possible magnitude of summer cooling provided by the new ecosystems. The new ecosystems will likely increase ET along the Yongding River, however its impact on human comfort is unknown. Simply increasing water and vegetation on a landscape without estimating ET can result in water losses impairing water storage while providing minimal improvements in human comfort. Evaporation from the lakes is influenced by the surface water area: lake volume ratio; shallow lakes evaporate more quickly than deeper lakes since they have less heat storage (i.e., less differential between air temperature and water temperature). The challenge is managing the lakes and wetlands to get efficient water storage to minimize water losses while obtaining some local cooling benefits. Management wants guidance on balancing the tradeoff between evaporative cooling and water loss. An important first step is estimating water storage and local climate regulation via ET.

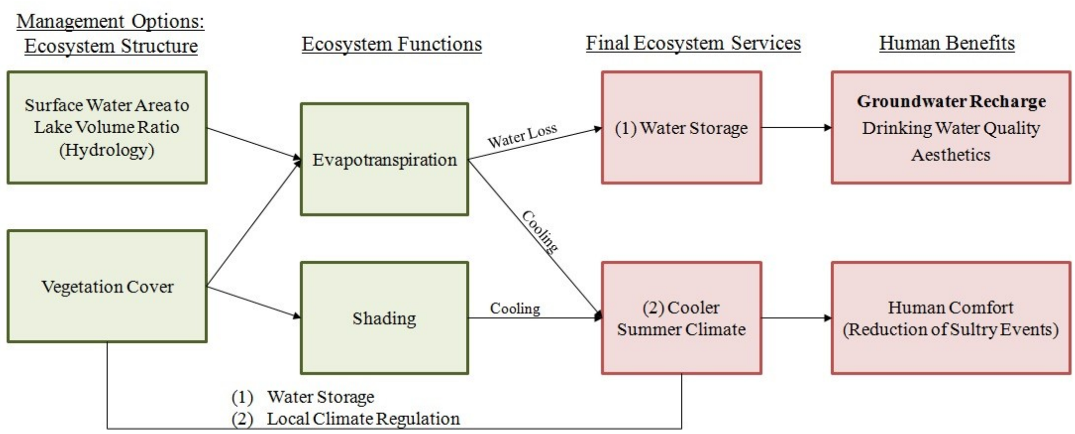


FIG. 21. Conceptual diagram linking management options as changes in ecosystem structure to ecosystem functions to final ecosystem services and human benefits. Human benefit in bold is the direct benefit of concern to management regarding water storage, however water storage underpins other ecosystem services explored in other chapters.

In this chapter I estimate water storage and local climate regulation from the new ecosystems on the Yongding River. First I selected final services using BWA endpoints for water storage, and the Beijing Meteorological Bureau endpoint for sultry events. I determined service shortfalls using modeling results and monitoring data. Second I modeled ET and sensible heat flux using the Variable Infiltration Capacity model (VIC). Third I created ecological production functions using ordinary least squares (OLS) regression models to link ecosystem characteristic metrics and final service indicators. I found it was useful to combine a process-based model with production functions to understand how possible changes in ecological mechanisms could cause final service outcomes. Chapter objectives are to estimate: (1) ET from the new ecosystems on the Yongding River, (2) service shortfalls, (3) marginal effects of surface water area: lake volume ratio on ET; marginal effects of ET on summer heat index values, and (4) the spatial distribution of these services.

METHODS

Below I provide a brief outline of how I present my methods and results in this chapter. My measurement approach consists of seven general steps shown in Fig. 22. Unlike other chapters, I first present the results for the ecosystem characteristic (i.e., ET) prior to presenting the shortfalls because both water storage and local climate regulation are regulated by ET. To reduce confusion I present the ET results then the shortfalls and marginal effects for each ecosystem service separately. First I estimated changes in ET from the new lakes and wetlands from changes in climate between the pre- and post-Corridor periods using the VIC model. Second I measured the final service indicators to determine shortfalls for each service. Third I estimated the marginal effects of the ecosystem characteristic metrics on final service indicators by creating ecological production functions using OLS regression models. Fourth I created ecosystem service maps to provide spatially explicit results using ArcGIS.

In summary I evaluated water storage and local climate regulation by: (1) estimating the contribution of the lakes/wetlands to changes in ET, (2) the spatial distribution of water storage and local climate regulation, and (3) the marginal effect of lake dimensions on water loss, and the marginal effect of ET on heat index values (Table 11). In Table 12, I outline the data collected and methods used to assess water storage and local climate regulation. The methodological steps are explained in detail in the following subsections.

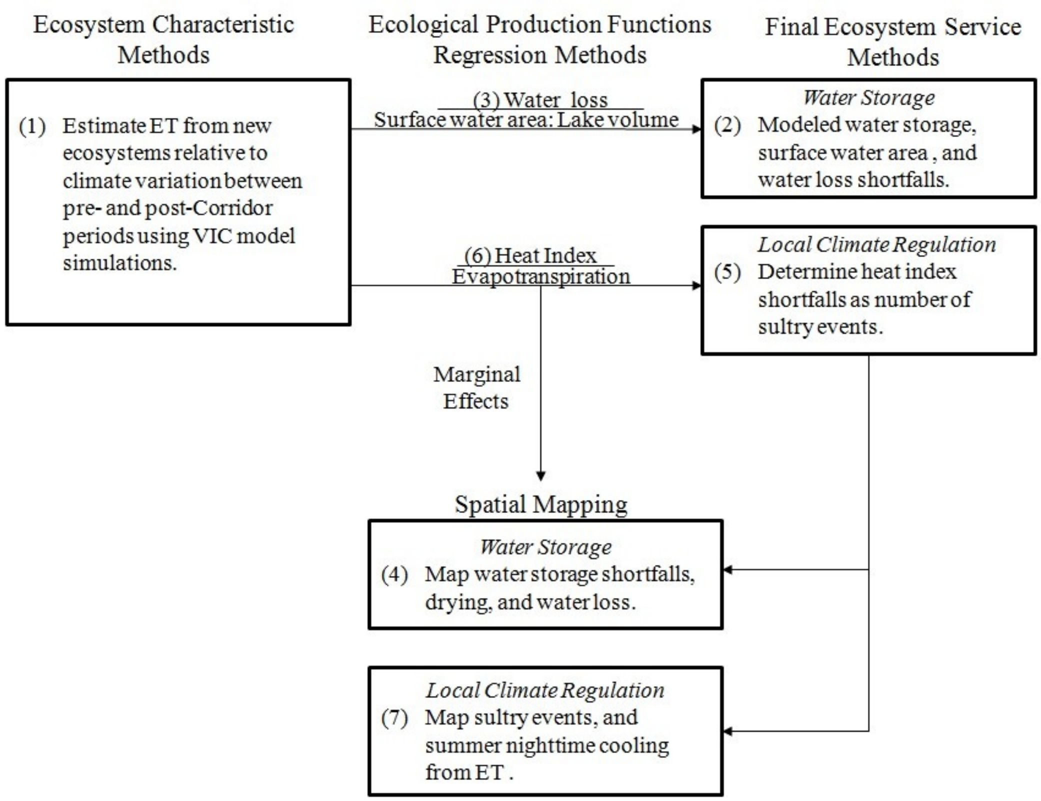


FIG. 22. Methodological steps to estimate water storage and local climate regulation from the Yongding River Ecological Corridor.

TABLE 11. Description of the main measurement steps to evaluate water storage and local climate regulation from the Yongding River Ecological Corridor.

Ecosystem Service Measurement Steps	Water Storage and Local Climate Regulation
Relating Management Options to Ecosystem function	Determine ET rates for pre- and post-Corridor periods. Determine changes in ET rates from the new ecosystems relative to changes in climate between both periods.
Relating Final Service to Potential Beneficiaries	Determine the distribution of water storage along Yongding Corridor, and local climate regulation at varying distances from the Yongding River in the summer.
Relating Ecosystem function to Final service	Determine the marginal effect of lake dimensions on water loss, and the marginal effect of ET on heat index values.

TABLE 12. Summary of data used to measure water storage and local climate regulation.

Data to Measure Water Storage and Local Climate Regulation							
Category	Water storage indicators	Local climate regulation indicators	Data to parameterize VIC model				Modeled ecosystem characteristics
Data type	Lake volumes (million m^3) Water area (ha) ET (million m^3)	Air temperature (°C) Relative humidity (%) Heat index values	Land use and land cover data	Climate data: precipitation, wind speed, relative humidity, daily max and min air temperature	Lake and wetlands: engineering data	Vegetation and soil data: albedo, roughness, displacement etc.	Evapotranspiration Sensible Heat Flux
Data source	VIC model simulations	Mentougou Meteorological Bureau (daily data) Hobo data loggers (hourly data)	Landsat remote sensing images	Mentougou Meteorological Bureau and Hobo data loggers	Beijing Water Authority	VIC global datasets and literature values	VIC model simulations
Purpose	Benefit is groundwater recharge, and water landscapes.	Benefit is local cooling effects during summer.	Land cover change to evapotranspiration.				

Study area

The study area is the Yongding River in Beijing known as the Yongding River Ecological Corridor. The spatial scale of the analysis is: (1) *regional* defined as the full Yongding Corridor 170 km long and 1,188 km^2 and (2) *local* defined as the seven lakes and wetlands in the urban section 20 km long 19.5 km^2. The BWA wants the local ecosystem changes to improve regional ecosystem services, thus the region represents the desired scale of beneficiaries. However management actions are implemented at individual lakes/wetlands at the district-level. Hence the BWA wants information on each lake/wetlands matching the districts, and a general understanding on how the lakes/wetlands scale to the region. The seven lakes/wetlands (from north to south) are: (1) Mencheng Lake (Mentougou district), (2) Wetlands (Mentougou and Shijingshan districts), (3) Lianshi Lake (Mentougou and Shijingshan districts), (3) Garden Expo Lake (Shijingshan and Fengtai districts), (4) Xiaoyue Lake (Fengtai district), (5) Wanping Lake (Fengtai district), and (6) Daning Reservoir (Fengtai district) (Fig. 23).

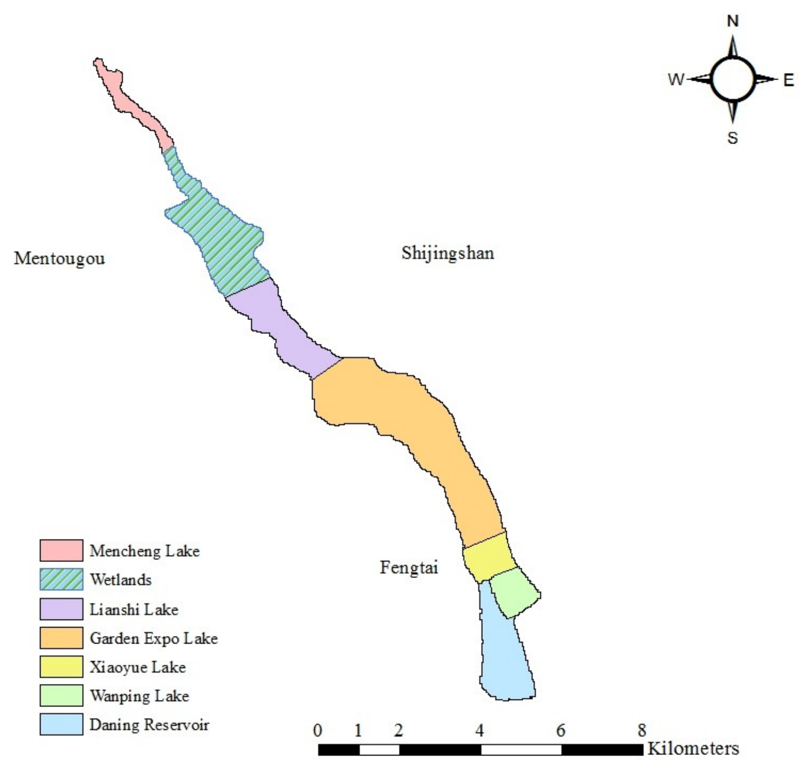


FIG. 23. Map of the seven lakes and wetlands and their respective districts.

The temporal scale of the analysis is: (1) pre-Corridor (June 1, 2009 to June 30, 2010) and (2) post-Corridor (June 1, 2012 to June 30, 2013). I selected the pre- and post-Corridor periods to estimate how the LULC changes from the new ecosystems impact ET rates by conducting the analysis at the local and regional scales. The temporal and spatial scales of the analysis are summarized in Table 13.

TABLE 13. Description of the temporal and spatial scales of the analysis.

Temporal and Spatial Scales			
	Temporal	Spatial	
Category	Before and After Yongding Corridor	New ecosystems	Beneficiaries
Scale	Pre-Corridor: June 2009 to June 2010 Post-Corridor: June 2012 to June 2013	Local: lakes/wetlands in urban section. Regional: full Corridor.	Climate data from 3 government stations and 5 Hobo data loggers.
Purpose	Estimate ET from the new ecosystems relative to climate variation between pre- and post-Corridor periods.	Local vs. regional contributions to changes in ET.	Distribution of water storage (i.e., lake drying) on the Yongding Corridor, and local climate regulation at varying distances from the Yongding Corridor in the summer.

Beijing has a seasonal temperate and semiarid continental monsoonal climate characterized by four distinct seasons (winter, spring, summer, and fall). The average annual precipitation spans 550 to 660 mm in which roughly 85% of the rainfall occurs from June to September. Spring is dry and windy, summer is hot and humid, and winter is cold; the annual average daily temperature is 10-12 °C.

Final services and final service indicators

For water storage, I selected the final services using BWA management targets. BWA planning documents articulated quantitative endpoints for lake volumes, total surface water area, and total annual ET (Table 14). The final service indicators were estimated using VIC model results on lake volumes, surface water area, and ET (Table 15). I used a water loss indicator defined as ET/lake volume.

TABLE 14. Final services for water storage using management endpoints.

Water Storage Final Services				
Source	Lakes/Wetlands	Lake volume (million m^3)	Surface water area (ha)	ET (million m^3)
Beijing Water Authority	Mencheng Lake and Wetlands	0.43	---	---
	Lianshi Lake	0.47	---	---
	Garden Expo Lake, Xiaoyue Lake, and Wanping Lake	3.16	---	---
	Daning Reservoir	3	---	---
	Total Lakes	12.05	651	200.48

TABLE 15. Water storage final service indicators and data collection method.

Water Storage Final Service Indicators	
Indicators	Data Collection Method
Lake Volume (million m^3) Surface Water area (ha) ET (million m^3)	VIC model calibrated using field observations of seasonal lake drying.

For local climate regulation, the BWA described its target using a qualitative statement as the reduction of UHI effects by decreasing summer nighttime air temperatures. I used the Beijing Meteorological Bureau Heat Index (HI) equation to pinpoint endpoints (Wang et al. 2010):

$$HI = T - 0.55(1 - RH)(T - 14.5) \quad (1)$$

where *HI* is the heat index value, *T* is air temperature (°C), and *RH* is relative humidity (fraction). The Beijing Meteorological Bureau uses equation (1) to predict human comfort in response to outdoor air temperature and relative humidity on hot summer days (Table 16). I discussed the legitimacy of Beijing's HI with engineers and policy analysts at the Beijing Water Science and Technology Institute (BWSTI). They agreed on my selection of Beijing's HI to link the BWA's qualitative goal of reducing summer nighttime air temperatures to government metrics on human comfort.

TABLE 16. Local climate regulation final services using the Beijing Meteorological Bureau's heat index endpoints.

Local Climate Regulation Final Services		
Source	HI Endpoints	Description
Beijing Meteorological Bureau Heat Index	27-28	Sultry
	29-30	Heavy sultry
	>30	Extreme sultry

I collected data on the final service indicators using air temperature and relative humidity Hobo data loggers deployed at each lake/wetlands, and datasets from government monitoring stations (Table 17). Hobo U23 Pro V2 data loggers were deployed at five lakes/wetlands: (1) Mencheng Lake, (2) Wetlands, (3) Lianshi Lake, (4) Xiaoyue Lake, and (5) Wanping Lake (Fig. 24). No data loggers were deployed at the Garden Expo Lake and Daning Reservoir because of prohibited access. Hobo data loggers were placed inside radiation shields at a height of 2 m above the ground in shoreline trees adjacent to the lakes/wetlands. Data loggers were set to record air temperature and relative humidity at 30-min intervals for 8 months from November 9, 2012 to June 30, 2013. The accuracy of the instrument, as claimed by the manufacturer is Temp: ± 0.2 °C at 0-50 °C with resolution of 0.02 °C; RH: ± 2.5% from 10-90% with resolution of 0.03%. Data loggers were calibrated before installation, and data were downloaded monthly. I compared summer (i.e., June 2013) data logger data to government monitoring stations 1-5km from the lakes/wetlands. The objective was to determine: (1) whether there was a difference in summer nighttime air temperature of the lakes/wetlands to more urbanized locations, and (2) the spatial distribution of the local climate regulation service.

TABLE 17. Local climate regulation final service indicators and data collection methods.

Local Climate Regulation	Final Service Indicators
Indicators	Data Collection Methods
Hourly air temperature (°C) Hourly relative humidity (%)	Hobo data loggers and government monitoring stations.

Final service indicators were used to determine shortfalls as the difference between modeled/measured results and final service levels. For water storage, the shortfalls occurred when water storage and surface water area were below the respective final service levels, and annual ET was greater than the respective final service level. For local climate regulation, a sultry event is defined as a HI value above 26, thus a shortfall occurred when HI values were greater than 26. Unlike local climate regulation, water storage shortfalls were not based on empirical data. Engineering information, field observations, and LULC data were used to calibrate the VIC model to estimate water storage shortfalls from 2012-2013.

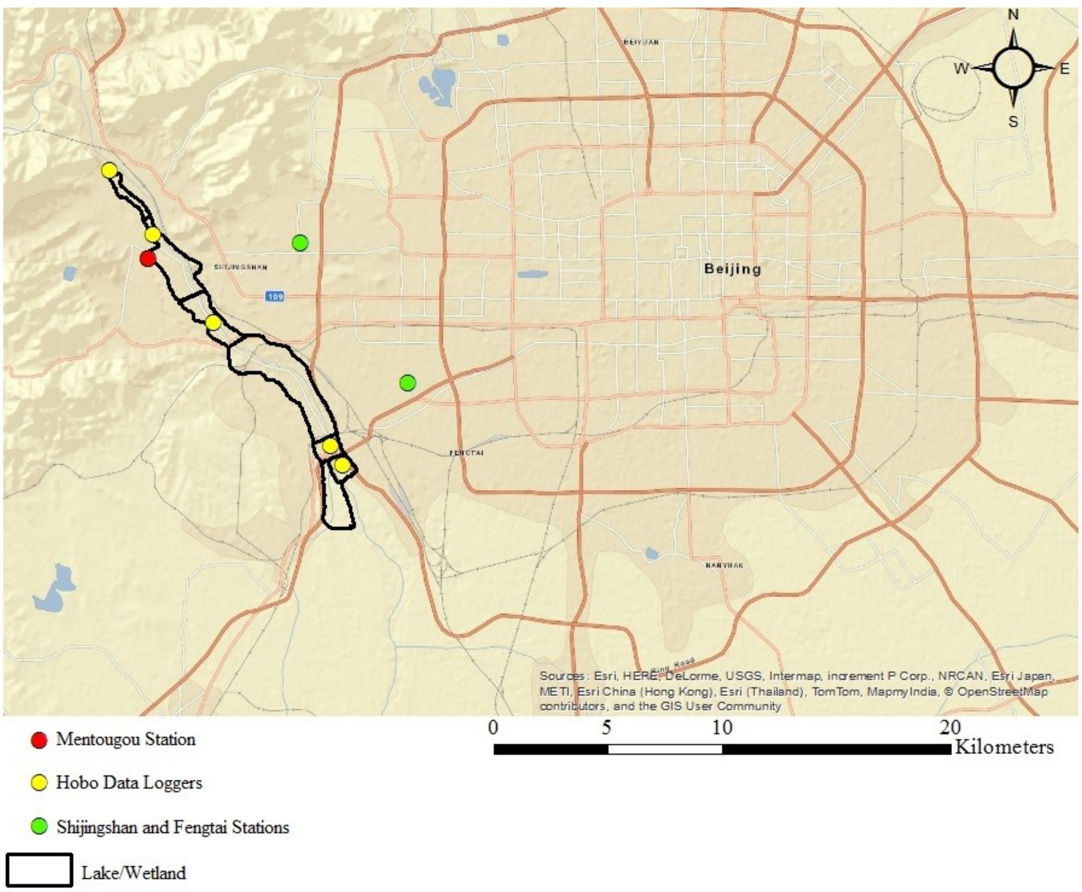


FIG. 24. Map of Hobo data loggers, Mentougou meteorological station, and Shijingshan and Fengtai meteorological stations. Note distance between new ecosystems and urban core of Beijing at the far right. This region is suburban, but it is becoming urbanized.

Variable Infiltration Capacity model

The VIC model version 4.1.2 with its lake/wetland algorithm was used to simulate water volume, surface water area, ET, and sensible heat flux at local and regional scales (Liang et al 1994, Bowling and Lettenmaier 2010, Mishra et al. 2010, Gao et al. 2011). The Yongding Corridor lakes and wetlands are engineered ecosystems where the main water loss factor is ET. The Yongding Corridor is designed for a controlled inflow and outflow rate, and near-zero infiltration due to an impervious liner. Surface runoff into lakes/wetlands is controlled because channels divert stormwater to retention basins, however under large flood events there will likely be surface runoff into the lakes/wetlands. Inflow and outflow are controlled by a complex network of underground pipes driven by pumping stations that link the lakes/wetlands. However there are minimal direct surface water connections between the six lakes because of dams and man-made waterfalls. Given the engineered conditions my main model assumptions were: (1) the environmental water input is precipitation, (2) inflow and outflow rates are controlled using engineered parameters, (3) no infiltration, (4) no surface water or subsurface connections between the lakes and wetlands (i.e., no use of the routing sub-model), and (5) the water loss factor is ET.

VIC models the energy and water balances of the land surface as uniform grid cells (i.e., topography, soil type) where heterogeneity is represented as the fraction of different LULC types. The VIC model does not create spatially explicit results, VIC simply averages energy and hydrological fluxes across LULC types to generate values for each grid cell of a given size and location selected by the user (see Appendix B). For the regional scale, I used one grid cell to represent the full Corridor. For the local scale, I modeled seven grid cells defining the lake/wetlands dimensions of: (1) Mencheng Lake, (2) Wetlands, (3) Lianshi Lake, (4) Garden Expo Lake, (5) Xiaoyue Lake, (6) Wanping Lake, and (7) Daning Reservoir (Fig. 25). The individual LULC classes (e.g., deciduous broad leaf trees, grass, cropland, etc.) in each grid cell are represented as tiles covering a particular fraction of the total grid cell area. I used the LULC data from Chapter 4 to parameterize the respective grid cells. The Yongding Corridor represents a suburban/agricultural environment that is urbanizing, thus the VIC model was selected instead of an urban climate model.

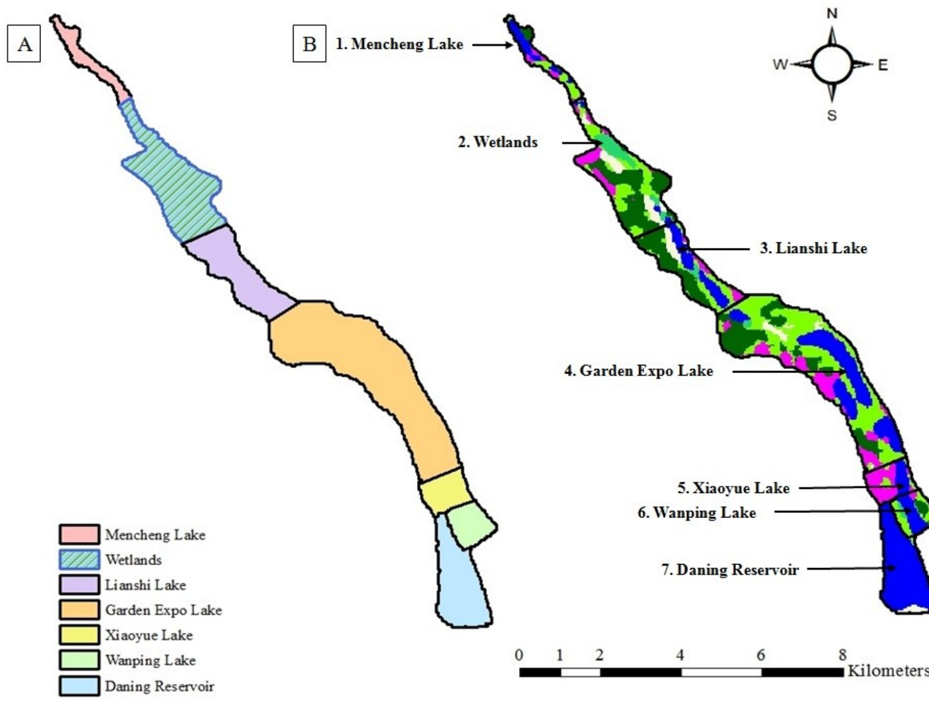


FIG.25. Map of (A) the seven grid cells representing (B) the seven lakes and wetlands.

The VIC model has a lake and wetland algorithm designed to represent the effects of isolated lakes and wetlands using a lake/wetland land cover class. The lake and wetland algorithm considers a depression where surface water accumulates as the lake and the surrounding land as the wetland. The analyst defines the vegetation parameters characterizing the wetland around the lake. The lake and wetland exchange water as follows: all drainage from the wetland discharges directly to the lake then the lake expands in turn reducing the amount of wetland area. Simply put when the lake is at its maximum extent there are no wetlands present and as the lake shrinks the wetland area expands. In all other ways the lake/wetland class is simulated like other land cover classes.

The lake model parameters are: (1) n_L (number of lake layers), (2) d_{min} (lake depth below which channel outflow is 0), (3) w_{frac} (width of lake outlet, as a fraction of the lake perimeter), (4) d_0 (initial lake depth), (5) r_{pct} (fraction of runoff from the grid cell's non-wetland vegetation tiles that enters the lake), and (6) bathymetric profile (lake depth and area at each layer) (Table 18). More details of the algorithm are provided in Bowling and Lettenmaier (2010). For the Yongding Corridor, all the lakes and wetlands were constructed in concrete channels, thus a bathymetry of a trapezoid channel was used. The basin depth: basin area values were derived from engineering and remote sensing data (see Appendix B). Also for the lake/wetland grid cells I used an inflow forcing parameter based on engineered inflow rates (Table 18), which were altered during calibration to simulate observed seasonal drying.

Within the VIC model, soil parameters fall into two categories: those that are fixed and those subject to calibration. Fixed soil parameters were taken from the global VIC input parameter dataset calculated at a spatial resolution of 0.5° (Nijssen et al. 2001), which include all physical properties that can be derived from soil texture (e.g., porosity and hydraulic conductivity). The parameters subject to calibration include thicknesses of the model's three hydrologic soil layers, the shape of the moisture infiltration capacity distribution (b_{infilt}), and the shape of the relationship between bottom layer moisture storage and baseflow (D_s, W_s, and D_{smax}) (Liang et al. 1994). For pre-Corridor, I used the global input dataset values, but for post-Corridor I calibrated the D_{smax} to represent outflow in the engineered system (Table 18).

TABLE 18. Lake and wetland parameters, engineering, and LULC data for calibration.

Grid Cell	Description	Lake/Wetland Parameters			Engineered Parameters			LULC
		d_0 (m)	r_{pct} (fraction)	Max area (km^2)	Inflow (m^3d^{-1})	Outflow (m^3hr^{-1})	Capacity (million m^3)	Area (km^2)
Full Corridor	Lakes and wetlands in urban section modeled together.	2.0	0.0	24.48	361,644	365,520	10.40	5.93
Mencheng Lake	Lake with shoreline wetlands and trees.	1.5	1.0	0.61	40,000	55,000	0.60	0.34
Wetlands	Wetland islands with streams; shallowest portion.	1.0	1.0	1.52	40,000	40,000	0.62	0.09
Lianshi Lake	Expansive lake.	1.8	1.0	1.25	190,000	150,000	1.84	0.61
Garden Expo Lake	Expansive lake.	2.0	1.0	3.28	80,000	60,000	3.50	1.89
Xiaoyue Lake	Lake with shoreline wetlands and trees.	2.0	1.0	0.29	150,000	150,000	0.32	0.28
Wanping Lake	Lake with shoreline wetlands and trees.	2.0	1.0	0.67	150,000	150,000	0.49	0.38
Daning Reservoir	Expansive lake.	4.0	1.0	2.53	150,000	150,000	3.00	2.34

$n_L = 10$; $d_{min} = 0$; $w_{frac} = 0$ for all lake/wetland simulations.

The main vegetation parameters that influence ET are: (1) r_{arc} (architectural resistance of vegetation), (2) r_{min} (minimum stomatal resistance of vegetation type), (3) *LAI* (leaf-area index of vegetation type per month), (4) *albedo* (shortwave albedo for vegetation type per month), (5) *roughness* (vegetation roughness length per month), and (6) *displacement* (vegetation displacement height per month) (Table 19). I used the global VIC input parameter dataset (Nijssen et al. 2001), which was used for these LULC classes: (1) deciduous broad-leaf trees, (2) grass, and (3) cropland (Table 19). VIC datasets currently do not have an urban and wetland class, thus these classes were parameterized using literature values (see Appendix B).

TABLE 19. The key vegetation parameters for the LULC classes.

		Season			
Vegetation Class	Variable	Winter	Spring	Summer	Fall
Deciduous broad-leaf*	LAI	1.52-2.0	1.68-4.90	4.60-5.00	2.16-3.44
	Albedo (fraction)	0.18	0.18	0.18	0.18
	Roughness (m)	1.23	1.23	1.23	1.23
	Displacement (m)	6.70	6.70	6.70	6.70
Grass*	LAI	2.00-2.25	2.95-3.85	3.20-3.55	2.60-3.30
	Albedo (fraction)	0.20	0.20	0.20	0.20
	Roughness (m)	0.07	0.07	0.07	0.07
	Displacement (m)	0.40	0.40	0.40	0.40
Wetland (*Phragmites*)†	LAI	2.00	2.25	5.00	2.25-5.00
	Albedo (fraction)	0.20	0.20	0.20	0.20
	Roughness (m)	0.31	0.31	0.31	0.31
	Displacement (m)	1.68	1.68	1.68	1.68
Cropland (corn)*	LAI	0.02-0.05	0.05-1.50	3.00-5.00	0.05-2.50
	Albedo (fraction)	0.10	0.10-0.20	0.20	0.10-0.20
	Roughness (m)	0.01	0.006-0.01	0.06-0.18	0.006-0.21
	Displacement (m)	0.03	0.03-0.07	0.34-1.01	0.03-1.17
Urban‡	LAI	0.00	0.00	0.00	0.00
	Albedo (fraction)	0.14	0.12	0.10	0.12
	Roughness (m)	0.63	0.63	0.63	0.63
	Displacement (m)	5.82	5.82	5.82	5.82

Winter: December, January, and February; Spring: March, April, and May; Summer: June, July, and August; Fall: September, October, and November.
* VIC global input dataset Nijssen et al. 2010
† Zhou and Zhou 2009, Liang et al. 2011, Irmak et al. 2013
‡ Oke 1988, Miao et al. 2012

Meteorological data from the Mentougou station were obtained for the pre- and post-Corridor period (Fig. 24), which are daily: (1) maximum air temperature, (2) minimum air temperature, (3) precipitation, and (4) wind speed. The VIC model uses MTCLIM algorithms (Kimball et al. 1997, Thornton and Running 1999) to convert daily maximum and minimum air temperatures to humidity and incoming shortwave radiation. VIC then uses the Tennessee Valley Authority algorithm (Bras 1990) to deduce incoming long wave radiation from humidity and temperature. VIC also computes atmospheric pressure and density from grid cell elevation and global mean pressure lapse rate. Finally VIC converts these daily meteorological values into hourly values. In addition to these downscaled climate values hourly air temperature and relative humidity from the Hobo data loggers from November 9, 2012 to June 30, 2013 were used to refine ET estimates at each lake/wetland. Lianshi Lake data was applied to the Garden Expo Lake and Wanping Lake data was applied to Daning Reservoir. The downscaled hourly data closely matched observed hourly data from the Hobo data loggers. However the VIC algorithm overestimated hourly relative humidity in the winter months and slightly underestimated relative humidity in June 2013 (Fig. 26).

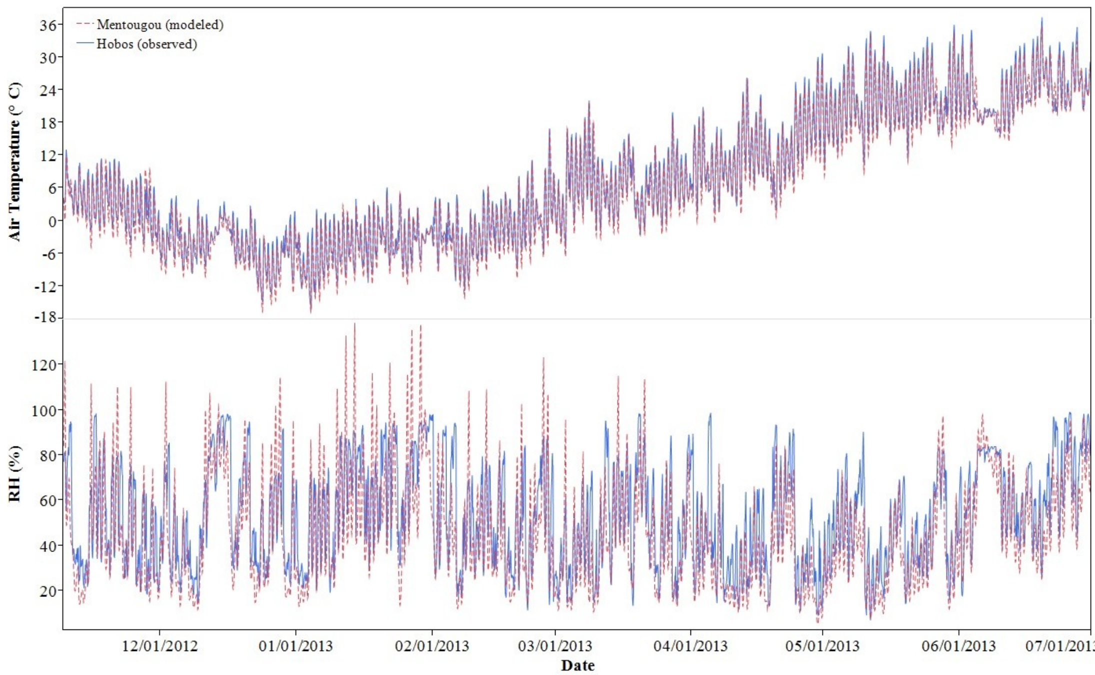


FIG. 26. VIC downscaled hourly air temperature (°C) and relative humidity (RH) (%) values using daily data from the Mentougou Meteorological Bureau (red-dashed) versus observed hourly air temperature and relative humidity from the Hobo data logger at Mencheng Lake (blue-solid). I ran the VIC model at an hourly time step using the downscaled hourly air temperature and relative humidity, thus this graph illustrates the fit between downscaled hourly values and observed hourly values.

I used the VIC model to estimate the contribution of the new ecosystems to changes in ET on the Yongding River. I created a series of simulations in an attempt to untangle the land cover changes (i.e., addition of water and vegetation) from climate changes before and after the Yongding Corridor. First I parameterized the VIC model using engineered parameters then calibrated the model altering inflow rates to have lake volumes and surface water area reflect observed changes. For all simulations, the grid cells were simulated at an hourly time-step independent of each other, meaning I ran the entire simulation for each grid cell separately. The model was initialized by iterating to steady-state prior to running each simulation. Next I conducted four simulations comparing a control group (no lakes and wetlands) to a treatment group (presence of lakes/wetlands) under pre-and post-Corridor climates. The four simulations were defined as: (1) control group before the change (no lakes/wetlands using pre-Corridor climate), (2) control group after the change (no lakes/wetlands using post-Corridor climate), (3) treatment group before the change (lakes/wetlands using pre-Corridor climate), and (4) treatment group after the change (lakes/wetlands using post-Corridor climate). To estimate the individual contributions of lakes/wetlands and climate on changes in ET between the post- and pre-Corridor periods two equations were used:

$$Lake = ET_{post,\, lakes} - ET_{pre,\, lakes} \tag{2}$$

$$Climate = ET_{post,\, nolakes} - ET_{pre,\, nolakes} \tag{3}$$

where *Lake* is the estimated contribution of the lakes/wetlands to changes in average hourly ET and *Climate* is the estimated contribution of climate variation to changes in hourly average ET. The first subscript denotes the time period and second subscript the treatment effect. I took a simple a “difference in differences” (DID) to assess whether the magnitude of the change in ET from the lakes/wetlands was larger than the change in ET from climate variation:

$$DID = (ET_{post,\, lakes} - ET_{pre,\, lakes}) - (ET_{post,\, nolakes} - ET_{pre,\, nolakes}) \tag{4}$$

Next I evaluated model sensitivities of four key variables known to impact ET: (1) precipitation, (2) LAI, (3) albedo, and (4) air temperature (see Appendix B). Model sensitivities were estimated using four scenarios: (1) ± 20% in albedo, (2) ± 20% increase in leaf area index (LAI), (3) ± 20% increase in precipitation, (4) ± 20% increase in air temperature (see Appendix B).

My modeling approach was informed by consultations with VIC modelers at the University and Washington and BWSTI scientists familiar with the VIC model, who agreed on my model assumptions and the use of global parameter files. Everyone felt a simple modeling approach was the preferred method for my study. To calibrate the model, I had to rely heavily on my on-the-ground knowledge of each lake because I observed dramatic deviations from engineered values from 2012-2013 (Figs. 27-28). My on-the-ground knowledge consisted of monthly field visits to each lake where I photographed changes in lake and wetland dimensions. Also lake depth and water temperatures were taken from shoreline platforms, however these measurements were not continuous across the post-Corridor period. Therefore the modeled lake volumes, surface water area, and ET rates were not validated with empirical data.

I evaluated the VIC model results comparing: (1) VIC potential ET (PET) values to Penman-Monteith (P-M) values, (2) VIC ET values to literature ET values for the Yongding River in Beijing, and (3) VIC net radiation values to observed net radiation values in Beijing (see Appendix B). The mean VIC vegetation PET (PET_{veg}) was 717-841 mm and the P-M PET_{veg} was 776-859 mm, however the VIC water PET (PET_{water}) was lower than the P-M PET_{water}. Next I compared the full Corridor ET results to Zhang et al. (2013) values. Zhang et al. (2013) estimated a mean ET value of 494 mm from 1999-2009 on the Yongding River in Beijing, which was similar to the VIC estimate of 542 mm for the pre-Corridor period. Lastly, I compared VIC net radiation (R_n) values to observed R_n at the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences for the pre-Corridor period. The VIC model was able to estimate the energy balance in Beijing evident in the similar diurnal and seasonal cycles between modeled and observed net radiation values (see Appendix B). Mean modeled R_n was 53.18 W m^{-2} with a standard deviation of 177.67 while mean observed R_n was 53.53 W m^{-2} with a standard deviation of 152.71.

FIG.27. Photos illustrating the seasonality of the wetlands, which are the most vulnerable to drying because they are shallow: (A) winter, (B) spring, (C) summer, and (D) fall. The upper wetland section below Mencheng Lake also experienced drying: (E) spring and (F) summer (picture taken in same location note tower in background as landmark).

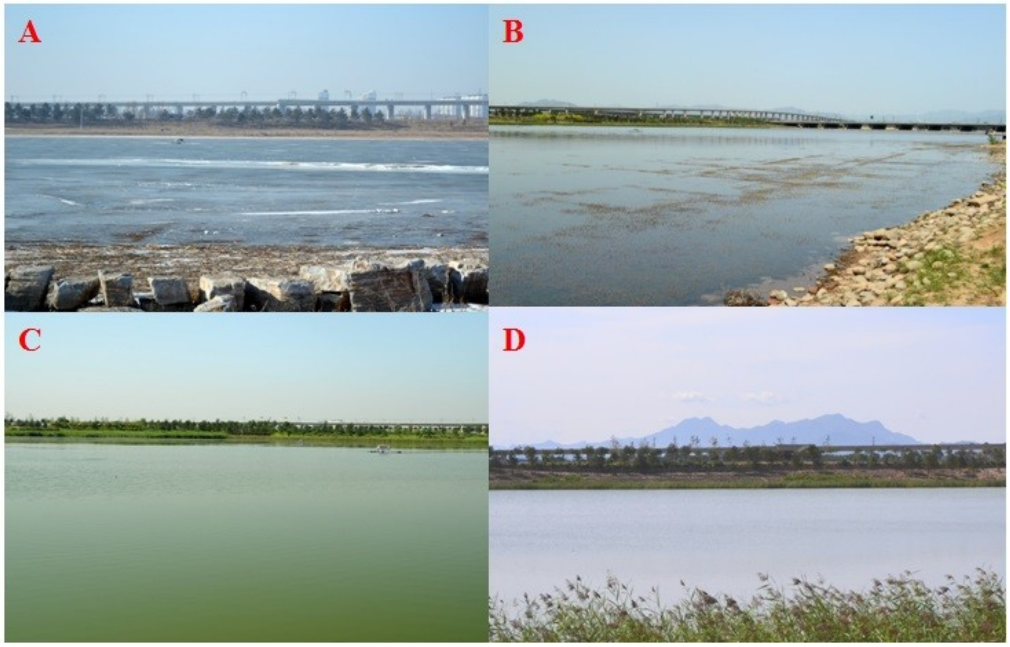


FIG.28. Photos illustrating the seasonality of the lakes, these images are of Wanping Lake: (A) winter, (B) spring (note water recession and visibility of the lake bottom from the shoreline), (C) summer, and (D) fall.

Ecological production functions: Ordinary least squares regression models

I created ecological production functions using OLS regression models to estimate the marginal effects of ecosystem characteristics on final service indicators using Stata 12.1 (see Appendix C). All models were tested for their explanatory power using the Ramsey RESET test, link test, and variance inflation factor. The ecological production functions were designed for the lakes/wetlands at the local scale.

For water storage, the ecological production function was:

$$logWaterLoss = \beta_0 + \beta_1 logSA\_V + \varepsilon \qquad (5)$$

where β_0 is the constant (y intercept), β_1 is the marginal effect (regression coefficient) of surface water area (ha): lake volume (million m^3) noted as *SA_V* on annual water loss (ET (m^3): lake volume (m^3)) noted as *WaterLoss*, and ε is the error term. The y and x variables were logarithmically transformed because they have a power-law relationship, thus a semi-log relationship was used to create an OLS regression model. Economists commonly use the log-log transformation to interpret marginal effects of non-linear relationships. Note *natural* logarithms were used where the base is *e* (approx. 2.71828).

For local climate regulation, I evaluated summer climate using June 2013 data to estimate the cooling effect of the lakes/wetlands on reducing summer air temperature and HI values. Local climate regulation production functions were created for: (1) Mencheng Lake, (2) Wetlands, (3) Lianshi Lake, (4) Xiaoyue Lake, and (5) Wanping Lake. I created ecological production functions for hourly daytime values defined as 06:00-20:00 (N = 480 per lake/wetland). I also created ecological production functions using hourly nighttime values defined as 21:00-05:00 (N = 240 per lake/wetland). The local climate regulation ecological productions were:

$$Temperature = \beta_0 + \beta_1 ET + \beta_2 Sensible + \beta_3 Pressure + \varepsilon \qquad (6)$$

$$HI = \beta_0 + \beta_1 ET + \beta_2 Sensible + \beta_3 Pressure + \varepsilon \qquad (7)$$

where *Temperature* is air temperature (°C) and *HI* is heat index. β_0 is the constant (y intercept), β_1 is the marginal effect of evapotranspiration (mm hr^{-1}) as *ET*, β_2 is the marginal effect of sensible heat (W m^{-2} hr^{-1}) as *Sensible*, β_3 is the marginal effect of pressure (kPa) as *Pressure*, and ε is the error term. I used the statistical tests listed above to evaluate both regression models, and these three variables consistently showed the best predictive power with minimal multicollinearity while maintaining efficiency (see Appendix C). These three variables influence air temperature because ET is latent heat flux where sensible heat is converted to latent heat when water vaporizes. Typically as sensible heat in the air decreases, the temperature drops, and as pressure increases air temperature increases.

Spatial mapping

Results are presented as maps using ArcGIS to provide simple illustrations of marginal ecosystem effects on final services, and assess the spatial distribution of each service. For water storage, three maps were created as: (1) water storage shortfalls, (2) sensitivity to drying, and (3) water loss. For local climate regulation, three maps were created as: (1) HI shortfalls as number of sultry events, (2) summer cooling rate, and (3) summer nighttime air temperature within 5km buffer using inverse distance weighted spatial interpolation.

RESULTS

Pre- and post-Corridor climate conditions

The post-Corridor climate was slightly warmer and wetter than the pre-Corridor climate. Mean daily maximum air temperature was 0.25 °C and minimum air temperature was 0.19 °C higher than the pre-Corridor; post-Corridor mean humidity was 4% less than pre-Corridor (Table 20). The most significant difference was precipitation since the mean total was 879 mm in the post-Corridor period while the pre-Corridor was 520 mm. The summer 2012 was the wettest period in 60 years in Beijing.

TABLE 20. Mean daily differences between post- and pre-Corridor climate.

Post-Pre Corridor								
ΔTotal Prec. (mm)	ΔTmax (°C)	Std. dev.	ΔTmin (°C)	Std. dev.	ΔWS ($m\ s^{-1}$)	Std. dev.	ΔRH (%)	Std. dev.
356	0.25	5.57	0.19	3.81	-0.2	1.16	-4	27

ΔTotal Prec. change in mean total annual precipitation between both periods.
ΔTmax max air temperature, ΔTmin minimum air temperature
ΔWS wind speed, and RH relative humidity; std. dev standard deviation

Evapotranspiration from lakes and wetlands

ET increased between the pre- and post-Corridor periods, however the increase in mean hourly ET from the addition of the lakes/wetlands was estimated to be smaller than the increase in mean hourly ET from the climatic differences between both periods. The post-Corridor climate was wetter and warmer than the pre-Corridor climate, thus there were significant climatic differences between both time periods. At the lakes scale, the pre-Corridor estimated mean hourly ET was 0.061 mm (total annual 509 mm) and post-

Corridor was 0.118 mm (total annual 985 mm). Between both periods, ET increased by an estimated 0.057 mm hr^{-1} (476 mm yr^{-1}). The estimated increase in ET from the addition of the lakes/wetlands was 0.011 mm hr^{-1} (105 mm yr^{-1}), but the estimated increase in ET due to climate variation between both periods was 0.038 mm hr^{-1} (344 mm yr^{-1}). This result suggests that the warmer and wetter climate in the post-Corridor period caused an estimated 0.027 mm hr^{-1} (239 mm yr^{-1}) greater change in ET compared to the change in ET from the addition of the lakes/wetlands (Table 21). At the full Corridor scale, the pre-Corridor estimated mean hourly ET was 0.065 mm (total annual 541 mm) and post-Corridor was 0.126 mm (total annual 1088 mm) (Table 21). Between both periods, ET increased by an estimated 0.061 mm hr^{-1} (547 mm yr^{-1}). The estimated increase in ET from the addition of the lakes/wetlands was 0.014 mm hr^{-1} (120 mm yr^{-1}), and the estimated increase in ET due to climate variation between both periods was 0.025 mm hr^{-1} (218 mm yr^{-1}). This result for the regional scale was similar to the local scale, suggesting the increased precipitation in the post-Corridor period (i.e., addition of water from climate) caused a 0.011 mm hr^{-1} (98 mm yr^{-1}) greater change in ET compared to the change in ET from the addition of the lakes/wetlands.

TABLE 21. Mean hourly and annual ET for pre- and post- Corridor simulations.

Lakes: Local Scale			
Hourly ET (mm hr^{-1})	Pre Corridor (2009 to 2010)	Post Corridor (2012 to 2013)	Post Corridor – Pre Corridor
Lakes/Wetlands (Treatment)	0.107 (0.106)	0.118 (0.112)	0.011
No Lakes/Wetlands (Control)	0.061 (0.087)	0.099 (0.119)	0.038
Treatment-Control	0.046	0.019	DID = -0.027
Annual ET (mm yr^{-1})	Pre Corridor (2009 to 2010)	Post Corridor (2012 to 2013)	Post Corridor – Pre Corridor
Lakes/Wetlands (Treatment)	880	985	105
No Lakes/Wetlands (Control)	509	853	344
Treatment-Control	371	132	DID = -239
Full Corridor: Regional Scale			
Hourly ET (mm hr^{-1})	Pre Corridor (2009 to 2010)	Post Corridor (2012 to 2013)	Post Corridor – Pre Corridor
Lakes/Wetlands (Treatment)	0.112 (0.140)	0.126 (0.153)	0.014
No Lakes/Wetlands (Control)	0.065 (0.100)	0.090 (0.117)	0.025
Treatment-Control	0.047	0.036	DID = -0.011
Annual ET (mm yr^{-1})	Pre Corridor (2009 to 2010)	Post Corridor (2012 to 2013)	Post Corridor – Pre Corridor
Lakes/Wetlands (Treatment)	968	1088	120
No Lakes/Wetlands (Control)	541	759	218
Treatment-Control	427	329	DID = -98

Note the DID is the "difference in differences" (the difference between the treatment and control groups for each column), thus the negative sign indicates the change in ET from climate variation is greater than the change in ET from the land cover changes in the post-Corridor period (i.e., addition of lakes/wetlands).

The sensitivity analysis suggests that modeled ET is more sensitive to climate variables than vegetation and soil variables (Table 22). Overall the pre- and post-Corridor scenario results matched baseline results evident in the similar means and low standard deviations between scenario results and baseline results. For the pre-Corridor the sensitivity ranking was: precipitation> temperature> LAI> albedo. At the lakes scale a ± 20% change in precipitation led to an average percent change of 285% in mean hourly ET. For the post-Corridor it was: temperature>precipitation>LAI>albedo. The difference between the sensitivity rankings of the pre- and post-Corridor periods makes sense because increased precipitation on the already wetter climate in the post-Corridor period has less of an effect compared to the drier climate of the pre-Corridor period. A detailed description of the sensitivity analysis results are presented in Appendix B for ET and lake volumes per lakes/wetlands.

TABLE 22. ET Sensitivity statistics

Lakes					
	Pre-Corridor Baseline	±20% Albedo	±20% LAI	±20% Prec.	±20% Temp.
Mean (mm hr^{-1})	0.065	0.062	0.065	0.068	0.066
Std. dev.	0.100	0.100	0.100	0.100	0.100
Average percent change (%)	---	2.0	40.4	284.8	270.2
	Post-Corridor Baseline	±20% Albedo	±20% LAI	±20% Prec.	±20% Temp.
Mean (mm hr^{-1})	0.118	0.119	0.118	0.118	0.119
Std. dev.	0.128	0.129	0.128	0.128	0.131
Average percent change (%)	---	2.7	4.8	9.0	18.7
Full Corridor					
	Pre-Corridor Baseline	±20% Albedo	±20% LAI	±20% Prec.	±20% Temp.
Mean (mm hr^{-1})	0.06	0.06	0.06	0.06	0.09
Std. dev.	0.09	0.09	0.09	0.09	0.13
Average percent change (%)	---	3.0	5.9	46.4	20.8
	Post-Corridor Baseline	±20% Albedo	±20% LAI	±20% Prec.	±20% Temp.
Mean (mm hr^{-1})	0.127	0.127	0.126	0.124	0.128
Std. dev.	0.153	0.153	0.153	0.152	0.157
Average percent change (%)	---	2.1	4.8	12.6	17.5

Baseline = Calibrated conditions
Sensitivity scenarios: LAI is leaf area index, Prec. is precipitation, and Temp. is temperature
Std. dev. = standard deviation

Hydrologic conditions

Modeled water storage, surface water area, and ET rates illustrated the seasonal drying at the various lakes/wetlands on the Yongding Corridor. Estimated mean lake volumes (million m^3) went from (Table 23): Daning Reservoir (4.44)>Garden Expo Lake (2.68)> Lianshi Lake (0.47)>Wanping Lake, Mencheng Lake (0.30)>Xiaoyue Lake (0.19)>Wetlands (0.13). Estimated mean surface water area (hectares) went from (Table 24): Garden Expo Lake (233)> Daning Reservoir (228)> Lianshi Lake (61)>Wanping Lake (36)>Mencheng Lake (32)>Wetlands (29)>Xiaoyue Lake (23). Lastly total annual estimated ET (million m^3) went from (Table 25): Garden Expo Lake (77.51)>Wetlands (44.01)>Lianshi Lake (26.74)> Daning Reservoir (22.96)> Wanping Lake (10.77)>Xiaoyue Lake (9.30)>Mencheng Lake (9.19). From 2012-2013, the Wetlands showed the most severe drying matching the modeling results. The Wetlands are shallow with measured depth from 0.1-1.0 m, and the modeling suggests it had the second highest total volume of water loss compared to the other lakes/wetlands.

TABLE 23. Modeled lake volumes (million m^3) and water depth (m) presented as seasonal and mean annual values. The difference between modeled mean annual lake volumes and final service levels are water storage shortfalls shown for different lakes/wetlands and total lakes/wetlands.

Lake volumes (million m^3)								
Season	Mencheng Lake	Wetlands	Lianshi Lake	Garden Expo Lake	Xiaoyue Lake	Wanping Lake	Daning Reservoir	Total Lakes
Summer	0.30 (1.7)	0.3 (1.0)	0.53 (1.6)	2.24 (2.0)	0.16 (1.4)	0.31 (1.6)	4.33 (3.7)	8.17
Fall	0.32 (1.8)	0.08 (0.3)	0.52 (1.6)	3.13 (2.4)	0.21 (1.6)	0.26 (1.4)	4.4 (3.7)	8.92
Winter	0.37 (1.5)	0.06 (0.2)	0.41 (0.8)	3.14 (1.9)	0.24 (1.3)	0.39 (1.4)	4.73 (3.4)	9.34
Spring	0.22 (1.3)	0.08 (0.3)	0.41 (1.3)	2.19 (1.9)	0.15 (1.2)	0.23 (1.2)	4.30 (3.5)	7.58
Mean	0.30	0.13	0.47	2.68	0.19	0.30	4.44	8.50
Final Service Indicator (Mean)	0.43 (Mencheng and Wetlands)		0.47	3.16 (Garden Expo, Xiaoyue, and Wanping)			4.44	8.50
Final Service Level	1.21		1.84	6.00			3.00	12.05
Shortfalls	-0.78		-1.37	-2.84			---	-3.55

Note mean water depth (m) in parentheses.

TABLE 24. Modeled surface water area (hectares) presented as seasonal and mean annual values, and surface water area shortfalls for total lakes/wetlands.

Surface Water Area (ha)								
Season	Mencheng Lake	Wetlands	Lianshi Lake	Garden Expo Lake	Xiaoyue Lake	Wanping Lake	Daning Reservoir	Total Lakes
Summer	35	57	66	219	22	39	233	671
Fall	36	17	65	261	26	35	236	676
Winter	30	12	51	219	21	33	214	580
Spring	27	18	54	204	19	29	223	573
Final Service Indicator (Mean)	32	29	61	233	23	36	228	625 modeled 594 measured
Final Service Level (Total surface area)	651							
Shortfall	-26 modeled -57 measured							

Note measured final service indicator is estimated total surface water area from land use and land cover data for 9/1/2013.

TABLE 25. Modeled ET (million m^3) presented as seasonal and total annual values, and ET shortfalls for total lakes/wetlands.

ET (million m^3)								
Season	Mencheng Lake	Wetlands	Lianshi Lake	Garden Expo Lake	Xiaoyue Lake	Wanping Lake	Daning Reservoir	Avg. Lakes
Summer	3.91	18.25	11.25	32.72	4.82	4.51	9.09	12.08
Fall	2.18	11.74	6.72	19.49	2.21	2.64	5.36	7.19
Winter	0.33	1.18	0.89	2.83	0.31	0.35	1.19	1.01
Spring	2.77	12.84	7.88	22.47	1.95	3.27	7.32	8.36
Total Annual	9.19	44.01	26.74	77.51	9.30	10.77	22.96	28.64
Final Service Indicator (Total Annual)	200.48							
Final Service Level	128.85							
Shortfall	71.63 (exceedance of engineered ET rate)							

Note the ET shortfalls represent an exceedance of the engineered ET rate.

Water storage shortfalls

For all three water storage final services there were estimated shortfalls with lower mean water storage, lower mean surface water area, and higher total annual ET values compared to final service levels (Tables 23-25). For total lakes, the estimated mean lake volume shortfall was 3.55 million m^3 (Fig. 29), mean surface water area shortfall was 26 hectares, and total annual ET shortfall was 71.63 million m^3. Based on field observations, lake drying was most severe in the winter and spring. The model results depicted the seasonality in the system since for most lakes/wetlands the lake volumes and water area were lowest during the winter and spring. To illustrate the drying, I used the modeled results on lake volumes and surface water areas and my on-the-ground knowledge to create a qualitative ranking of the lakes in terms of vulnerability to drying. BWSTI staff stated managers wanted a simple map showing vulnerable areas to drying, which is shown in Fig. 30. I did not use an algorithm or weighting system to rank the lakes/wetlands.

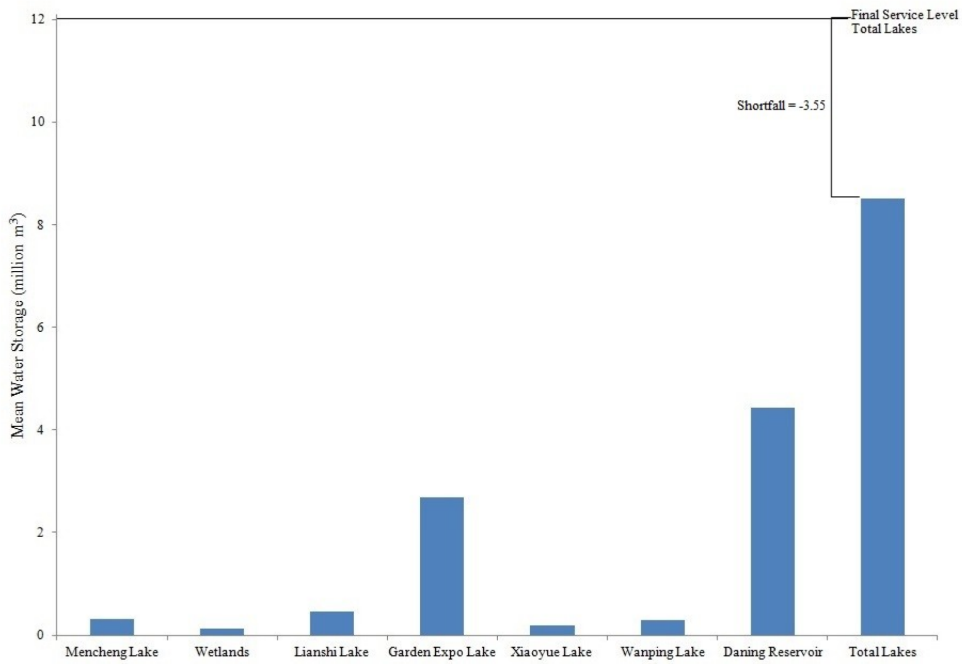


FIG.29. Modeled mean water storage (million m^3) for each lake, and total lakes with respective final service level to illustrate the estimated shortfall.

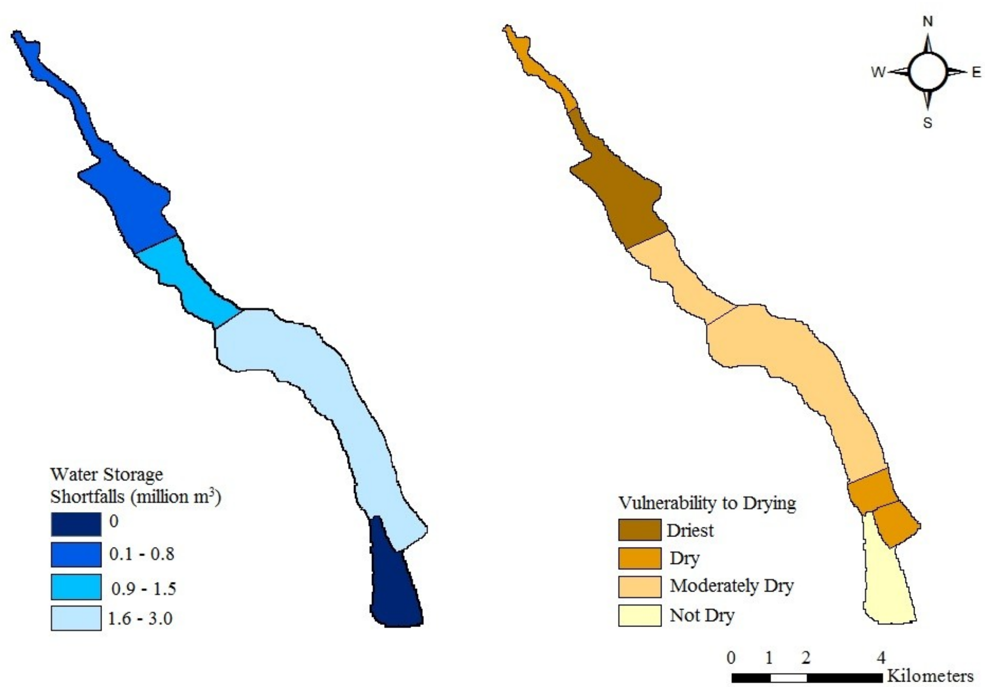


FIG. 30. The water storage shortfalls portrayed for each lake/wetlands section, and a qualitative ranking of vulnerability to drying to reflect reductions in surface water area at each lake/wetlands.

Water storage production function: Lake dimensions to water loss

I found water loss had a power-law relationship to the surface water area: lake volume ratio, which suggests as surface water area: lake volume gets larger through a decrease in volume then evaporation increases. First the surface area: volume ratio and water loss values were calculated for each lake/wetlands shown in Table 26. Water loss values are the amount of water loss from ET per unit of water in the lake. For instance, for each 1 m^3 of water in the Wetlands an estimated 339 m^3 of water was lost per year, thus on average over 300 times more water was lost per unit of water stored (Fig. 31). Using the data in Table 23 and Table 25, the estimated 2012-2013 water loss value is 23.59, and the engineered target water loss value is 10.69, thus the water loss shortfall is 12.90 (i.e., exceedance of engineered value).

TABLE 26. Surface water area: lake volume ratios and annual water loss values.

Water Efficiency Metrics		Mencheng Lake	Wetlands	Lianshi Lake	Garden Expo Lake	Xiaoyue Lake	Wanping Lake	Daning Reservoir
Management Options (*Ecosystem Characteristics*)	Surface Area (ha) : Volume (million m^3)	106	221	130	87	121	120	51
Water Loss (*Final Service Indicator*)	ET (m^3) : Volume (m^3)	30	339	57	29	49	36	5
	ET (mm) : Volume (million m^3)	3366	8793	2279	364	4662	3658	204

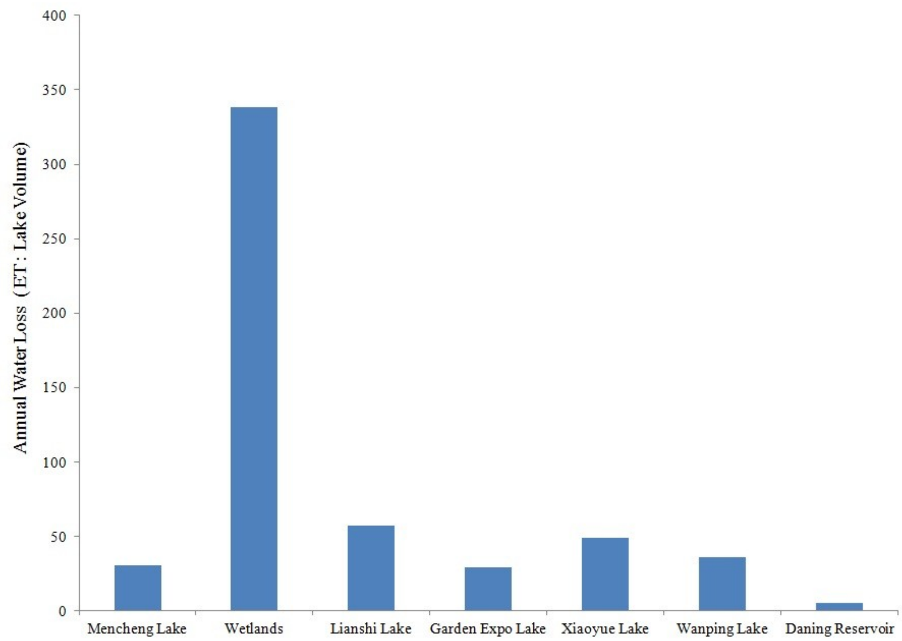


FIG.31. Annual water loss values for each lake/wetlands as (ET (m^3): lake volume (m^3)).

Lastly, an ecological production function was created to determine the marginal effect of the surface water area: lake volume ratio on water loss. For ecosystem services, economists commonly use OLS regressions to interpret regression coefficients as marginal effects (i.e., how marginal changes in ecosystem characteristics impact final services). To interpret the log-log regression coefficient (i.e., elasticity) economists use percent change, the interpretation is given as an expected percent change in Y when X increases by 1%. Water storage is estimated where on average a 1% increase in surface water area: lake volume ratio would likely result in an estimated 3.1% increase in water loss (Table 27). A water loss map was created to illustrate where potential water loss is greatest relative to lake volume, thus water efficiency increases moving from dark red to light red on Fig. 32.

TABLE 27. Regression statistics for the water storage production function.

Annual Water Loss					
	Log SA: V Coefficient (Marginal Effect)	P-Value	95% CI	R^2	RMSE
Log Water Loss	3.11 (0.47)	0.00	1.96 - 4.26	0.88	0.54

Note SA: V is the surface water area (hectares) to lake volume (million m^3)
Water loss is ET (m^3): Lake Volume (m^3); natural log was used to transform variables.
R^2 is coefficient of determination, the standard errors are reported in parenthesis to coefficients
CI is confidence interval
RMSE is root mean squared error

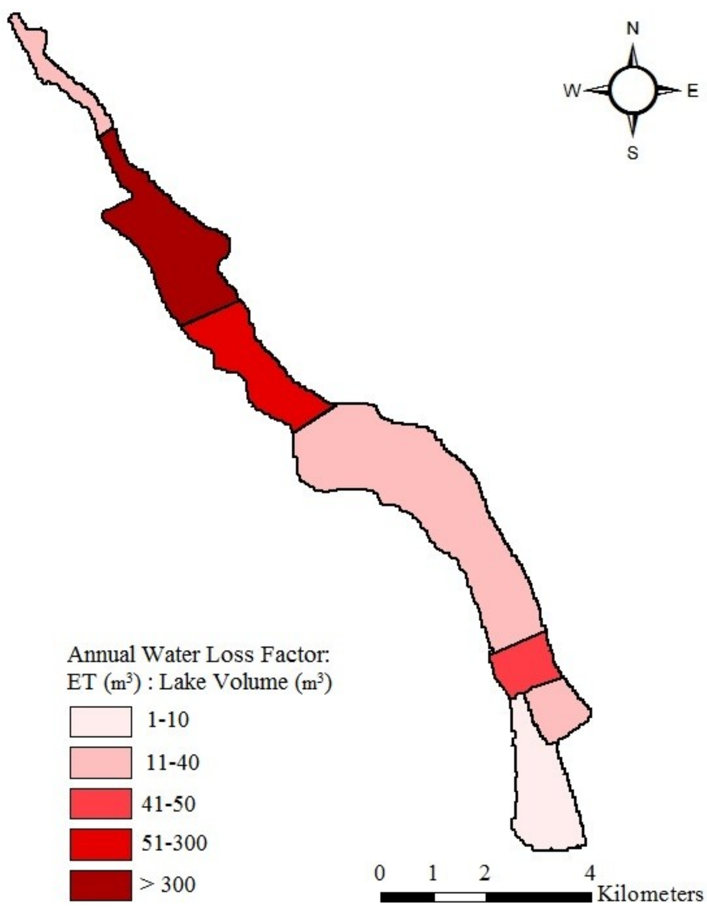


FIG. 32. Map illustrating the estimated annual water loss at each lake/wetlands site. Water efficiency increases from dark red (least efficient) to light red (most efficient).

Summer climate conditions

There was minimal observed difference in mean hourly summer air temperature and mean hourly summer relative humidity among the lakes/wetlands, however Xiaoyue Lake had lower relative humidity than other lakes/wetlands. For the lakes/wetlands during June 2013, the mean hourly daytime air temperature ranged from 25.07-25.89 °C and mean hourly daytime humidity ranged from 43-72%, resulting in an average HI of 23 (Table 28). For the lakes/wetlands, the mean hourly nighttime air temperature ranged from 21.33-22.11 °C and mean hourly nighttime humidity ranged from 45-84%, resulting in an average HI of 21. Mean hourly air temperature and mean hourly humidity had low variance among the lakes/wetlands, but Xiaoyue Lake on average had lower humidity values.

The lakes/wetlands on average were cooler than the meteorological stations (more urbanized) in the nighttime but warmer in the daytime. On average the lakes/wetlands during the daytime in the summer were 0.50 °C warmer with 1% lower relative humidity than the stations, and during the nighttime in the summer were 0.49 °C cooler with 3% lower relative humidity than the stations (Table 28). I created a map using spatial interpolation to illustrate the slightly cooler summer nighttime temperatures on the lakes/wetlands compared to the stations. The map shows hotspots of nighttime cooling at Mencheng Lake and Lianshi Lake (Fig. 33). In particular note the slightly higher air temperatures moving eastward towards Shijingshan and Fengtai, which are closer to the city center.

TABLE 28. Average hourly air temperature, relative humidity, and heat index with standard deviations for daytime and nighttime periods in June 2013.

June 2013 Daytime						
Station	T (°C)	Std. dev.	RH (%)	Std. dev.	HI	Std. dev.
Mencheng Lake	25.07	4.93	72	21	23	3
Wetlands	25.34	4.85	70	22	23	3
Lianshi Lake	25.48	4.77	70	22	23	3
Xiaoyue Lake	25.79	4.79	43	26	22	4
Wanping Lake	25.89	4.99	70	21	24	3
Avg. Lakes/Wetlands	25.51	0.33	65	12	23	0
Mentougou	24.78	4.15	63	20	22	3
Shijingshan	25.11	4.15	69	21	23	2
Fengtai	25.18	3.97	70	21	23	2
Avg. Stations	25.02	0.21	67	4	23	0
$\Delta_{Lakes - Stations}$	0.49	0.12	-3	9	0	0

June 2013 Nighttime						
Station	T (°C)	Std. dev.	RH (%)	Std. dev.	HI	Std. dev.
Mencheng Lake	21.47	2.69	82	15	21	2
Wetlands	21.61	2.81	82	15	21	2
Lianshi Lake	21.33	2.70	84	14	21	2
Xiaoyue Lake	22.11	2.71	45	32	20	3
Wanping Lake	21.67	2.58	84	14	21	2
Avg. Lakes/Wetlands	21.64	0.29	75	17	21	0
Mentougou	21.96	2.40	72	16	21	2
Shijingshan	22.22	2.35	78	15	21	2
Fengtai	22.25	2.17	81	14	21	2
Avg. Stations	22.14	0.16	77	5	21	0
$\Delta_{Lakes - Stations}$	-0.50	0.14	-1	12	0	0

$\Delta_{Lakes-Stations}$ is the difference between mean lakes/wetlands and mean stations values.

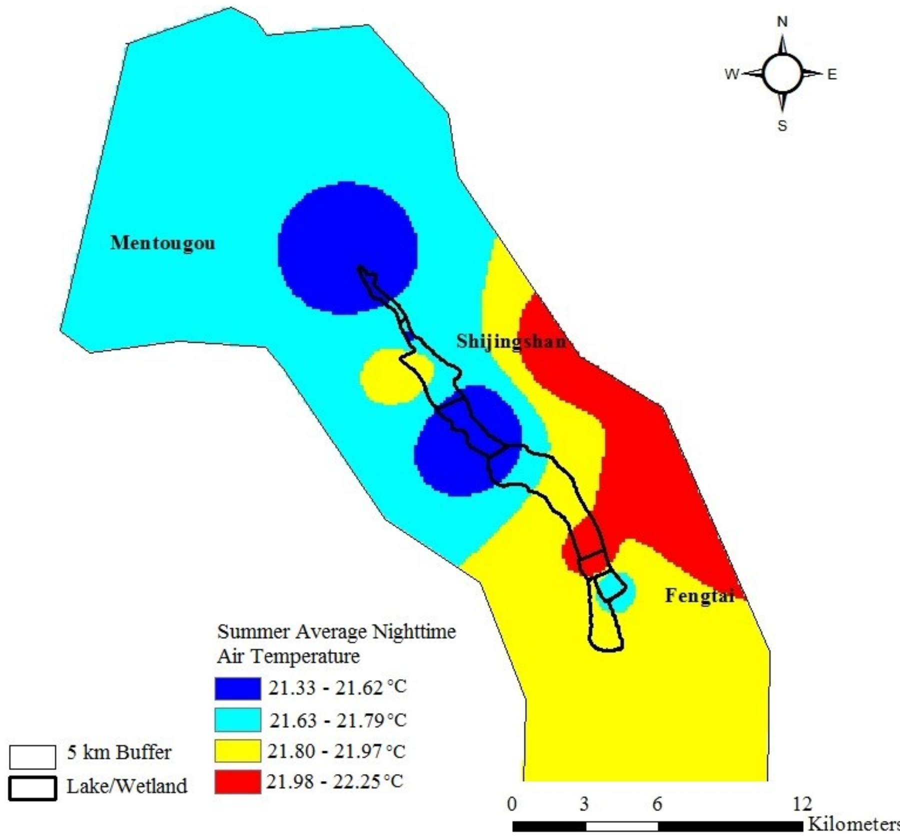


FIG. 33. Mean June 2013 (i.e., summer) nighttime air temperatures June 2013 within 5km buffer of the lakes/wetlands; government districts are shown where Shijingshan and Fengtai are closer to the urban center moving eastward.

Local climate regulation shortfalls

The VIC model results suggest the pre-Corridor period had more sultry events than the post-Corridor period, and there were observed differences in the number of sultry events between the lakes/wetlands at the local scale (Table 29). The sultry events for the Mentougou station in Table 29 are based on downscaled air temperature and humidity values, which suggest there were 38 more sultry events in the pre-Corridor period. At individual lakes and wetlands there were differences in the number of observed sultry events: Wanping Lake> Xiaoyue Lake>Mencheng Lake>Lianshi Lake> Wetlands. During the sultry events, the mean air temperature was similar at all lakes and wetlands, but humidity was highest at Xiaoyue and Wanping lakes. However on average the higher daytime air temperatures at Xiaoyue Lake and Wanping Lake likely explain the increased frequency of sultry events at these sites (Table 29).

TABLE 29. Climate regulation shortfalls as the number of sultry events.

	Pre Corridor	Post Corridor					
Sites	Mentougou Station*	Mentougou Station‡	Mencheng Lake†	Wetlands†	Lianshi Lake†	Xiaoyue Lake†	Wanping Lake†
Shortfalls	142	104	69	51	59	72	98
Mean HI	27-28	27-28	27-29	27-29	27-29	27-29	27-30
Mean T (°C)	33.24 (1.97)	33.07 (1.84)	32.73 (2.04)	32.75 (2.36)	32.59 (2.42)	32.41 (2.29)	32.55 (2.23)
Mean RH (%)	42 (11)	41 (11)	48 (14)	48 (16)	48 (16)	52 (16)	51 (16)

*6/1/2009 to 6/30/2010
‡ 6/1/ 2012 to 6/30/2013
† 11/9/2012 to 6/30/2013

Next ecosystem structure was linked to the number of sultry events using the LULC data for each lake/wetlands. Wanping Lake, Xiaoyue Lake, and Mencheng Lake had the lowest percentage of trees, but the largest surface water area. The sultry events occur mostly in the daytime, and the results suggest that shading from tree cover in combination with ET had an impact on the number of sultry events at each site (Table 30). The Wetlands and Lianshi Lake had less surface water area, but an estimated tree cover of 37% with high ET rates, which experienced the fewest number of sultry events in June 2013. Mencheng Lake is adjacent to the Wetlands; however it had 18 more sultry events than the Wetlands. The higher number of sultry events at Xiaoyue Lake and Wanping Lake compared to Mencheng Lake is likely due to increased urbanization around Xiaoyue Lake and Wanping Lake. Xiaoyue Lake has dense settlements close to the banks, however the settlements do not encroach onto the banks at Wanping Lake, but considerable construction is occurring in Fengtai not picked up in the LULC data. I created a map using spatial interpolation to illustrate the potential relationship between vegetation cover and number of sultry events (Fig. 34).

TABLE 30. Relating ecosystem structure (land use and land cover) to sultry events.

	LULC Area (km^2)								
Lake/Wetland	Water (km^2)	Wetland (km^2)	Trees (km^2)	Grass (km^2)	Bare soil (km^2)	Urban (km^2)	Total (km^2)	Total ET (mm $month^{-1}$)	Sultry Events
Mencheng Lake	0.34 (38%)	---	0.11 (12%)	0.29 (32%)	---	0.16 (18%)	0.9	83	69
Wetlands	0.09 (2%)	0.44 (11%)	1.41 (37%)	0.96 (25%)	0.45 (12%)	0.50 (13%)	3.85	93	51
Lianshi Lake	0.61 (24%)	0.07 (3%)	0.94 (37%)	0.49 (20%)	0.19 (8%)	0.20 (8%)	2.51	86	59
Garden Expo Lake	1.89 (24%)	0.04 (1%)	1.54 (19%)	3.18 (40%)	0.20 (2%)	1.11 (14%)	7.96	79	---
Xiaoyue Lake	0.28 (27%)	---	---	0.15 (14%)	0.01 (1%)	0.62 (58%)	1.05	71	72
Wanping Lake	0.38 (38%)	0.07 (7%)	0.12 (12%)	0.39 (39%)	---	0.04 (4%)	0.99	89	98
Daning Reservoir	2.34 (92%)	---	---	0.04 (2%)	0.14 (5%)	0.01 (1%)	2.53	73	---

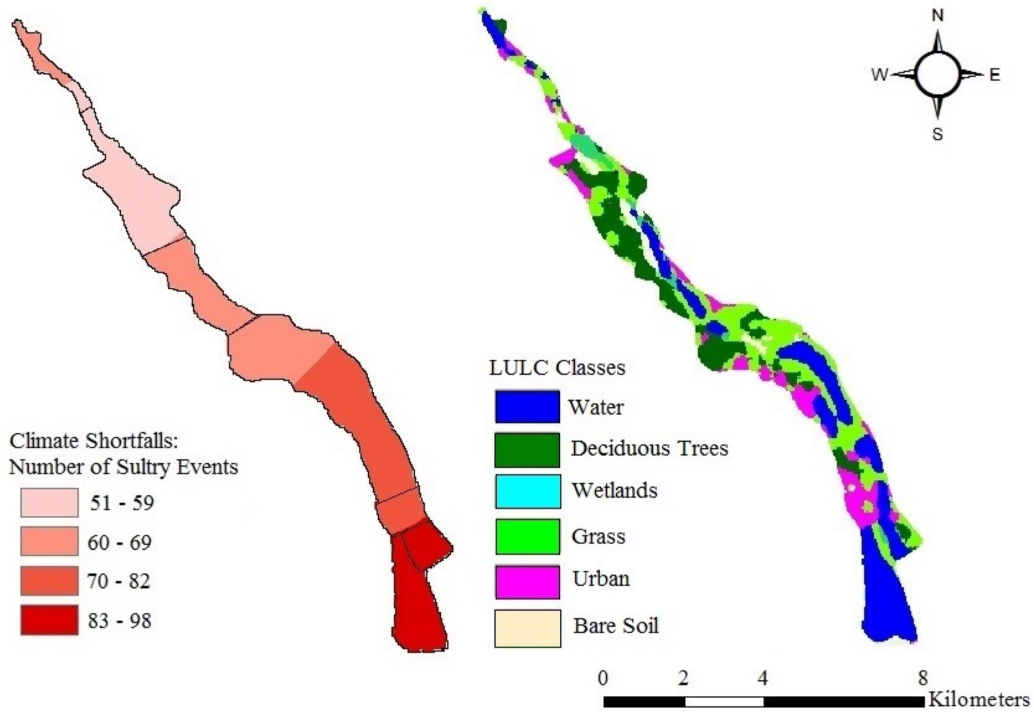


FIG. 34. The number of sultry events and LULC of each lake/wetlands.

Local climate regulation production functions: ET to summer temperature and heat index

I created local climate regulation production functions relating hourly summer ET and air temperature and human comfort using the HI. I linked modeled ET to observed daytime and nighttime air temperature and HI values in June 2013. All production functions for both daytime and nighttime were statistically significant using an F-test at $P<0.05$ level. The R^2 suggest that 75-89% of the variation in air temperature and HI about their respective means were explained by variations in modeled ET, sensible heat, and pressure.

For summer daytime air temperature, all ET coefficients except Mencheng Lake were statistically significant at $P<0.05$ level. I use the statistically significant regression coefficients to assess the marginal effects of ET on daytime air temperature, which suggests given a 1 mm increase in hourly ET one would expect air temperature to decrease by 1.20-8.39 °C depending on the lake/wetlands (Table 31). In more practical units of measure, if hourly ET increases by 0.01 mm than one would expect air temperature to decrease by 0.01– 0.08 °C. The daytime cooling effect differed among the lakes/wetlands: Wanping Lake>Lianshi Lake>Wetlands>Xiaoyue Lake.

For summer daytime HI, all ET coefficients except Mencheng Lake were statistically significant at $P<0.05$ level. I use the statistically significant regression coefficients to assess the marginal effects of ET on daytime HI, which suggests given a 1 mm increase in hourly ET one would expect the HI to decrease by 1.00-6.44 depending on the lake/wetlands (Table 31). In more practical units of measure, if hourly ET increases by 0.01 mm than one would expect the HI to decrease by 0.01 – 0.06. The daytime cooling effect on HI differed among the lakes/wetlands: Wanping Lake>Lianshi Lake>Wetlands>Xiaoyue Lake.

TABLE 31. Summary statistics of summer daytime air temperature and heat index production functions.

Air Temperature Production Function: June 2013 Daytime					
Lake/Wetland	ET Coefficient (Marginal Effect)	P-Value	95% CI	R^2	RMSE
Mencheng Lake	-0.01 (0.59)	0.98	-1.17 to 1.15	0.88	1.74
Wetlands	-3.79 (0.56)	0.00	-4.87 to -2.69	0.89	1.63
Lianshi Lake	-4.70 (0.70)	0.00	-6.07 to -3.32	0.87	1.70
Xiaoyue Lake	-1.20 (0.34)	0.00	-1.87 to -0.53	0.83	1.99
Wanping Lake	-8.39 (0.86)	0.00	-10.07 to -6.70	0.87	1.78
Heat Index Production Function: June 2013 Daytime					
Lake/Wetland	ET Coefficient (Marginal Effect)	P-Value	95% CI	R^2	RMSE
Mencheng Lake	-0.67 (0.46)	0.15	-1.57 to 0.24	0.84	1.25
Wetlands	-2.37 (0.48)	0.00	-3.31 to -1.43	0.84	1.17
Lianshi Lake	-3.36 (0.58)	0.00	-4.49 to -2.22	0.82	1.24
Xiaoyue Lake	-1.00 (0.29)	0.00	-1.58 to -0.43	0.75	1.80
Wanping Lake	-6.44 (0.65)	0.00	-7.72 to -5.17	0.84	1.25

R^2 is coefficient of determination; standard errors are reported in parentheses
CI is confidence interval
RMSE is root mean squared error
ET is evapotranspiration (mm hr^{-1})

For nighttime air temperature all ET coefficients were statistically significant at P<0.05 level. I use the statistically significant regression coefficients to assess the marginal effects of ET on nighttime air temperature, which suggests given a 1 mm increase in hourly ET one would expect air temperature to decrease by 5.42-15.95 °C depending on the lake/wetlands (Table 32). In more practical units of measure, if hourly ET increases by 0.01 mm than one would expect air temperature to decrease by 0.05 – 0.16 °C. The nighttime cooling effect differed among lakes/wetlands: Xiaoyue Lake>Wetlands>Wanping Lake>Lianshi Lake> Mencheng Lake.

For nighttime HI all ET coefficients except Xiaoyue Lake were statistically significant at $P<0.05$ level. I use the statistically significant regression coefficients to assess the marginal effects of ET on nighttime HI, which suggests given a 1 mm increase in hourly ET one would expect the HI to decrease by 1.22-4.60 depending on the lake/wetlands (Table 32). In more practical units of measure, if hourly ET increases by 0.01 mm than one would expect the HI to decrease by 0.01 – 0.05. The nighttime cooling effect on HI differed among lakes/wetlands: Wetlands>Wanping Lake>Lianshi Lake>Mencheng Lake. Because managers are concerned about summer nighttime air temperature, I used spatial interpolation to create a map showing the nighttime marginal cooling effect of ET on air temperature and HI (Fig. 35). The maps show an estimated hotspot at Xiaoyue Lake for nighttime cooling on reducing air temperature, and estimated hotspots at Wanping Lake, Wetlands, and Lianshi Lake for nighttime cooling on reducing the HI.

Table 32. Summary statistics of summer nighttime air temperature and heat index production functions.

Lake/Wetland	ET Coefficient (Marginal Effect)	P-Value	95% CI	R^2	RMSE
Air Temperature Production Function: June 2013 Nighttime					
Mencheng Lake	-5.42 (0.88)	0.00	-7.16 to -3.68	0.84	1.07
Wetlands	-7.54 (0.93)	0.00	-9.37 to -5.71	0.87	1.00
Lianshi Lake	-6.52 (0.83)	0.00	-8.15 to -4.89	0.89	0.90
Xiaoyue Lake	-15.95 (1.66)	0.00	-19.22 to -12.69	0.85	1.04
Wanping Lake	-7.53 (0.79)	0.00	-9.09 to -5.97	0.87	0.93
Heat Index Production Function: June 2013 Nighttime					
Lake/Wetland	ET Coefficient (Marginal Effect)	P-Value	95% CI	R^2	RMSE
Mencheng Lake	-2.24 (0.75)	0.00	-3.71 to -0.77	0.85	0.82
Wetlands	-4.60 (0.62)	0.00	-5.82 to -3.38	0.88	0.76
Lianshi Lake	-4.41 (0.71)	0.00	-5.81 to -3.00	0.87	0.80
Xiaoyue Lake	-1.22 (1.80)	0.50	-4.77 to 2.32	0.79	1.17
Wanping Lake	-4.50 (0.66)	0.00	-5.80 to -3.20	0.87	0.76

R^2 is coefficient of determination; standard errors are reported in parentheses
CI is confidence interval
RMSE is root mean squared error
ET is evapotranspiration (mm hr^{-1})

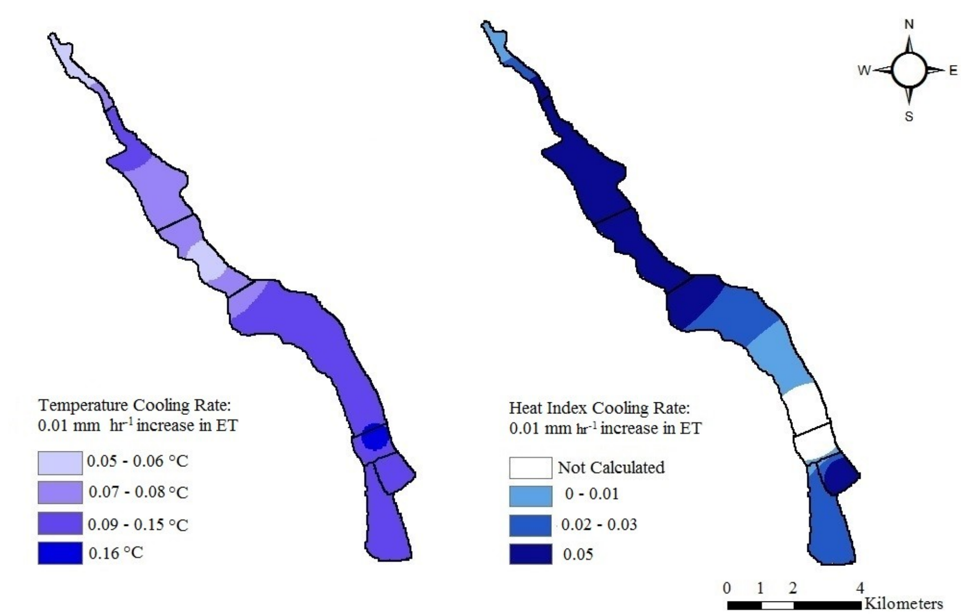


FIG. 35. Estimated cooling rates of summer nighttime air temperature and heat index from ET. The maps show expected decreases in air temperature and heat index for 0.01 mm increases in hourly summer nighttime ET.

DISCUSSION

Lakes/Wetlands contribution to ET

At both the local and regional scales there was an estimated increase in ET between the pre- and post-Corridor periods, however the majority of the increase came from climatic changes with a smaller contribution from the addition of lakes/wetlands. Between the pre- and post-Corridor periods, ET increased by 0.06 mm hr^{-1} (476 mm yr^{-1} at local scale; 547 mm yr^{-1} at regional scale). The slightly higher regional increase in ET is likely due to an increase in deciduous trees across the Yongding Corridor. Climatic differences accounted for the majority of the increase between both periods. The 2012-2013 climate was one of the wettest in Beijing's recent history compared to the relatively dry climate in 2009-2010. Total annual precipitation increased by 69% (356 mm) between both periods. Increased precipitation led to increased soil moisture across the Yongding River in Beijing, thus the results suggest that ET from increased precipitation was larger than the increased water and vegetation from the constructed lakes/wetlands alone. Between the pre- and post-Corridor periods, I estimated that the lakes/wetlands alone increased ET by an estimated 0.01 mm hr^{-1} (105 mm yr^{-1} at local scale; 120 mm yr^{-1} at regional scale).

Water storage shortfalls

I used the VIC model to simulate the observed seasonal drying of the lakes/wetlands to estimate water storage shortfalls, which I found useful in understanding the potential relationship between surface water area: lake volume and water loss from ET. Despite the wetter climate of 2012-2013, I observed lake drying at all lakes/wetlands from 2012-2013. The most severe was at the Wetlands during fall, winter, and spring with near complete drying in April 2013 (Figs. 27-28). Engineers designed the system where ET is the main water loss factor since there should be near-zero leakage because of an impervious liner. In 2012 managers stated there were water circulation problems leading to inconsistent inflow across the lakes/wetlands (Gao 2012). Hence I calibrated the VIC model to first see whether or not drying would occur at various sections if the model was parameterized using the engineered inflow and outflow rates. If the inflow and outflow rates matched engineered parameters the model showed there should be no drying at the lakes/wetlands in 2012-2013. I then altered inflow rates to simulate the seasonal drying to assess how water losses from ET were changing because of alterations in the surface water area: lake volume ratio from inconsistent inflow.

I estimated water storage shortfalls as: (1) 3.55 million m^3 lower water storage, (2) 26 hectares lower surface water area, and (3) 71.63 million m^3 higher water loss from ET. The current design scheme is shallow lakes/wetlands with the intent of creating a water landscape that looks expansive. At first glance the rationale seems correct, but in practice the shallow lakes/wetlands are likely water inefficient, thus in total they are losing more water than if the lakes/wetlands were deeper. Deeper lakes/wetlands would require more initial water investment, but they have a higher likelihood of being sustained over time since they have a higher water regulation capacity. Shallow lakes are more vulnerable to seasonal drying because they have higher surface water area: lake volume ratios, which can cause increased evaporation. The modeling suggests that given the lake dimensions and climate in the post-Corridor period that inflow rates likely fluctuated across the time-series. Inconsistent inflow coupled with Beijing's seasonal temperate, semiarid climate likely led to noticeable reductions in lake volume and surface water area in the winter and spring, which caused water storage shortfalls. For example, the Wetlands had the lowest mean water storage yet highest surface water area: volume ratio, resulting in the second highest total volume of water loss. The Wetlands had a near 10-times greater water loss than other lakes/wetlands in 2012-2013.

I created a water storage production function to evaluate the impact of surface water area: lake volume to water loss values to evaluate the water efficiency of the system in 2012-2013. It was estimated that on average a 1% increase in surface water area: lake volume would result in a 3% increase in water loss from ET for a given unit of water stored. For 2012-2013, the estimated total water loss shortfall considering all lakes/wetlands is 12.94, which would require a 55% decrease to meet the final service level for total water loss. The water loss coefficient suggests an 18% reduction in total surface water area: lake volume would be needed to decrease water loss by 55%.

Local climate regulation shortfalls

I determined local climate regulation shortfalls as the number of sultry events, which differed between the lakes/wetlands: Wanping Lake (98 events)> Xiaoyue Lake (72 events)>Mencheng Lake (69 events)>Lianshi Lake (59 events)>Wetlands (51 events). The differences in sultry events between the lakes/wetlands were likely due to differences in vegetation cover among sites. Mencheng Lake, Wanping Lake, and Xiaoyue Lake had the lowest tree cover with an estimated percent cover of 12% compared to the Wetlands and Lianshi Lake with an estimated percent cover of 37%. Wanping Lake had relatively high ET rates, but it had the highest mean summer daytime air temperature. The higher summer daytime air temperatures and sultry events at Wanping Lake are likely because of the high amount of construction surrounding Wanping Lake.

I created local climate regulation production functions relating summer daytime and nighttime ET to air temperature and HI. ET had a higher cooling effect on summer nighttime air temperature and HI than summer daytime air temperature and HI. Based on the regression coefficients, I found that an hourly increase of 0.01 mm hr^{-1} of ET would likely reduce summer nighttime air temperature by 0.05-0.16 °C, and reduce the summer nighttime HI by 0.01-0.05. Overall the local climate regulation results suggest the lakes/wetlands are providing a cooling effect, which is likely due to increased vegetation and ET from the new ecosystems. However on average the ET cooling effect is small since mangers would need to obtain a 100-fold increase in the ET rate to have any potential impact on reducing the number of sultry events in the summer.

Limitations

The limitations of this analysis should be considered when interpreting these results. First the modeled ET, water storage, surface water area, and sensible heat flux were not validated. Typically to validate ET and sensible heat flux requires an eddy covariance tower; to validate lake volumes would require water gauges on the Yongding Corridor. These instruments were unfeasible because of budget limitations and time constraints. However the VIC ET values were similar to P-M and literature ET values. Lastly the modeled ET, sensible heat, and pressure were able to explain 75-89% of the variance in observed hourly summer air temperature and humidity at the lakes/wetlands.

Second the analysis on summer cooling was conducted for only June 2013; it did not extend to the hottest periods of the year, which are July and August. Sultry events are felt the most during these months, and my current analysis does not capture this critical period. Despite not considering the hottest months there were still measurable sultry events and cooling effects from ET in June 2013.

CONCLUSION

In summary the model results suggest the new ecosystems increased ET on the Yongding Corridor, but the current design of the lakes/wetlands is likely resulting in poor water efficiency, causing water storage shortfalls while having a small estimated cooling effect on reducing human comfort shortfalls. My results suggest managers could improve water efficiency of the lakes/wetlands by creating deeper lakes. Shallow lakes with high surface water area: lake volume ratios are vulnerable to lake drying, especially when inflow rates are not consistently maintained. Deeper lakes would require more initial water investment, but likely mangers would get more long-term water savings. However altering the current design of the lakes/wetlands may be unfeasible, which simply places more importance on maintaining consistent water inflow rates. Secondly, ET from the lakes/wetlands is likely not providing enough cooling to reduce summer sultry events (i.e., noticeable changes in human comfort). A possible solution for management is to focus cooling efforts on planting trees selecting appropriate species with sufficient canopy cover to provide shading. Shade cover from trees would likely have more impact on reducing local temperatures than ET from the lakes/wetlands on the Yongding Corridor.

Key findings from this chapter are:

- New ecosystems increased ET by 0.01 mm hr^{-1} (105 mm yr^{-1} at local scale; 120 mm yr^{-1} at regional scale) between the pre- and post-Corridor period.
- Water storage shortfalls were estimated as lower mean water storage, lower mean surface water area, and higher total annual water loss.
- Across all lakes/wetlands a 1% increase in surface water area: lake volume would likely result in a 3% increase in water loss; an 18% reduction in surface water area: lake volume would likely be needed to meet desired water storage level.
- The number of sultry events on the lakes/wetlands ranged from 51-98 events in June 2013 with most events occurring at sites with less vegetation cover.
- An hourly increase of 0.01 mm hr^{-1} of summer nighttime ET would likely reduce air temperature by 0.05-0.16 °C and decrease HI by 0.01-0.05.

CHAPTER 6

WATER PURIFICATION

ABSTRACT

Beijing officials are implementing a large-scale constructed wetland scheme to improve water purification on the Yongding River. In this chapter I determine the water purification of wetlands on lake water quality on the Yongding Corridor from March 2013 to August 2013. In general nutrient levels were much higher than the total nitrogen (TN) and total phosphorus (TP) final service levels (Grade III – drinking water quality). Across all months the best average water quality was at upper Mencheng Lake (TN = 2.03 mg/L; TP = 0.08 mg/L) and worst average water quality was at upper Lianshi Lake (TN = 21.72 mg/L; TP = 1.94 mg/L). The majority of lake sections had water purification shortfalls with average TN and TP higher than Grade V (no permitted water uses). Nutrient pollution was concentrated at the wetlands, and the likely source is domestic sewage from shoreline homes. The average nutrient load for TN was 18.88 mg/L and for TP was 1.80 mg/L. However wetland nutrient retention was 61% for TN and 66% for TP. Using an empirical denitrification equation, I estimated that denitrification on average contributed 17% to TN retention. I created ecological production functions using ordinary least squares regression models. The regression coefficients suggests that given a 1 ha increase in wetland area one would likely expect a 0.01 mg/L decrease in TP, and given a 1 mg/L increase in nutrient load one would likely expect a 0.41 mg/L increase in TN. Based on these findings mangers would likely have to increase wetland area by 50% to obtain the TP final service level, and reduce the mean TN nutrient load concentration by 75% to obtain the TN final service level.

INTRODUCTION

China possesses grand water pollution challenges, and a serious concern is the eutrophication of water bodies, which can threaten economic growth and human livelihoods. In recent decades China set national targets on industrial wastewater discharges and implemented wastewater treatment technologies, resulting in reductions of toxic constituents and sanitation improvements in cities. However excess nitrogen (N) and phosphorus (P) remain problematic, and are of primary concern because they can cause eutrophication of water bodies (Carpenter et al. 1998). In 2012 China's Ministry of Environmental Protection (MEP) classified 60% of the nation's lakes as eutrophic, and over 30% of its rivers as unsuitable for drinking water. Urban runoff is considered an important contributor to excess nutrients in China's waterways.

Treatment plants often only provide primary and secondary treatment, which does not remove N and P from wastewater. Therefore effluent that does not undergo nutrient treatment (i.e., tertiary treatment) can increase nutrients in freshwater ecosystems (Paul and Meyer 2001). The removal of nutrients from wastewater is a challenge for many countries since it is a costly, energy intensive process. For example in the United States only 36.5% of domestic sewage undergoes tertiary treatment before being released into waterways because the expectation is that ecosystems will provide the necessary tertiary treatment (US NRC 2012). However as population sizes in cities grow so do effluent volumes, which can overwhelm the water purification capacity of freshwater ecosystems making tertiary treatment either through wastewater treatment plants and/or constructed wetlands increasingly important.

Another challenge facing Chinese cities is stormwater management because nonpoint pollution sources of agricultural fertilizer, domestic sewage, and toxic materials can contaminate water bodies. During stormwater pulses, many cities have combined sewer stormwater overflows, such that when stormwater inputs are too high, raw sewage combined with surface runoff is allowed to overflow directly into urban rivers. The uncontrolled connection between sewage and surface water leads to high fecal coliform concentrations and nutrient loads in many freshwater ecosystems in urban areas and downstream of cities (Bernhardt and Palmer 2007). In particular the rapid growth of Chinese cities makes domestic sewage and stormwater urgent management challenges in addressing China's water pollution problems.

In Beijing sewage and stormwater releases are rising while rivers are drying resulting in poor water quality. Since the 1990s, the levels of industrial wastewater discharges have stabilized, but domestic wastewater has risen considerably. In 2003 the Beijing government enacted stringent controls on industry leading to the treatment of 91% of industrial wastewater in contrast to only 32% of domestic sewage (Shao et al. 2006). In 2006 it was reported that 60% of the rivers, lakes, and reservoirs in Beijing were seriously polluted (Jing 2006) with large areas of algal blooms present in Beijing's surface water (Du et al. 2005). The Green Olympics were instrumental in establishing 14 new wastewater treatment plants in Beijing (Wei 2005). However despite the implementation of treatment plants, Beijing's lakes and rivers continue to struggle with poor water quality. Ren et al. (2014) conducted a recent study of total nitrogen, and found surface water still exceeds a Grade V of the national water quality standard (not suitable for any water uses), and using isotopes identified the major N source as domestic sewage. Managers are realizing that mere replication of traditional treatment approaches is limited and not entirely feasible in China (Zhang et al. 2009). China's large populations and rapid development have created a need for high efficiency, low cost wastewater treatment methods. Beijing has been testing alternative treatment and stormwater techniques, such as integrating wetland ecosystems into the built environment for water purification (Zhang et al. 2009).

Water purification is a critical ecosystem service for many human benefits, such as drinking water quality, agricultural production, recreation, and biodiversity protection (Carpenter et al. 1998, Postel and Thompson 2005). A water purification ecosystem service is defined as the decomposition and capture of nutrients and contaminants by ecosystems (Rusi et al. 2013). An important ecosystem function underpinning water purification is nutrient retention. Nutrient retention is the capacity of an ecosystem to remove N and P (or other nutrients) from the water column through physical, chemical, and biological processes, and/or storage of nutrients that cannot be released under normal conditions (Reddy et al. 1999). Wetlands are well known as effective ecosystems for N and P retention, which have led to their widespread use for wastewater treatment as constructed wetlands (Zedler and Kercher 2005).

Constructed wetlands are popular because they often provide water purification at lower costs with more energy savings than wastewater treatment facilities while providing amenities and habitat for fish and bird species (Zhang et. al. 2009). Wetlands remove N via denitrification, plant uptake, and sedimentation, and remove P via plant uptake and sedimentation (Kadlec and Knight 1996, Vymazal 2007). However unlike engineered systems constructed wetlands are "open systems" regulated by climate, hydrology, and vegetation (Kadlec and Wallace 2009). Therefore they are not as consistent as wastewater facilities, yet they can be strategically located to address difficulties of managing nonpoint pollution while providing multiple services. Vymazal (2007) reviewed nutrient removal of constructed wetlands finding removal rates between 40-60% for both N and P. N is commonly measured as ammonia (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), and total nitrogen (TN), and P as phosphate (PO_4^{3-}) and total phosphorus (TP). In China constructed wetlands have shown a mean NH_4^+ removal efficiency of 37% and a mean PO_4^{3-} removal efficiency of 80% (Zhang et al. 2009).

Beijing is a pioneer in the experimentation of constructed wetlands testing various designs for their treatment abilities at small-scales, and is trying a large-scale design for the first time on the Yongding River. Ecological engineers define constructed wetlands as surface flow and subsurface flow wetlands. Surface flow wetlands mimic natural wetlands with large open water areas and emergent vegetation while subsurface flow wetlands contain the water primarily in the plant root zone (Mitsch and Gosselink 2007). As early as the mid-1990s, Beijing began implementing small-scale surface flow wetlands to treat municipal wastewater, such as Changping and Qinghe, which showed nutrient removal efficiencies of 65% and 29% for TN and 55% and 54% for TP, respectively (Zhang et al. 2009). In 2008 subsurface flow technology was employed to construct the Beijing Olympic Forest Park. Xie et al. (2012) calculated average nutrient removal efficiencies of 11% (NH_4^+), 39% (NO_3^-), 20% (TN), 49% (PO_4^{3-}), and 44% (TP).

In 2010 the Beijing government decided to fund a large-scale project known as the Yongding River Ecological Corridor. The Yongding Corridor will have three subsurface flow wetlands and surface flow wetlands, and is one of the largest municipal wetland schemes for water purification in the world.

The Yongding Corridor will provide tertiary treatment using subsurface flow wetlands and stormwater treatment using surface flow wetlands. Every year 130 million m^3 of recycled water will first enter the subsurface flow wetlands then will be distributed to the surface flow wetlands and lakes (Fig. 36). Pumping stations circulate the water to maintain aeration then the water is pumped into aquifers to recharge groundwater. The subsurface flow wetlands are located along the banks of the Yongding Corridor, and are designed to provide tertiary treatment before the water enters the "open system." In 2012-2013 six lakes and surface flow wetlands were completed. The surface flow wetlands are designed as "wetland islands" where streams meander through the wetlands. Surface flow wetlands are strategically located between Mencheng Lake and Lianshi Lake to buffer the lakes from nonpoint pollution. In May 2013, the first subsurface flow wetland was completed at the Garden Expo Lake, which is 246 ha designed to process 80,000 m^3 of recycled water a day (Shi 2013, Fig. 37). Engineers have not completed the Mayu and Nandahuang subsurface flow wetlands.

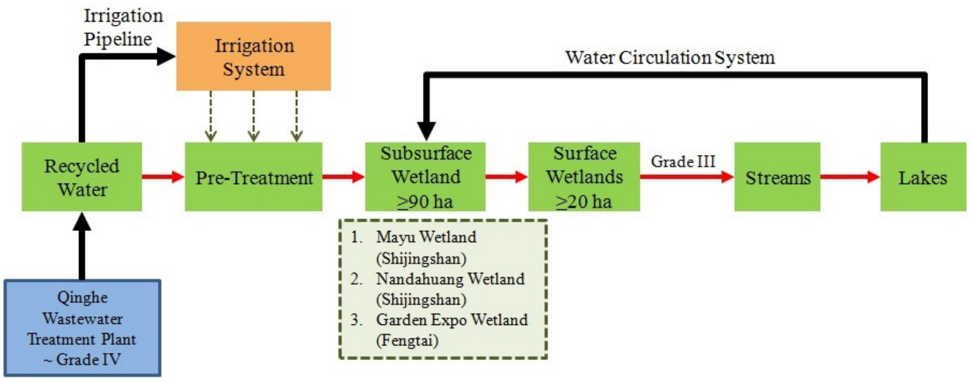


FIG.36. Water purification scheme of the Yongding River Ecological Corridor using subsurface and surface flow constructed wetlands.

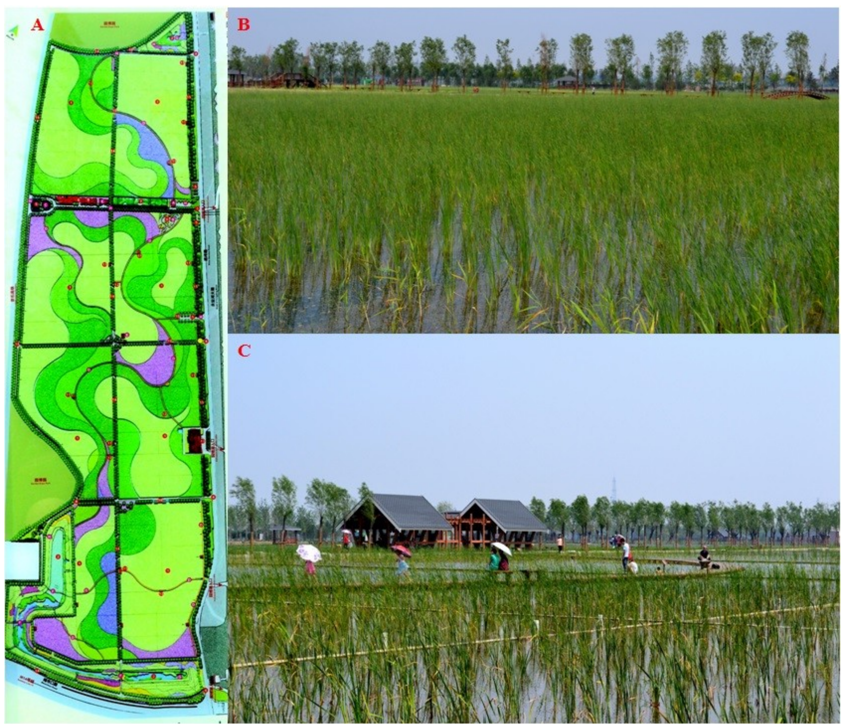


FIG.37. Garden Expo subsurface flow wetland completed in May 2014: (A) map of the wetlands each color represents different plant species and pathways allow visitors to interact with the wetlands, (B) young *Phragmites* (i.e., common reed), and (C) bridges for visitors to walk through wetlands.

The six lakes and surface flow wetlands have been in operation for two years, and managers have identified water pollution problems since TN and TP levels are much higher than the drinking water quality standard. The Beijing Water Authority (BWA) wants the wetlands to improve water quality of effluent from Grade IV (industrial and recreational use) to Grade III (drinking water quality), which are based on national water quality standards (GB3838-2002). In 2012 the BWA published water quality results on the lakes and surface flow wetlands (Lü et al. 2012). The BWA found that TN and TP levels were at a Grade IV and V at the lakes and wetlands, which resulted in summer algal blooms (Fig. 38). They concluded that low water levels, inconsistent inflows, and local domestic sewage are likely causing the water quality problems. They state effort must be made to improve: (1) the water circulation system for consistent inflows and aeration, (2) direct control of runoff into the lakes, and (3) nutrient retention using floating vegetation.

Managers have started using water hyacinth (i.e., *Eichhornia crassipes*) in addition to emergent wetland plants (i.e., *Phragmites*) at areas showing eutrophication. Water hyacinth is popular for nutrient control since one hectare can absorb the daily N and P waste production of over 800 people (Rogers and Davis 1972). Managers are watching plant growth closely because if not removed water hyacinth can exacerbate eutrophication effects causing low dissolved oxygen (DO) levels leading to fish kills. The lakes on the Yongding Corridor are stocked with carp, and are popular parks for recreational fishing, thus maintaining fish populations is important to visitors (Fig. 38).

FIG.38. (A-B) summer algal blooms in wetland islands, (C) Yongding Corridor staff removing algae, (D) water hyacinth used to remove nutrients, (E) harvested water hyacinth, and (F) popular recreational activity is fishing at the lakes.

The BWA wants information on lake water quality to identify pollution sources and wetland nutrient retention to improve nutrient management. The challenge is linking management options (e.g., wetland area and nutrient loading) to nutrient retention to lake water quality (i.e., final services) (Fig. 39). The Yongding Corridor is an open system vulnerable to nonpoint pollution entering as domestic sewage and stormwater. Managers created the surface flow wetlands to buffer lakes from excess N and P, but currently managers are unaware of the nutrient load, and amount of nutrients retained by the wetlands. Not knowing the loading rate relative to wetland retention makes it difficult to determine the functionality of the current design in removing nutrients and/or whether the nutrient load is simply greater than the design capacity. Furthermore the BWA wants advice on its monitoring scheme to determine where to concentrate monitoring to improve actions on controlling urban runoff entering the system.

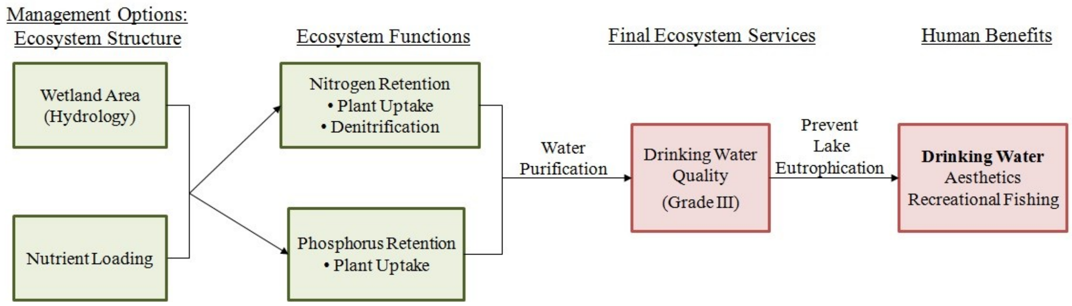


FIG.39. Conceptual diagram linking management options as changes in ecosystem structure to ecosystem functions to final ecosystem services and human benefits. Human benefit in bold is direct benefit of concern to management regarding water purification, however water quality underpins cultural ecosystem services explored in chapter 8.

In this chapter I estimate the water purification from the surface flow wetlands on improving lake water quality on the Yongding Corridor in Beijing. First final services were selected using China's national surface water quality standards. Second a water quality monitoring protocol was implemented to determine water quality shortfalls, pollution hotspots, nutrient loading, and wetland nutrient retention. Third I estimated denitrification rates using an empirical equation to assess potential nitrogen removal from microbial activity. Fourth I created ecological production functions using ordinary least squares (OLS) regression models to link wetland area and nutrient loading to final service indicators. Chapter objectives are to estimate: (1) water quality shortfalls, (2) nutrient retention from the surface flow wetlands, (3) marginal effects of wetland area and nutrient loading on final service indicators, and (4) spatial distribution of nutrient pollution and water purification.

METHODS

Below I provide a brief outline of how I present my methods and results in this chapter. My measurement approach consists of seven general steps shown in Fig. 40. First I selected the final services using BWA water quality endpoints then I measured the final service indicators (TN and TP) using field data. I used the water quality data to determine TN and TP shortfalls. Second I mapped the water quality results, and TN and TP shortfalls to locate the main water pollution source (i.e., high nutrient loading location) on the Yongding Corridor. Third I used the field data to calculate nutrient loading and nutrient retention on the Yongding Corridor. Fourth I mapped the nutrient loading and nutrient retention results. Fifth I estimated denitrification rates (a key ecosystem process supporting nutrient retention) using modeled wetland hydrology values from the VIC model (presented in Chapter 5) and an empirical denitrification equation for constructed wetlands. Lastly I created two ecological production functions to determine the marginal effects of wetland area and nutrient loading on TN and TP at Lianshi Lake (the lake downstream of the Wetlands).

In summary I evaluated water purification by: (1) calculating nutrient loading and wetland nutrient retention using field measurements, (2) the spatial distribution of water pollution, and (3) the marginal effects of wetland area and nutrient loading on TN and TP (Table 33). In Table 34, I outline the data collected and methods used to assess water purification. The methodological steps are explained in detail in the following subsections.

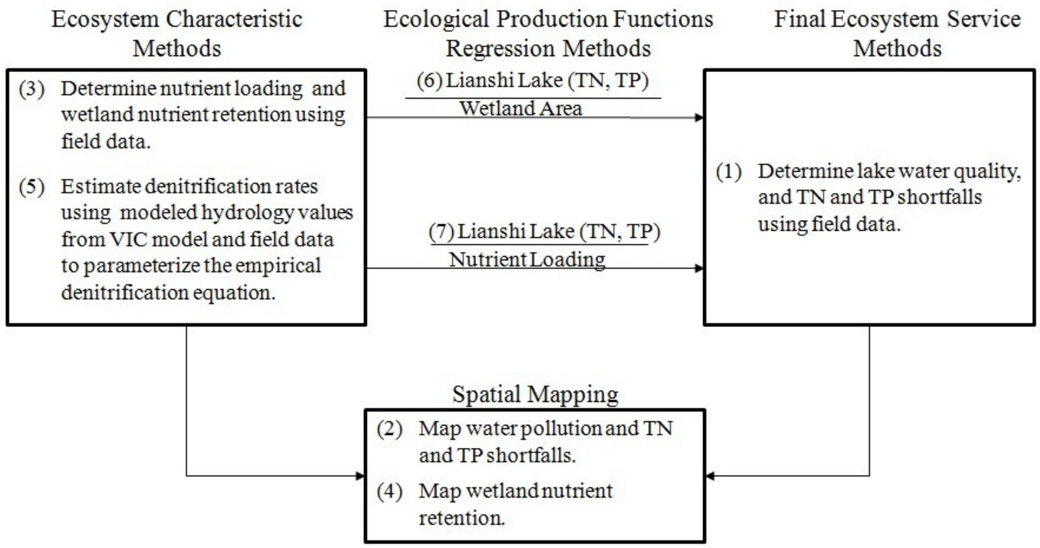


FIG.40. Methodological steps to estimate water purification from the Yongding River Ecological Corridor.

TABLE 33. Description of the main measurement steps to evaluate water purification from the Yongding River Ecological Corridor.

Ecosystem Service Measurement Steps	Water Purification
Relating Management Options to Ecosystem function	Determine nutrient loading and wetland nutrient retention using field data. Estimate denitrification rates using modeled wetland hydrology from the VIC model and an empirical denitrification equation for constructed wetlands.
Relating Final Service to Potential Beneficiaries	Determine the distribution of water pollution along the Yongding Corridor.
Relating Ecosystem structure to Final service	Determine marginal effects of wetland area on TN and TP at Lianshi Lake, and marginal effects of nutrient loading on TN and TP at Lianshi Lake.

TABLE 34. Summary of data used to measure water purification.

Data to Measure Water Purification				
Category	Water purification indicators	Data to parameterize denitrification equation		Ecosystem characteristics
Data type	Total nitrogen (mg/L) Total phosphorus (mg/L)	Wetland hydrology data: flow rate, water volume, and wetland area	Water quality data: nitrate + nitrite concentrations and water temperature	Nutrient retention Wetland area Denitrification
Data source	Field data	VIC model (presented in Chapter 5)	Field data	Field data, VIC model, and empirical denitrification equation

Study area

The Yongding Corridor lakes are: (1) Mencheng Lake, (2) Lianshi Lake, (3) Garden Expo Lake, (4) Xiaoyue Lake, (5) Wanping Lake, and (6) Daning Reservoir. The surface flow wetlands are located between lower Mencheng Lake and upper Lianshi Lake (Fig. 41). In this study, I refer to the surface flow wetlands simply as Wetlands. I examine the water purification of the Wetlands on Lianshi Lake water quality. I also determine the water quality at Mencheng Lake, Lianshi Lake, Xiaoyue Lake, and Wanping Lake. The subsurface flow wetland, Garden Expo Lake, and Daning Reservoir are excluded because these three water bodies were under construction when this study was conducted.

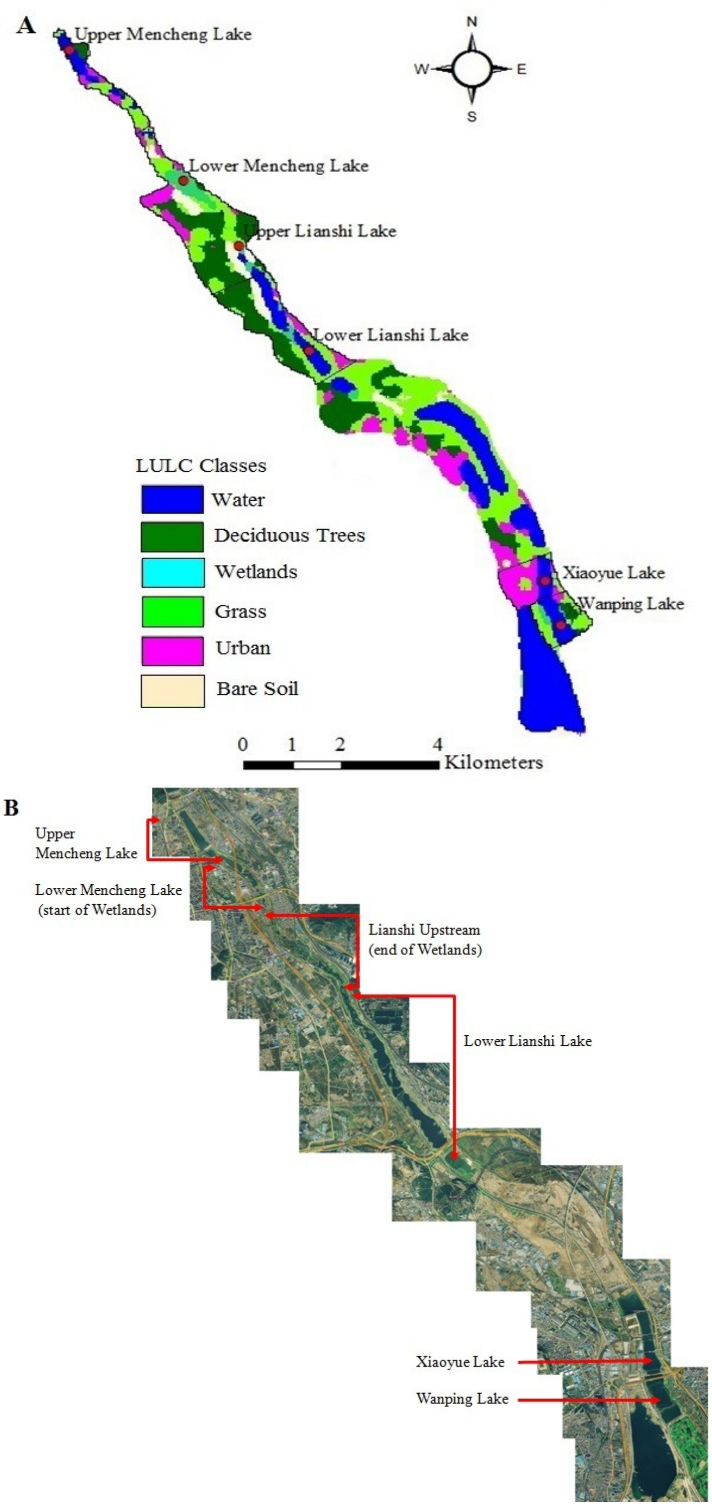


FIG. 41. Wetlands are located between upper Mencheng Lake and Lower Lianshi Lake: (A) 2013 land use and land cover map and (B) 2012 high resolution remote sensing image.

Construction of the four lakes and surface flow wetlands started in June 2010 and were completed in October 2011. The total max surface area of the Wetlands is 80 ha. To prevent leakage of water in the system, geosynthetic clay liners line the bottoms of the lakes, streams, and wetlands. A complex network of underground pipes connects the lakes and surface flow wetlands via pumping stations. Water circulates from north to south, starting at upper Mencheng Lake to Wanping Lake then back to upper Mencheng Lake (Fig. 42). The engineered daily inflow rates are shown between pumping stations and each water body in Fig. 42. There are surface flow connections between lower Mencheng Lake, upper Lianshi Lake, and lower Lianshi Lake.

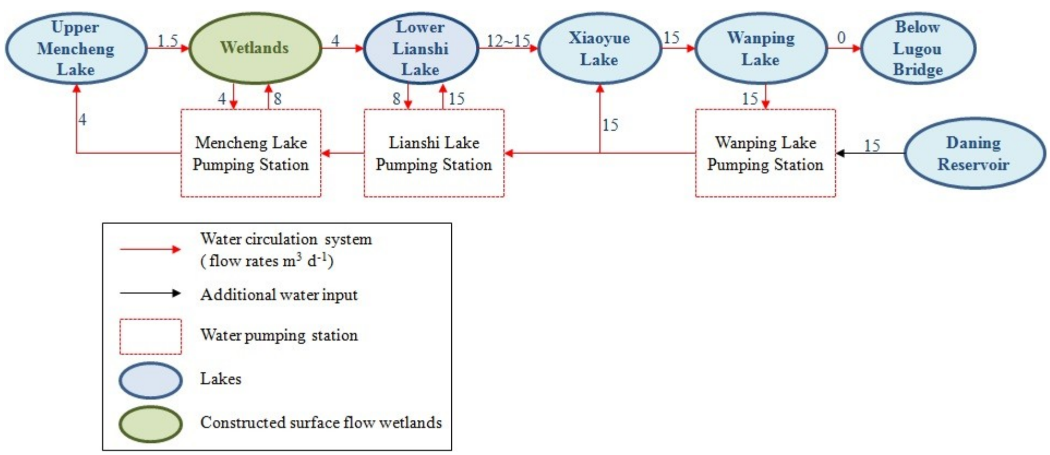


FIG.42. Water circulation system showing the hydrologic connections between lakes and constructed surface flow wetlands (listed are daily flow rates).

TABLE 35. Description of the temporal and spatial scales of the analysis.

Temporal and Spatial Scales			
Temporal		Spatial	
Category	After Yongding Corridor	New ecosystems	Beneficiaries
Scale	March 2013 to August 2013	Local: lakes/wetlands in urban section.	Water quality data from 20 water sampling sites on the Yongding Corridor.
Purpose	Calculate the nutrient loading and wetland nutrient retention on the Yongding Corridor.	N/A	Distribution of water pollution on the Yongding Corridor.

The Wetlands are designed for water purification and engineers selected emergent vegetation with known N and P retention capabilities. The dominant vegetation type in the Wetlands is *Phragmites* (i.e., common reed) then *Typha Latifolia* (i.e., cattail) (Fig. 43). The vegetation cover is highest in the summer and September then all vegetation is harvested to prevent nutrient release back into the system via decomposition in late-fall and winter. Furthermore floating vegetation (i.e., water hyacinth) is used in the Wetlands during the summer months, which is also harvested to prevent decomposition (Fig. 38).

FIG.43. Dominant wetland plants are *Phragmites* and *Typha Latifolia*: (A) *Phragmites* is the most common wetland species, (B) *Phragmites* harvested in the fall, and (C) *Typha Latifolia*.

Final services and final service indicators

The BWA had clear management endpoints for water purification defined as a Grade III - the national drinking water quality standard. The MEP's surface water quality standards for TN and TP were selected as final services (Table 36). Water quality shortfalls were calculated as the difference between measured final service indicators and required concentrations for a Grade III.

TABLE 36. Final services for water purification are the listed endpoints for a Grade III.

People's Republic of China Ministry of Environmental Protection
National Surface Water Quality Standards (GB 3838-2002)

Water Quality Endpoints (mg/L)	Grade I	Grade II	Grade III	Grade IV	Grade V	>Grade V
Total Nitrogen (TN)	0.2	0.5	1.0	1.5	2.0	>2.0
Total Phosphorus (TP)	0.02	0.1	0.2	0.3	0.4	>0.4

Grade I pertains mainly to national nature reserves and headwaters of water sources.
Grade II pertains to class A water source protection for centralized drinking water supply, sanctuaries for rare fish species, and spawning grounds for fish and shrimp species.
Grade III pertains to class B water source protection for centralized drinking water supply, sanctuaries for fish species, and swimming zones.
Grade IV pertains to industrial water supply and recreational waters in which there is no direct human contact with the water.
Grade V pertains to agricultural water supply and general landscape requirements.
>Grade V no permitted water uses.

Water quality data were collected by taking monthly water samples at 20 sites from March 2013 to August 2013 (Fig. 44). At each site one water sample was taken from the shoreline using common water grab sampling techniques, and one water sample was taken 6m from the shoreline using a telescoping pole. Water quality parameters were collected in situ: DO (EcoSense DO200, YSI Inc., Yellow Springs OH, USA), temperature (EcoSense DO200, YSI Inc., Yellow Springs OH, USA), pH (pH pen, Bluelab Corp., Tauranga, New Zealand), and water depth. All field instruments were calibrated in the laboratory before each sampling period. The water samples were stored in ice chests then NH_4^+, NO_3^-, and NO_2^- were filtered within 24-hours and stored in freezers. All samples were analyzed within 2-3 days of the sampling date. The UV spectrophotometric method was used to assess NH_4^+, NO_3^-, NO_2^-, TN, and TP analyzed on UV PharmaSpec 1700 Shimadzu (Shimadzu Corp., Kyoto, Japan).

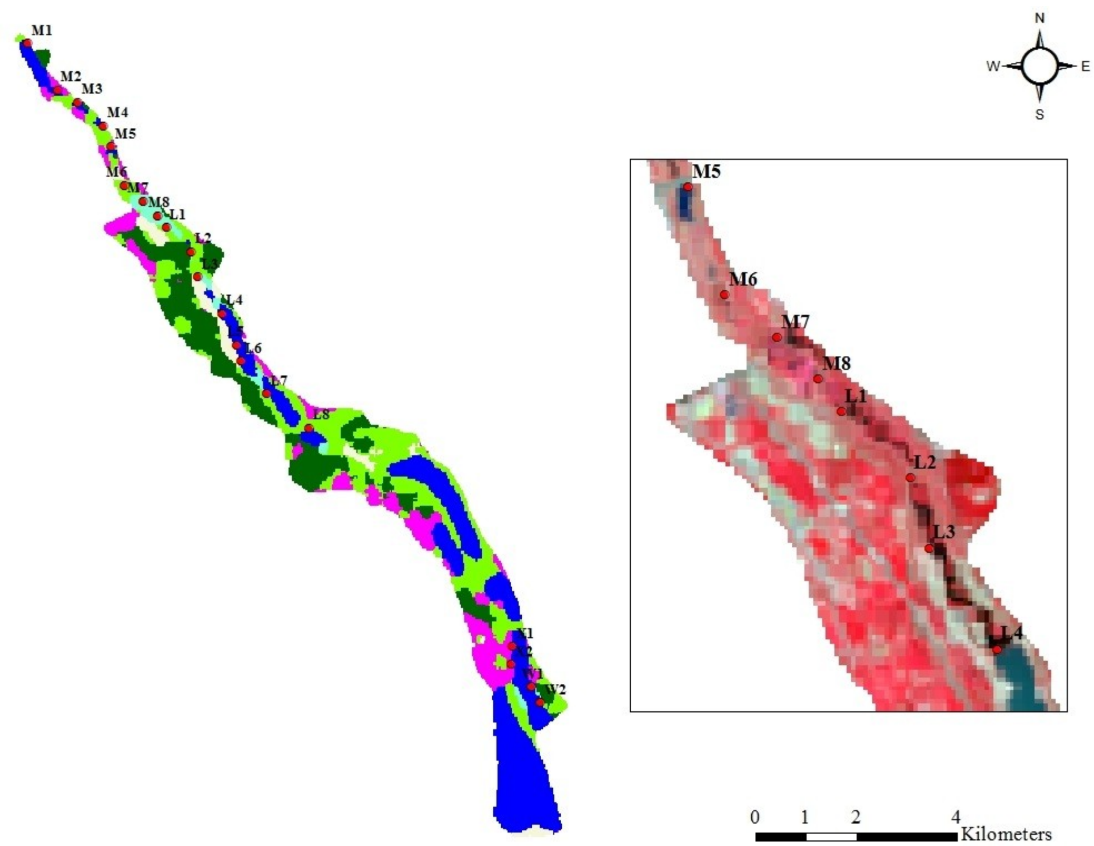


FIG. 44. The 20 water sampling sites at Mencheng Lake (M), Lianshi Lake (L), Xiaoyue Lake (X), and Wanping Lake (W); shown are Wetland sites using a 2013 Landsat 8 image.

The 20 sites were classified into different groups to assess lake water quality, and calculate nutrient loading and nutrient retention on the Yongding Corridor (Table 37). Lake water quality was evaluated using the BWA monitoring designations for the four lakes shown in Table 37, and average TN and TP per month were determined for each section. Based on the monthly water quality results at the 20 sites, I identified a high nutrient loading source entering directly into the Wetlands. I used the water quality data from the 20 sites to calculate wetland nutrient retention. I simplified the system comparing the TN and TP at three sections: (1) above the Wetlands (i.e., water sampling sites upstream of the Wetlands), (2) Wetlands (i.e., water sampling sites in the Wetlands), and (3) Lianshi Lake (i.e., water sampling site downstream of the Wetlands). I calculated nutrient loading using equation (8) and nutrient retention using equation (9):

$$Loading = Upstream - Wetlands \tag{8}$$

$$Retention = Wetlands - LianshiLake \tag{9}$$

where *Loading* is the average TN and TP added to the system, *Upstream* is the average TN and TP upstream of the Wetlands, and *Wetlands* is the average TN and TP within the Wetlands. *Retention* is the average TN and TP removed and *LianshiLake* is average TN and TP downstream of the Wetlands in Lianshi Lake.

TABLE 37. The groups to evaluate nutrient loading, nutrient retention, and water quality.

Nutrient Loading and Nutrient Retention	
Sections	Sites
Upstream of Wetlands	M1-M6
Wetlands	M7-L5
Lianshi Lake	L6-L8
Lake Water Quality	
Sections	Sites
Upper Mencheng Lake	M1-M4
Lower Mencheng Lake	M5-M8
Upper Lianshi Lake	L1-L4
Lower Lianshi Lake	L5-L8
Xiaoyue Lake	X1-X2
Wanping Lake	W1-W2

Variable Infiltration Capacity model and denitrification equation

Hydrology is considered the most important determinant to maintaining wetland functionality (Mitsch and Gosselink 2007). Improper hydrological design is often the root cause of failed constructed wetlands. Ecological engineers use key hydrologic parameters, such as hydroperiod, hydrologic residence time (HRT), and hydraulic loading rate (HLR) to manage the hydrologic conditions of constructed wetlands. Hydroperiod is water depth in a wetland over time, which represents the seasonal pattern of water storage in the wetland. HRT (day) is the water detention time defined as:

$$HRT = \frac{V}{Q} \tag{10}$$

where Q is inflow (m^3 day^{-1}) and V is wetland volume (m^3).

HLR (m day^{-1}) is the rate of water application for a given wetland area:

$$HLR = \frac{Q}{A} \tag{11}$$

where Q is inflow (m^3 day^{-1}) and A is wetland area (m^2). I used the Variable Infiltration Capacity (VIC) model to dynamically simulate wetland hydrology (Liang et al 1994, Bowling and Lettenmaier 2010, Gao et al. 2011). The VIC model was parameterized using engineered values and calibrated using field observations (see Appendix B). I calculated HRT (days) and HLR (cm d^{-1}) using VIC modeled outputs for wetland area (ha), water volume (m^3), depth (m), inflow (m^3 d^{-1}), and residence time (days) (Table 38).

TABLE 38. Modeled wetland hydrology using the VIC model.

VIC Modeled Wetland Hydrology						
Month	Area (ha)	Volume (m^3)	Depth (m)	Inflow (m^3 d^{-1})	HRT (d)	HLR (cm d^{-1})
March 2013	35	168,672	0.64	1,866	90	47.79
April 2013	5	7,880	0.04	6,734	1	16.44
May 2013	14	53,592	0.25	31,484	2	39.19
June 2013	52	245,480	0.94	5,577	44	47.46
July 2013*	58	311,149	1.05	14,610	21	53.47
August 2013*	66	399,929	1.20	16,078	25	60.28

* July and August 2013 values were based on simulations of July and August 2012

Residence time is an indicator used to evaluate the renewal rate and is an index of how rapidly the water in the system is replaced. The theoretical residence time calculated is often longer than the actual residence time of water flowing through a wetland where waters are stagnant and not well mixed.

I used an empirical denitrification equation to estimate $NO_3^- + NO_2^-$ removal, which was parameterized using VIC model values from Table 38 and field data. Ecological engineers often treat wetlands as continuously stirred tank or plug flow reactors, which assume uniform mixing (Kadlec and Knight 1996). Based on this assumption, scientists often use first-order models to calculate nutrient removal constants to estimate different biological processes that underpin wetland nutrient retention (Kadlec and Knight 1996):

$$\ln\left(\frac{LianshiLake_{VNN}}{Wetland_{VNN}}\right) = -k_{VNN} * HRT \tag{12}$$

where k_{VNN} is the volume-based $NO_3^- + NO_2^-$ removal rate constant (day^{-1}) - the key parameter in the denitrification equation.

A modeled denitrification rate was estimated to assess the denitrification potential of the Wetlands on TN removal. For many constructed wetlands the main N constituent of concern is NH_4^+, which is first converted to NO_3^- via nitrification then removed as N_2 gas via denitrification. The microbial processes regulating denitrification are greatly affected by temperature especially at less than 15 °C, and the optimal range of microbial activity is 20-35 °C (Kadlec and Reddy 2001). A removal rate constant for denitrification (k_{DN}) is calculated as a function of water temperature:

$$k_{DN} = k_{20DN}\, \theta^{(T-20)} \tag{13}$$

where k_{20DN} is the removal rate constant at 20 °C, $k_{20DN} = k_{VNN} * 20$. A temperature correction factor for denitrification (θ) can be calculated using the equation by Arheimer and Wittgren (2002), $\theta = (\frac{T}{20})^{\frac{1}{(T-20)}}$. Next the denitrification rate is calculated using the volume-based denitrification rate constant (k_{DN}):

$$DN = k_{DN} * C_{NN} \tag{14}$$

where DN is the modeled denitrification rate (mg/L day^{-1}) and C_{NN} is the concentration of $NO_3^- + NO_2^-$ (mg/L).

Ecological production functions

I created ecological production functions using OLS regression models in Stata 12.1 (see Appendix C). All models were tested for their explanatory power using the Ramsey RESET test, link test, and variance inflation factor. The two production functions related wetland area and nutrient loading to TN and TP in Lianshi Lake:

$$LianshiLake = \beta_0 + \beta_1 Area + \beta_2 Loading + \varepsilon \tag{15}$$

where β_0 is the constant (y intercept), β_1 and β_2 are marginal effects of the ecosystem characteristics on final service indicators, *Area* is wetland area (ha), *Loading* is TN and TP loading concentrations (mg/L), and *LianshiLake* is the TN and TP concentrations (mg/L) in Lianshi Lake, and ε is the error term.

Spatial mapping

I used ArcGIS to locate pollution hotspots and assess the spatial distribution of water purification. Four maps were created using inverse distance weighted spatial interpolation to display: (1) TN water quality, (2) TP water quality, (3) TN and TP shortfalls, and (4) wetland nutrient retention.

RESULTS

Lake water quality

First I determined the general water quality trends at each lake section using the same sections currently used in the BWA water quality monitoring program. Water quality differed among the lakes and wetlands with the best water quality at upper Mencheng Lake and worst at upper Lianshi Lake. Across all months there was a consistent pattern with higher TN and TP concentrations at upper Lianshi Lake, lower Lianshi Lake, and lower Mencheng Lake compared to other sections (Figs. 45-46). The lowest TN and TP values were at upper Mencheng Lake where on average the TN was 2.03 mg/L and TP was 0.08 mg/L. At upper Lianshi Lake the average TN was 10-fold and TP was 23-fold greater than average TN and TP values at upper Mencheng Lake. Seasonality also seemed important when evaluating TN with the highest values in July 2013 likely due to increased stormwater entering the system because of monsoon rains. TP showed a slightly different trend with high values in May and June 2013, but rapid declines in July and August 2013. The declines are likely due to increased plant growth; phosphorus may be more limiting than nitrogen in this system.

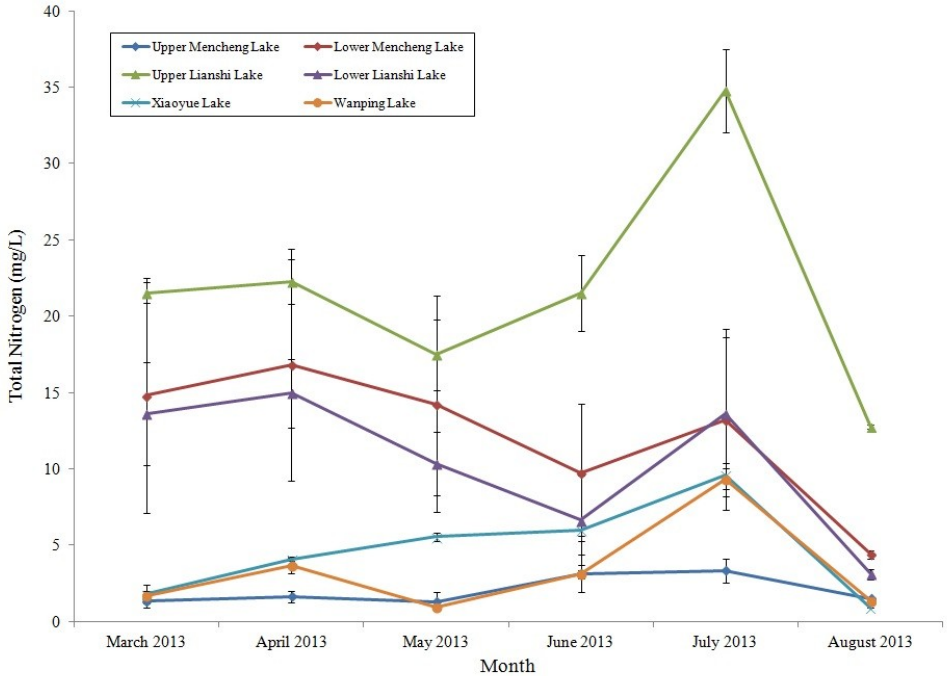


FIG.45. Average total nitrogen with standard error bars for each lake section from March 2013 to August 2013.

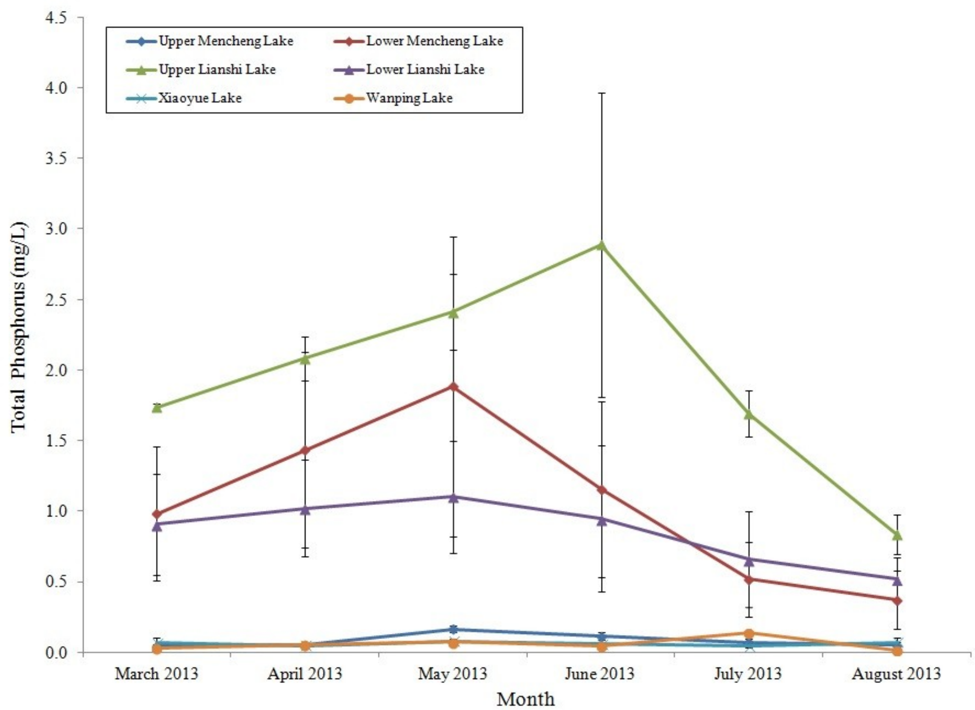


FIG.46. Average total phosphorus with standard error bars for each lake section from March 2013 to August 2013.

Next I created lake water quality maps to identify pollution hotspots, and the results indicate a substantial increase in TN (Fig. 47) and TP (Fig. 48) starting at site M7. At M6 the average TN was 2.68 mg/L and TP was 0.15 mg/L, however at M7 the average TN was 22.10 mg/L and TP was 2.17 mg/L. The sites are adjacent to each other approximately 480 m apart, and water travels between the sites via slow moving streams (Fig. 49). Two stormwater channels enter the system at M7 from both banks, and water directly from the channel was tested, which showed a TN of 58.24 mg/L and TP of 4.10 mg/L. The lake water quality results indicate that the nutrient loading source is the stormwater channels that feed into the Wetlands. In particular a dense human settlement, the largest on the Yongding Corridor, is located along the stormwater channel outlined in blue in Fig. 49. Wastewater from these homes runs directly into these channels, which flow into M7-L1. Also members of the field crew surveyed local residents to assess the likelihood of these neighborhoods contributing to the high nutrient levels. When asked about the water quality problems, local residents stated local sewage as the likely source of the water pollution on the Yongding Corridor (see Chapter 8). Also many identified water pollution as one of their top concerns for the future of the Yongding Corridor believing the pollution is causing the algal blooms in the Wetlands.

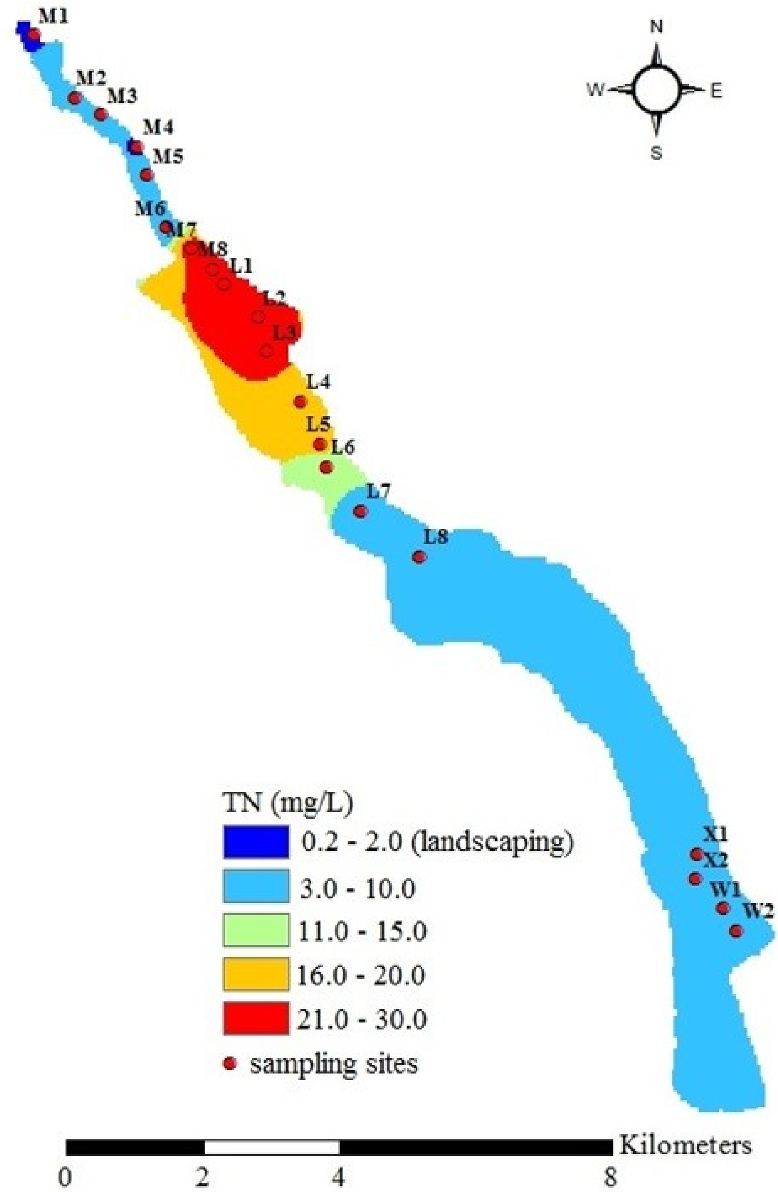


FIG. 47. Average total nitrogen on the Yongding River Ecological Corridor.

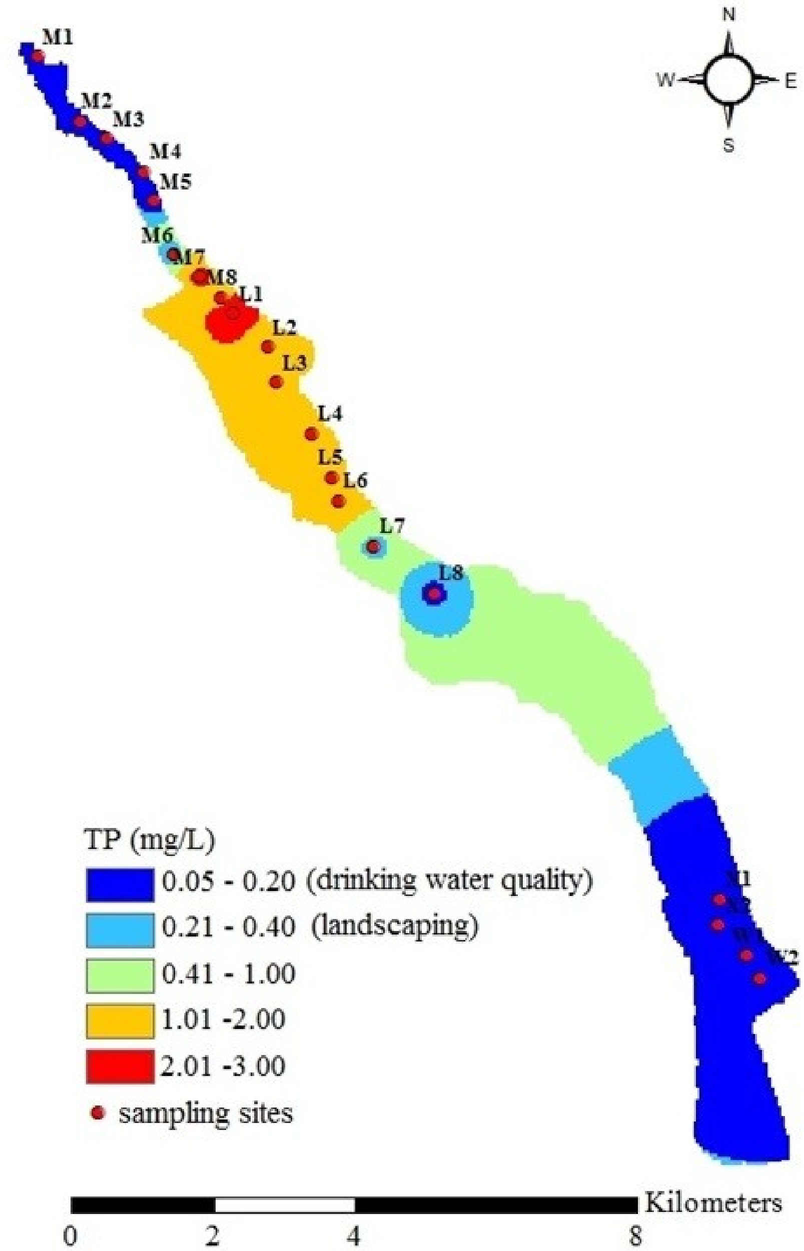


FIG. 48. Average total phosphorus on the Yongding River Ecological Corridor.

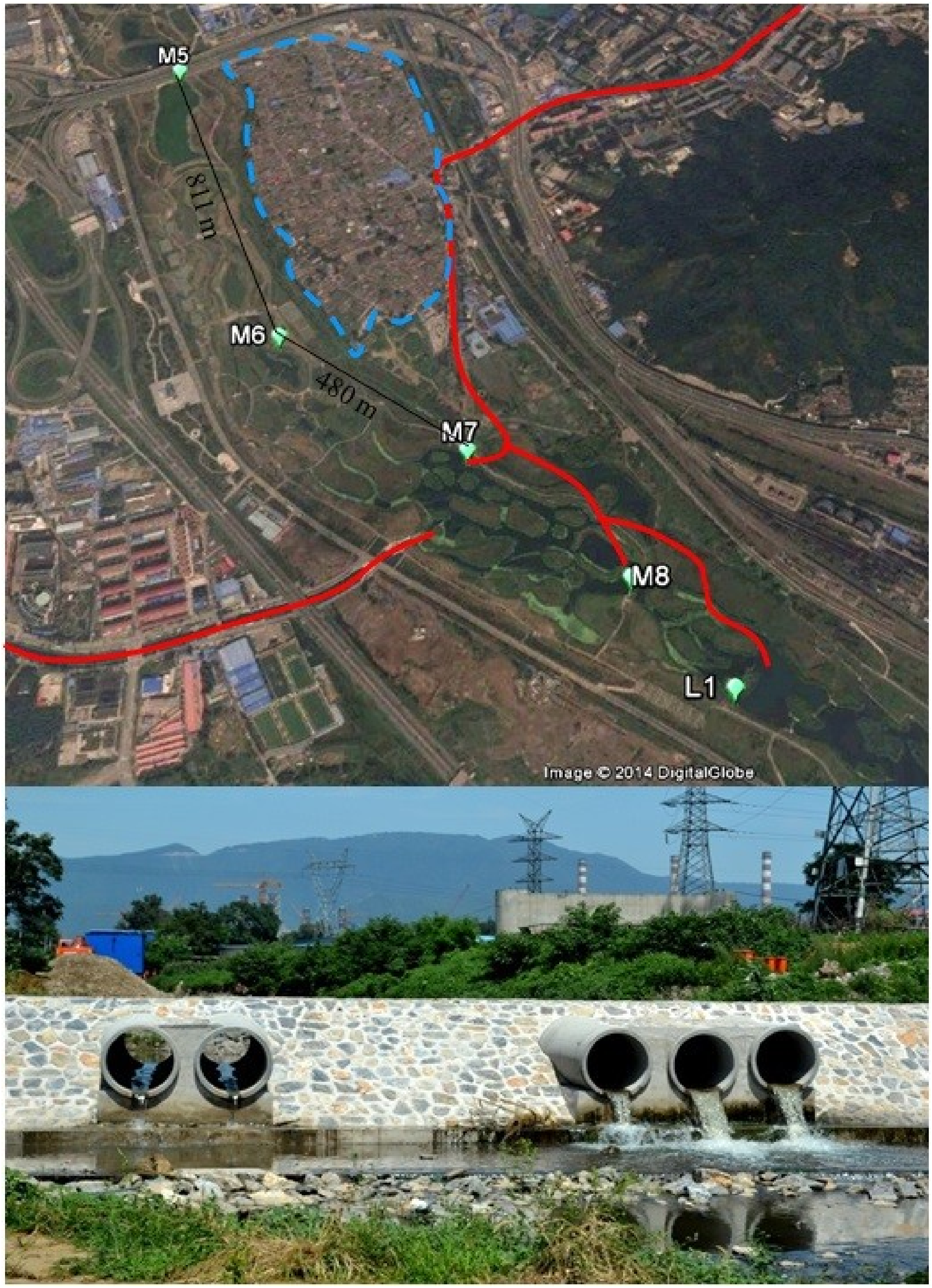


FIG. 49. Stormwater channels (outlined in red) feed into the Wetlands with water entering at M7. Outlined in dashed blue is a dense human settlement where wastewater has been seen going from the homes into the channels. The satellite image is of September 2013 taken from Google Earth, and the photo was taken at ground level at M7 in June 2013.

Water quality shortfalls

The majority of lake sections suffered water quality shortfalls since on average TN and TP were higher than a Grade V (Table 39). The BWA constructed the Yongding Corridor in part to improve water quality on the Yongding River from a Grade IV to a Grade III. All sections had water quality shortfalls for TN. The highest TN shortfalls were at lower Mencheng Lake, upper Lianshi Lake, and lower Lianshi Lake. The highest TP shortfalls were at the same sites, but upper Mencheng Lake, Xiaoyue Lake, and Wanping Lake met the desired standards with TP levels of a Grade II (Fig. 50).

TABLE 39. Final service shortfalls for Grade III endpoint.

Total Nitrogen Shortfalls (mg/L)						
Month	Upper Mencheng Lake	Lower Mencheng Lake	Upper Lianshi Lake	Lower Lianshi Lake	Xiaoyue Lake	Wanping Lake
March 2013	0.32	13.81	20.54	12.61	0.81	0.68
April 2013	0.62	15.80	21.28	13.95	3.09	2.68
May 2013	0.29	13.25	16.47	9.33	4.55	-0.09
June 2013	2.14	8.75	20.53	5.63	4.98	2.09
July 2013	2.32	12.21	33.77	12.64	8.60	8.29
August 2013	0.49	3.41	11.75	2.11	-0.11	0.32
Average	1.03	11.21	20.72	9.38	3.65	2.33
Total Phosphorus Shortfalls (mg/L)						
Month	Upper Mencheng Lake	Lower Mencheng Lake	Upper Lianshi Lake	Lower Lianshi Lake	Xiaoyue Lake	Wanping Lake
March 2013	-0.16	0.78	1.54	0.71	-0.13	-0.17
April 2013	-0.15	1.23	1.88	0.82	-0.15	-0.15
May 2013	-0.04	1.68	2.21	0.90	-0.12	-0.13
June 2013	-0.08	0.95	2.69	0.75	-0.14	-0.16
July 2013	-0.13	0.32	1.49	0.46	-0.16	-0.07
August 2013	-0.15	0.17	0.63	0.32	-0.13	-0.18
Average	-0.12	0.86	1.74	0.66	-0.14	-0.14

Note the negative numbers occur when the amount of the chemical concentration is lower than Grade III (i.e., improvement over the Grade III target).

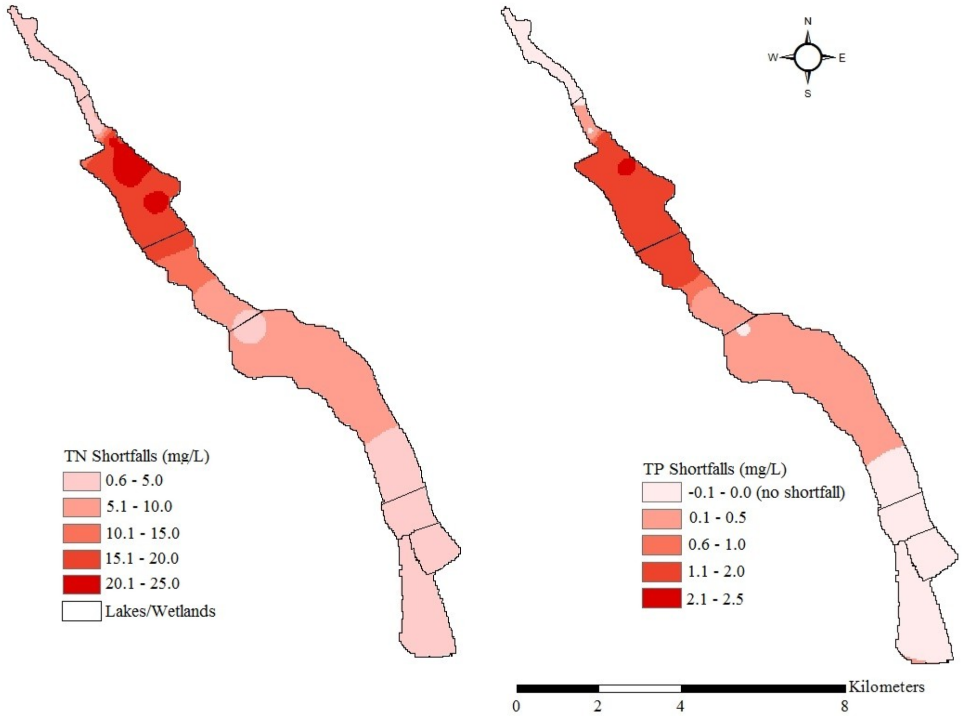


FIG.50. TN and TP shortfalls indicated that the water pollution enters at the Wetlands (lower Mencheng Lake, upper Lianshi Lake, and lower Lianshi Lake); relatively low nutrient levels at upper Mencheng Lake, Xiaoyue Lake, and Wanping Lake.

Nutrient loading and nutrient retention

After determining the water quality trends and shortfalls, I then calculated the nutrient loading and wetland nutrient retention to understand the problem causing the shortfalls. Upstream of the Wetlands the TN and TP were consistently lower than the TN and TP in the Wetlands (Table 40). Upstream of the Wetlands TN ranged from 1.39-3.38 mg/L and TP ranged between 0.05-0.12 mg/L. The Wetlands TN ranged from 10.10-30.20 mg/L and TP ranged between 0.80-2.63 mg/L. The Wetlands had a 9-fold increase in average TN and 19-fold increase in average TP compared to average upstream concentrations (Fig. 51). Lianshi Lake TN and TP were consistently lower than the Wetlands with TN from 2.67-11.81 mg/L and TP from 0.35-0.87 mg/L.

There were high nutrient loading concentrations, but substantial percent nutrient retention. The mean TN nutrient loading concentration was 18.88 mg/L and nutrient retention was 12.59 mg/L with a percent retention of 61% (Table 41). The mean nutrient retention was 1.80 mg/L and nutrient retention was 1.29 mg/L with a percent retention of 66%. Nutrient retention was highest for TN and TP in June and July 2013 likely due to increased wetland area. A nutrient retention map was created shown in Fig. 51.

TABLE 40. TN and TP (mg/L) for upstream, Wetlands, and Lianshi Lake.

Upstream of Wetlands				
Month	TN (mg/L)	Std. Dev.	TP (mg/L)	Std. Dev.
March 2013	1.40	0.68	0.08	0.07
April 2013	2.33	1.95	0.12	0.14
May 2013	1.53	1.01	0.16	0.05
June 2013	2.75	2.03	0.10	0.04
July 2013	3.38	1.25	0.07	0.04
August 2013	1.39	0.60	0.05	0.03
Wetlands				
Month	TN (mg/L)	Std. Dev.	TP (mg/L)	Std. Dev.
March 2013	23.04	3.83	1.73	0.08
April 2013	23.95	4.75	2.17	0.42
May 2013	19.44	6.03	2.63	0.99
June 2013	19.32	4.63	2.60	1.57
July 2013	30.20	7.46	1.47	0.42
August 2013	10.10	4.42	0.80	0.26
Lianshi Lake				
Month	TN (mg/L)	Std. Dev.	TP (mg/L)	Std. Dev.
March 2013	11.81	6.92	0.68	0.68
April 2013	13.65	4.46	0.83	0.69
May 2013	8.88	4.71	0.87	0.96
June 2013	4.15	3.73	0.54	0.80
July 2013	9.36	6.11	0.35	0.36
August 2013	2.67	1.64	0.39	0.21

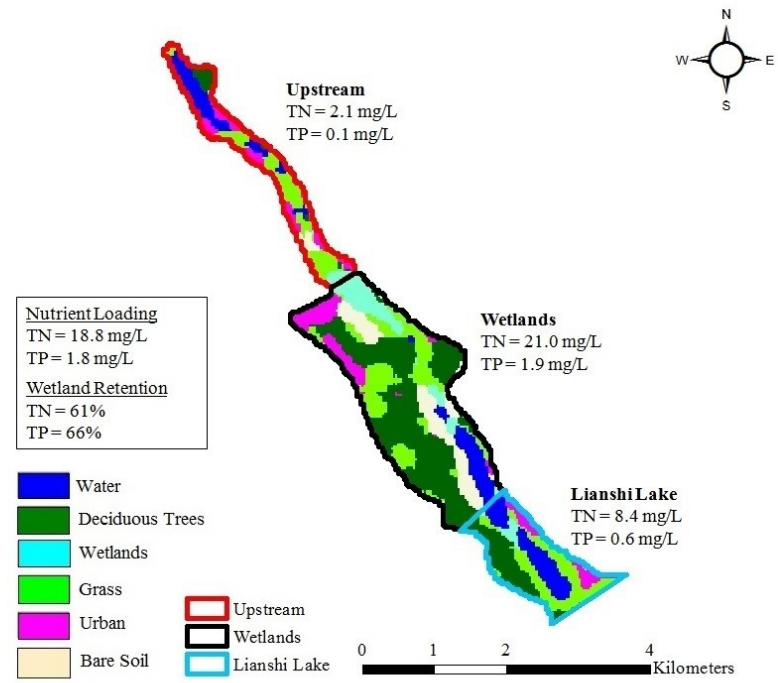


FIG. 51. Nutrient loading and wetland nutrient retention; shown are the average TN and TP concentrations of upstream of Wetlands, Wetlands, and Lianshi Lake sections.

TABLE 41. Nutrient loading and wetland retention.

Month	Loading mg/L	Loading kg ha day^{-1}	Retention mg/L	Retention kg ha day^{-1}	Percent Retention (%)
Total Nitrogen					
March 2013	21.63	1.14	11.23	0.59	49
April 2013	21.62	30.37	10.30	14.47	43
May 2013	17.92	41.25	10.57	24.32	54
June 2013	16.57	1.79	15.17	1.64	79
July 2013	26.81	6.73	20.83	5.23	69
August 2013	8.71	2.11	7.43	1.80	74
Average	18.88	13.90	12.59	8.01	61
Total Phosphorus					
March 2013	1.65	0.09	1.06	0.06	61
April 2013	2.05	2.89	1.34	1.89	62
May 2013	2.46	5.67	1.76	4.06	67
June 2013	2.49	0.27	2.05	0.22	79
July 2013	1.40	0.35	1.12	0.28	76
August 2013	0.75	0.18	0.41	0.10	51
Average	1.80	1.58	1.29	1.10	66

Modeled denitrification rates

To evaluate the biological processes underpinning the nutrient retention values, I first evaluated other key water quality parameters then modeled denitrification rates. I evaluated the seasonal changes of other water quality parameters: NH_4^+, NO_3^-+NO_2^-, DO, and pH, which indicated that biological processes are likely influencing nutrient retention (Table 42). Average NH_4^+ declined dramatically from the spring to summer since there were no plants in the spring. Managers remove all vegetation during the fall and winter months. In late-May 2013, managers replant the vegetation, which reaches peak growth in July and August. From March 2013 to June 2013, the mean NH_4^+ was 26.16 mg/L in the Wetlands. In July 2013 the NH_4^+ was 8.33 mg/L and 2.33 mg/L in August 2013. In contrast NO_3^-+NO_2^- levels started declining from May 2013 to August 2013. However unlike NH_4^+ there was low wetland retention of NO_3^-+NO_2^- in spring 2013, which suggests low denitrification rates.

DO is a good indicator of biological activity in the Wetlands, which went from an average 14.37 mg/L for March and April 2013 to as low as 3.25 mg/L in July 2013. Oxygen is produced during photosynthesis and consumed during respiration and decomposition. Increased temperature and/or excess nutrients may result in higher algal and plant growth, causing DO levels to increase. However when the algae and vegetation decompose, DO concentrations decline. The decrease in DO in the Wetlands is likely due to decomposition of algae in the summer months. The measured DO levels were similar to other surface flow wetlands, which have shown to range from 1.01-9.13 mg/L (Kadlec and Wallace 2009). Biological processes influence pH where open water zones within wetlands can develop high levels of algal activity (seen from June to August 2013 in Wetlands on the Yongding Corridor), which in turn create a high pH environment (Kadlec and Knight 1996). Bavor et al. (1988) showed that an unvegetated constructed wetland (wetland plants reduce establishment of algae by blocking sunlight) displayed high pH during summer periods (pH>9). The pH values were high in summer months at Lianshi Lake, which suggests algal growth.

TABLE 42. Inorganic N constituents, DO and pH at the Wetlands and Lianshi Lake.

	NH_4^+ (mg/L)		$NO_3^- + NO_2^-$ (mg/L)		DO (mg/L)		pH	
Month	Wetland	Lianshi Lake	Wetland	Lianshi Lake	Wetland	Lianshi Lake	Wetland	Lianshi Lake
March 2013	28.53	10.79	25.34	22.92	12.14	14.96	8.15	8.50
April 2013	29.61	12.90	21.23	23.26	16.60	13.66	9.03	9.20
May 2013	21.89	4.70	7.39	6.89	5.82	11.69	9.03	9.70
June 2013	24.60	3.17	3.80	2.17	5.09	9.96	8.59	9.37
July 2013	8.33	0.17	3.82	2.82	3.25	15.97	8.40	9.73
August 2013	2.33	0.33	4.60	2.91	4.56	9.35	8.04	8.90

The modeled denitrification rate indicates possible fluctuations in denitrification in the Wetlands ranging from 0.06-0.78 kg N ha d^{-1} (Table 43). Modeled denitrification was low in spring 2013 and higher in summer 2013 except July 2013. Increased denitrification in the summer would be expected because of higher temperatures, increased availability of organic material, and lower DO levels. For constructed wetlands, Chavan and Dennett (2008) calculated k_{DN} values from 0.09-0.91, and Kadlec and Knight (1996) calculated k_{DN} values from 0.026-0.62. The Wetlands k_{DN} values ranged from 0.001-0.047. For a *Phragmites* constructed wetland in Kunming City, Lu et al. (2009) calculated that the majority of N removal was due to plant uptake with an estimated 7% contribution from denitrification.

TABLE 43. Modeled denitrification rate using denitrification removal constant (k_{DN}).

Modeled Denitrification Rate						
Month	k_{VNN}	T	k_{DN}	DN (mg/L day^{-1})	DN (kg N ha d^{-1})	Percent of TN removal (%)
March 2013	0.001	9.21	0.001	0.01	0.06	10
April 2013	-0.078	14.87	-0.058	-1.23	-2.03	---
May 2013	0.042	22.64	0.047	0.35	1.37	6
June 2013	0.013	28.77	0.018	0.07	0.33	20
July 2013	0.014	29.41	0.021	0.08	0.43	8
August 2013	0.018	30.46	0.028	0.13	0.78	43

Ecological production functions: Wetland area and nutrient loading to lake water quality

Lastly I created ecological production functions using OLS regression models, which showed significant relationships between wetland area and TN and TP, and nutrient loading and TN using an F-test at $P<0.05$ level (Table 44). The ecological production functions had R^2 for TN of 0.86 and TP of 0.93. For wetland area the P-value for TN was 0.04 and 0.01 for TP, which are statistically significant. The regression coefficients suggest that a 1 ha increase in wetland area would likely result in a 0.10 mg/L decrease in TN and 0.01 mg/L decrease in TP at Lianshi Lake. For nutrient loading, only the regression coefficient for TN was statistically significant with a P-value of 0.03. A 1 mg/L increase in the TN load would likely result in an increase of 0.41 mg/L in TN at Lianshi Lake.

TABLE 44. Regression statistics for water purification ecological production functions.

Total Nitrogen								
	Area Coefficient (Marginal Effect)	P-Value	95% CI	Loading Coefficient (Marginal Effect)	P-Value	95% CI	R^2	RMSE
TN	-0.10 (0.03)	0.04	-0.19 to -0.01	0.41 (0.10)	0.03	0.09 to 0.72	0.86	2.04
Total Phosphorus								
	Area Coefficient (Marginal Effect)	P-Value	95% CI	Loading Coefficient (Marginal Effect)	P-Value	95% CI	R^2	RMSE
TP	-0.01 (0.001)	0.01	-0.01 to -0.003	0.04 (0.03)	0.28	-0.06 to 0.15	0.93	0.07

R^2 is coefficient of determination, the standard errors are reported in parentheses to coefficients
CI is confidence interval
RMSE is root mean squared error

DISCUSSION

Water quality shortfalls

From March 2013 to August 2013, the majority of lake sections had water quality shortfalls since on average the TN and TP concentrations were higher than a Grade V. The general trend of the water quality results matched the BWA water quality results (Lü et al. 2012). Across all months the best average water quality was at upper Mencheng Lake (TN = 2.03 mg/L; TP = 0.08 mg/L) and worst average water quality was at upper Lianshi Lake (TN = 21.72 mg/L; TP = 1.94 mg/L). Upper Mencheng Lake had no TP shortfalls across all months in fact the water quality was at a Grade II, and for the majority of months had no TN shortfalls except in June and July 2013. Upper Mencheng Lake marks the beginning of the water circulation system, and engineers noted the water circulation problems occurred below upper Mencheng Lake (Lü et al. 2012). The higher TN levels in June and July 2013 are likely because of stormwater from summer monsoons. Furthermore Xiaoyue Lake and Wanping Lake had no TP shortfalls across all months, but had TN shortfalls for the majority of months. The high nutrients were concentrated at upper Lianshi Lake with an average TN shortfall of 20.72 mg/L and TP shortfall of 1.74 mg/L. Managers were uncertain of the cause of the increased nutrient levels in this section. I identified that the likely cause of the increase in nutrients is domestic sewage from shoreline homes where water enters the system via stormwater channels in the Wetlands. Water entering the system via the stormwater channel had a TN of 58.24 mg/L and TP of 4.10 mg/L.

Nutrient loading and nutrient retention

The nonpoint pollution led to high nutrient loading concentrations in the Wetlands, but the Wetlands were able to provide substantial nutrient retention. The average TN loading concentration was 18.88 mg/L and average TP was 1.80 mg/L. The Wetlands provided an average percent retention of 61% for TN and 66% for TP. For TN the percent retention was highest from June to August 2013, and for TP the percent retention was highest from May to July 2013. Increased wetland retention is likely due to increased water volumes and vegetation in the summer months. It was estimated that denitrification only contributed on average 17% to TN retention. Managers attributed water circulation problems as the cause of water quality problems (Lü et al. 2012). However for the Wetlands to provide the water purification service they need high residence times (i.e., slow turnover rate) to allow plants to uptake nutrients and microbes to perform denitrification. If the water flows too quickly through the Wetlands it simply could lead to higher nutrient levels in Lianshi Lake. Summer algae blooms in constructed wetlands are common since they are high nutrient and low flow environments. The challenge is balancing functionality and aesthetics in the Wetlands. Managers are currently employing a useful technique of floating vegetation using water hyacinth to reduce algal establishment while increasing wetland nutrient retention, which maintenance workers harvest to prevent decomposition. Management believes water quality will improve after the subsurface wetlands are completed (Lü et al. 2012). However the subsurface wetlands are designed to improve water quality prior to entering the lakes/wetlands. From my analysis I found that nonpoint pollution is the problem, and the surface wetlands are providing a critical role in buffering Lianshi Lake.

Management

The use of 20 sites to monitor water quality provided valuable information on water quality shortfalls, nutrient loading, and wetland retention. Information from the 20 sites was used to select 8 sites for long-term monitoring by the State Key Laboratory of Urban and Regional Ecology (SKLURE) (Fig. 52). The SKLURE is taking monthly water samples at the 8 sites to assess water quality changes after the subsurface wetlands are completed. The 8 sites will be presented to the BWA to help improve the agency's water quality monitoring program on the Yongding Corridor. The BWA is currently monitoring to evaluate proximity of lake water quality to Grade III. Strategically selecting monitoring sites is useful for tracking performance and understanding the mechanisms driving outcomes to inform actions.

I created two ecological production functions to relate management options of wetland area and nutrient loading to Lianshi Lake water quality. Based on the statistically significant regression coefficients, the results suggests that given a 1 ha increase in wetland area one would likely expect a 0.10 mg/L decrease in TN and 0.01 mg/L decrease in TP at Lianshi Lake. Furthermore given a 1 mg/L increase in nutrient load one would likely expect a 0.41 mg/L increase in TN. Managers would likely have to increase wetland area by 40 ha to obtain the TP final service level, and reduce average TN nutrient load concentration by 14 mg/L to obtain the TN final service level. Managers can regulate urban runoff entering the system using retention ponds. However the most promising approach is working with neighborhood residents who have shown a concern for local water quality. District-level governments need to discuss with local residents to identify feasible alternatives to reduce the dumping of domestic waste into channels.

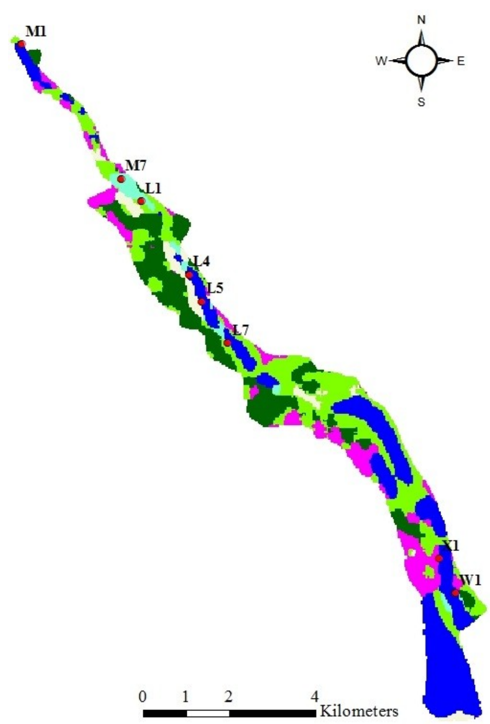


FIG.52. Final 8 water monitoring sites at Mencheng Lake (M), Lianshi Lake (L), Xiaoyue Lake (X), and Wanping Lake (W).

CONCLUSION

In summary the surface flow wetlands are improving water purification on the Yongding River, however the nutrient load is too high to meet the final service levels for TN and TP at the majority of lake sections. Management either needs to increase wetland area and/or reduce nutrient loading by regulating nonpoint pollution entering the lakes/wetlands. Working with local residents to reduce the dumping of waste into channels seems like the most promising option. The key findings from this chapter are:

- Across all months the best average water quality was at upper Mencheng Lake and worst was at upper Lianshi Lake.
- The majority of lake sections had water purification shortfalls with average TN and TP higher than Grade V.
- Nutrient pollution was concentrated at the Wetlands, and the likely source is domestic sewage from shoreline homes.
- Average nutrient load for TN was 18.88 mg/L and for TP was 1.80 mg/L.
- Average wetland nutrient retention was 61% for TN and 66% for TP.
- Given a 1 ha increase in wetland area one would likely expect a 0.01 mg/L decrease in TP, and given a 1 mg/L increase in nutrient load one would likely expect a 0.41 mg/L increase in TN.
- The results suggest that mangers would likely have to increase wetland area by 50% to obtain the TP final service level, and reduce the mean TN nutrient load concentration by 75% to obtain the TN final service level.

CHAPTER 7

DUST CONTROL

ABSTRACT

Particulate matter (PM) is a serious health concern among the public in China. In Beijing the primary air pollutant is PM_{10}, and the main local dust source believed to increase PM_{10} during peak dust months (i.e., March and April) is the Yongding River. Dust control from the Yongding River Ecological Corridor was evaluated comparing sand flux and PM_{10} levels for March – April 2010 (pre-Corridor) and March – April 2013 (post-Corridor). For both the pre- and post-Corridor periods, mean daily PM_{10} was higher than the Grade II national standard (150 μg m^{-3} – legal limit for urban residents), thus there were air quality shortfalls (20 days for pre-Corridor; 28 days for post-Corridor). Mean daily PM_{10} was not significantly different between both periods, but mean daily PM_{10} for March went from 173 μg m^{-3} (pre-Corridor) to 258 μg m^{-3} (post-Corridor). I used empirical wind erosion equations created for different land cover classes on the Yongding River in Beijing to estimate sand flux rates (also referred to as dust). The modeled sand flux emissions were low in both periods at local and regional scales. Monthly averages were: 0.004 g $month^{-1}$ (local) and 0.131 g $month^{-1}$ (regional) in pre-Corridor, and 0.001 g $month^{-1}$ (local) and 0.050 g $month^{-1}$ (regional) in post-Corridor. The percent reduction in modeled sand flux emissions was estimated to be 67% (local) and 50% (regional). Despite an estimated reduction in sand flux, ecological production functions using regression models indicated no significant and interpretable relationships between sand flux and PM_{10} at local and regional scales.

INTRODUCTION

China is notorious for severe air pollution, and according to the World Bank (2007) 16 of the world's 20 most polluted cities are in China. International scrutiny and public concern over air quality has led to revisions in national standards, municipal targets (e.g., Beijing's commitment to close all coal power plants by 2020), sulfur dioxide reductions (e.g., coal power plants with scrubbers at 10% in 2005 to 71% in 2010), and ecosystem restoration. An air pollutant of principal concern is particulate matter (PM), which has garnered significant media attention. PM poses a difficult challenge because it comes from multiple sources: dust from windstorms and construction, coal combustion, vehicle use, industrial emissions, etc.

PM pollution is an air-suspended mixture of solid and liquid particles that vary in size, shape, chemical composition, and origin (Pope and Dockery 2006). Coarse particles measured as PM_{10} (particles with a diameter<10 μm) are derived primarily from dust also known as sand from roads, farming, windstorms, etc. Fine particles measured as $PM_{2.5}$ (particles with a diameter<2.5 μm) are derived primarily from direct emissions from combustion processes, such as vehicle use, coal burning, industrial emissions etc. Health effects associated with high PM_{10} and $PM_{2.5}$ ($PM_{2.5}$ pose the greatest health risks) exposure are breathing and respiratory problems, and damage to lung tissue, which can lead to increased mortality rates (US EPA 1995). In 2003 58% of China's urban population was exposed to annual average PM_{10} levels reported to be greater than 100 $\mu g\ m^{-3}$ (twice the U.S. annual average standard) while only 1% had air considered safe in the European Union (World Bank 2007).

Beijing ranks as one of the worst cities in China in terms of air pollution, and the main air pollutant is PM. From 1999-2005, PM_{10} was reported to be the major air pollutant on about 90% of the days in Beijing (An et al. 2013). From 2003-2005, the annual average PM_{10} was 40% higher than the Ministry of Environmental Protection's (MEP) Grade II standard (100 μg m^{-3} for PM_{10}) and seven times higher than the World Health Organization (WHO) air quality guidelines (Chan and Yao 2005). Hao and Wang (2005) estimated the primary sources of PM_{10} in Beijing as: dust (49%), coal burning (28%), vehicle exhaust (8%), and other sources (15%). Several studies identified dust from bare soil as a key contributor to PM_{10} (Hao and Wang 2005, Wang et al. 2006), and background PM_{10} levels have shown significant increases during dust events (Wang et al. 2006). Scientists found sand flux is directly proportional to PM_{10} during dust events at Owens Lake in California (Gillette et al. 2004) and the Columbia Plateau in Washington (Claiborn et. al. 1998) causing PM_{10} to exceed U.S. air quality standards in these regions.

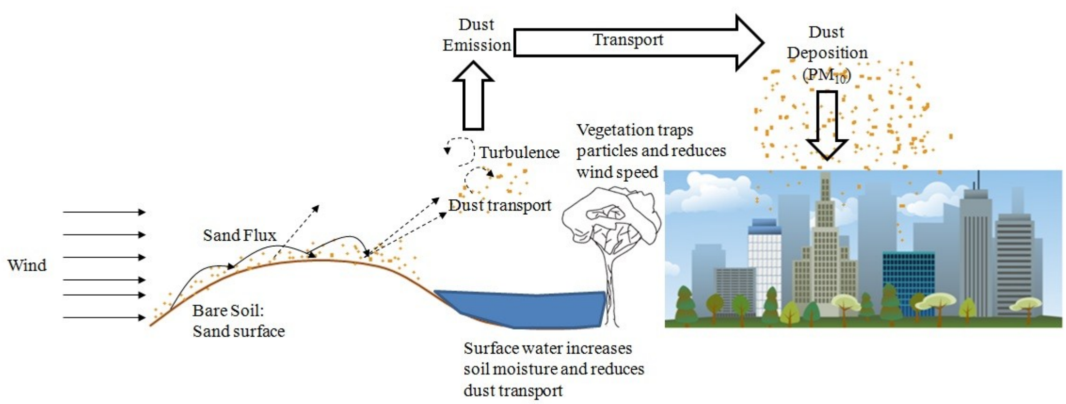


FIG. 53. Physical processes of wind erosion that influence dust emission, transport, and deposition leading to increased PM_{10} in Beijing. Information on processes from Lu and Shao 2001, Zhou et al. 2002, but conceptual drawing was constructed by me.

Seasonal wind conditions determine the frequency and magnitude of dust events. Wind erosion is the transport of soil particles by wind (Fig. 53), and is one of the most important processes leading to increased desertification in Northern China (Yue et al. 2006a). The Beijing Meteorological Bureau categorizes dust events as: floating dust (visibility<10km), blowing dust (visibility 1-10km), and dust storm (visibility<1km) (Zhang and Wang 2003). Blowing dust is primarily from local sources while floating dust and dust storms are derived from regional sources. In Beijing, the most common dust event is blowing dust (71%)>floating dust (20%)>dust storm (9%) (Xie et. al. 2005). Generally more than 90% of dust events in Beijing occur from February to June with an average PM_{10} of 202 μg m^{-3}, which is about a 25% increase from average PM_{10} from July to January (Wang et al. 2006). Increased coal burning for heating purposes is the principal cause of high PM_{10} in the winter, and dust is the main cause of elevated PM_{10} in the spring (Wang et al. 2006).

In recent years dust events have increased in frequency with enhanced intensity and expanded scale of influence in Beijing (Dong 2002, Wang et al. 2005). Dust events from bare soils come from local and regional sources (Hebei Province and Inner Mongolia Autonomous Region). The Yongding River is considered the largest of the five local sources of wind erosion in Beijing (Yue et al. 2006b). Scientists compared sand composition in Beijing to regional sands, and found the majority of sands during dust events originate from the Yongding River (Dong 2002). The Yongding River was once feared by many emperors as a flood threat, which led to centuries of manipulation to tame the river (signified in the river's current name *Yǒngdìng* meaning forever stable). The upper reaches of the Yongding River were altered by deforestation and flood regulation, which resulted in high soil erosion and increased sedimentation downstream. In the last 30 years, the Yongding River has been dry in Beijing, exposing sandy sediments. People exploited these barren lands creating sand pits to harvest sands for construction, and creating crop fields to utilize fertile sediments. Scientists recommend using ecosystems to reduce PM_{10} from dust events, and Beijing has been investing in ecosystem projects to improve dust control.

Dust control is quickly becoming an important ecosystem service in Beijing. Dust control is defined as the physical and biological processes of ecosystems to reduce dust deposition. In the past decade, the Beijing government began investing in afforestation on the Yongding River known as the "Green Wall" initiative where grass and row trees were planted as wind breaks (China Daily 2005). In 2010 the Beijing government decided to construct the Yongding River Ecological Corridor using a combination of lakes/wetlands and trees, in part to enhance dust control along the Yongding River (Fig. 53).

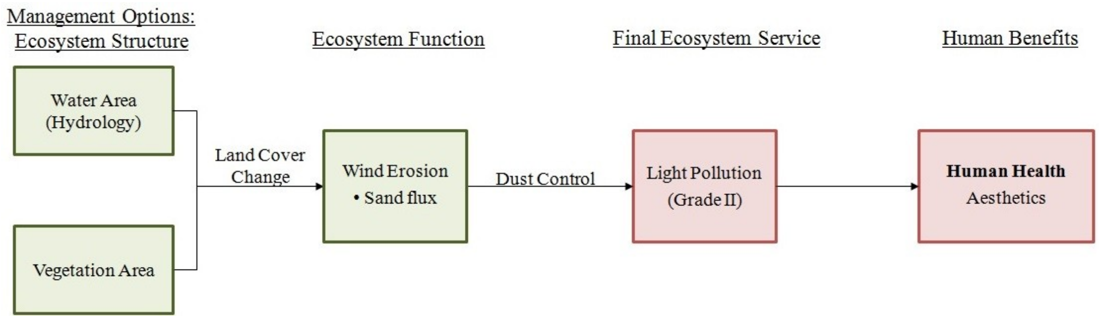


FIG. 54. Conceptual diagram linking management options as changes in ecosystem structure to ecosystem functions to final ecosystem services and human benefits. Human benefit in bold is direct benefit of concern to management regarding dust control, however air quality underpins cultural ecosystem services explored in Chapter 8.

The Beijing government wants the ecological improvements on the Yongding Corridor to reduce wind speed and sand flux to decrease PM_{10} levels (Shi 2013). The Beijing Water Authority (BWA) constructed six lakes/wetlands covering an area of 651 ha, and planted trees and grasses covering an area of 1,357 ha to prevent sand flux from the Yongding River (BWA 2009). The BWA wants information on the impact of the new ecosystems on improving dust control. Currently the relationship between dust control from the new ecosystems and PM_{10} are unknown. In the literature, the Yongding River is considered an important local dust source, but there is high uncertainty on whether or not reducing sand flux from its channels will translate to PM_{10} reductions. Information on the influence of increased water area and vegetation area in reducing PM_{10} could help assist air pollution efforts in Beijing. The challenge is linking management options (water area and vegetation area to reduce bare soil area) to sand flux to PM_{10} (Fig. 54).

In this chapter I estimate dust control by assessing changes in sand flux rates due to the addition of new ecosystems on the Yongding Corridor in Beijing. First final services were selected using China's national air quality standards. Second final service indicators were measured using Air Pollution Index/Air Quality Index (API/AQI) data to derive daily PM_{10} for 2009-2010 (pre-Corridor) and 2012-2013 (post-Corridor). Third I conducted a simple analysis to estimate sand flux emissions for pre- and post-Corridor periods using empirical wind erosion equations for different land cover classes on the Yongding River in Beijing. Fourth I created ecological production functions using ordinary least squares (OLS) regression models to link modeled sand flux to PM_{10}. Chapter objectives are to estimate: (1) air quality shortfalls, (2) dust control from the new ecosystems, (3) marginal effect of sand flux on PM_{10}, and (4) the spatial distribution of PM_{10} in Beijing in pre- and post-Corridor periods.

METHODS

Below I provide a brief outline of how I present my methods and results in this chapter. My measurement approach consists of six general steps shown in Fig. 55. First I selected the final service indicator as China's national PM_{10} standard using the Grade II endpoint (150 $\mu g\ m^{-3}$ – legal limit for urban residents). I determined mean daily PM_{10} levels during the pre-Corridor (March and April 2010) and post-Corridor (March and April 2013) periods using API/AQI data. I then determined air quality shortfalls taking the difference between mean daily PM_{10} levels and the Grade II level. Second I used ArcGIS to create PM_{10} maps to illustrate the difference in the spatial distribution of PM_{10} levels between the pre-and post-Corridor periods. Third I created air quality shortfall maps to identify the locations of air quality shortfalls. Fourth I estimated mean daily sand flux rates using Yongding River empirical equations, presented as an aggregate across all land cover classes. Fifth I estimated the percent reduction of sand flux between the pre- and post-Corridor periods. Lastly, I estimated the marginal effects of daily sand flux on average daily PM_{10} at local and regional scales for pre- and post-Corridor periods using ecological production functions as OLS regression models.

In summary I evaluated dust control comparing pre- and post-Corridor periods to: (1) estimate the potential change in sand flux rates from the land cover changes, (2) determine the distribution of PM_{10} levels, and (3) relate modeled sand flux rates to PM_{10} (Table 45). The data collected and methods used to measure PM_{10} and model sand flux rates are outlined in Table 46. The methodological steps are explained in detail in the following subsections.

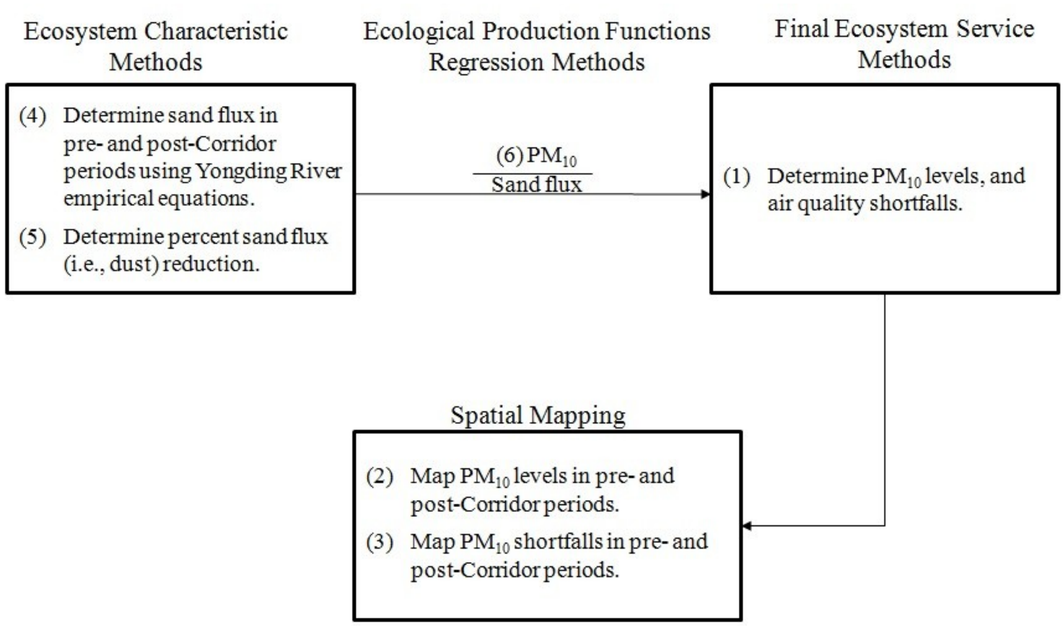


FIG.55. Methodological steps to estimate dust control from the Yongding River Ecological Corridor.

TABLE 45. Main measurement steps to evaluate dust control from the Yongding River Ecological Corridor.

Ecosystem Service Measurement Steps	Dust Control
Relating Management Options to Ecosystem function	Determine sand flux rates for pre- and post-Corridor periods during March and April. Determine percent sand flux reduction between both periods during March and April.
Relating Final Service to Potential Beneficiaries	Determine PM_{10} levels for pre- and post-Corridor periods at varying distances from the Yongding River during March and April.
Relating Ecosystem function to Final service	Determine marginal effect of sand flux on PM_{10} for pre- and post-Corridor periods during March and April.

TABLE 46. Data to measure dust control.

Data to Measure Dust Control					
Category	PM_{10} ($\mu g\ m^{-3}$) indicator	Data to parameterize model			Modeled ecosystem function
Data type	Air pollution index	Wind speed (m/s)	Land cover (ha)	Lake/wetland area (ha)	Sand flux (g cm^{-2} day^{-1})
Data source	Beijing Environmental Protection (BEP) Bureau	Mentougou Meteorological Bureau	Landsat remote sensing	Variable Infiltration Capacity model	Yue (2004), Yue et al. (2006b) wind erosion equations
Purpose	Benefit is air quality improvement.	Land cover change to sand flux.			

Study area

The Yongding Corridor is located on the Yongding River in Beijing, which consists of three sections: (1) mountainous, (2) urban, and (3) outerurban. In Beijing the wind direction is northwest and north in winter and spring, and southeast and south in summer and fall. The elevation of the mountainous section of the Yongding Corridor is greater than 1,000 m and the urban and outerurban sections are located in the flood plains having an elevation less than 150 m (Fig. 56). The difference in topography leads to increased wind speeds in the plain sections since winds are funneled through mountain passes, which intensify their effect in the urban and outerurban plains. The annual average wind speed on the Yongding River in Beijing spans 2.1 – 3.0 m/s. The fastest wind speed occurs in the spring with an average of 3.5 – 4.0 m/s, and slowest in the summer with an average of 1.5 – 2.5 m/s.

In Beijing dust events occur primarily in the spring and secondarily in the winter with both seasons accounting for over 90% of all dust events. There have been no recorded dust events from August – October; March and April have the highest frequency of dust events (Xie et al. 2005). In this study, I evaluate the sand flux and PM_{10} during peak dust months, which are March and April. Beijing has a seasonal temperate and semiarid continental monsoonal climate. The average annual precipitation spans 550 – 660 mm, and roughly 85% of the rainfall occurs from June – September. Spring is dry and windy, summer is hot and humid, and winter is cold; the annual average daily temperature is 10 – 12 °C.

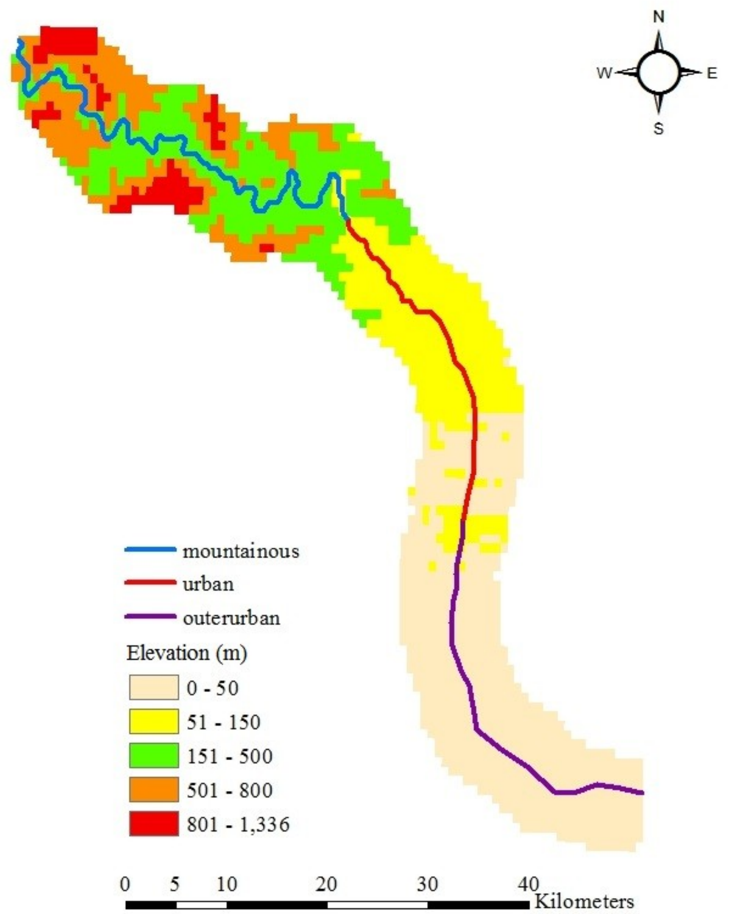


FIG.56. Elevation of mountainous, urban, and outerurban sections of the Yongding River Ecological Corridor in Beijing.

Yue et al. (2006a, 2006b) characterized the land cover of the Yongding River in Beijing as: (1) cropland (corn fields on coarse sandy soils), (2) grass (grass species are *Digitaria Sangurinalis* and *Chloric Virgata*), (3) bare soil (bare sand with sparse grasses), and (4) deciduous broad-leaf trees (*Populus Semori* plantations). Yue et al. (2006b) empirically calculated sand flux rates for each land cover, most substantial to least were: bare soil> cropland> grassland>deciduous broad-leaf trees. In 2010, I conducted field surveys to assess the land cover on the Yongding River before the addition of the new ecosystems; field observations matched Yue et al. (2006a, 2006b) classifications (Fig.57).

FIG.57. Different land cover types on Yongding River in 2010: (A-B) deciduous broad-leaf trees in mountainous section, (C-D) grass in urban section, and (E-F) deciduous broad-leaf trees as wind breaks and corn fields.

The spatial scale of the analysis is: (1) *local* defined as the six lakes and wetlands in the urban section (20 km long 19.5 km^2) and (2) (1) *regional* defined as the urban and outerurban sections of the Yongding Corridor + 5 km buffer (78 km long and 738 km^2). The temporal scale of the analysis is peak dust months: (1) pre-Corridor (March and April 2010) and (2) post-Corridor (March and April 2013). The temporal and spatial scales of analysis are summarized in Table 47.

TABLE 47. Description of the temporal and spatial scales of the analysis.

Temporal and Spatial Scales			
Category	Peak dust	New ecosystems	Beneficiaries
Scale	Pre-Corridor: March and April 2010 Post-Corridor: March and April 2013	Local: lakes/wetlands in urban section. Regional: urban and outerurban sections	PM_{10} data from 9 stations to assess air quality distribution in Beijing in March and April.
Purpose	Determine percent dust reduction.	Relate local land cover changes to regional sand flux.	Distribution of PM_{10} at varying distances from Yongding River.

Final services and final service indicators

China's ambient air quality standards on PM_{10} were used to determine the final service level for dust control. The BWA's management objective is to reduce dust from the Yongding River in Beijing to improve air quality. The MEP's daily PM_{10} endpoint for Grade II (GB 3095-1996) was selected as the final service level (Table 48). In Beijing PM_{10} levels above a Grade II are considered unsuitable. I discussed the Grade II endpoint for daily PM_{10} with the Beijing Water Science and Technology Institute (BWSTI) staff, who considered the national standard a legitimate final service for dust control.

TABLE 48. National ambient air quality standards in China for daily PM_{10}.

Peoples' Republic of China Ministry of Environmental Protection Air Quality Standards (GB3095-1996)			
Air Quality Endpoint ($\mu g\ m^{-3}$)	Grade I	Grade II	Grade III
Daily PM_{10}	50	150	250

Grade I pertains to nature reserves, resorts, and other areas in need of special protection.
Grade II pertains to residential areas (i.e., cities and rural areas).
Grade III pertains to industrial areas.

Air quality data is publicly reported as Air Pollution Index (API) values (June 2009 to December 2012), which were recently revised to Air Quality Index (AQI) values (January to June 2013). Chinese API and AQI values are a scientific measure of air quality used to alert the public about air pollution, warning people when to wear masks and avoid outdoor activities (Andrews 2008, Zheng et al. 2014). On February 29, 2012 the MEP approved a technical revision to the API, and since January 1, 2013 the Beijing Environmental Protection Bureau (BEP) began publishing daily AQI instead of API. The equation to convert PM_{10} to AQI is the same as for the API. The change between API and AQI for PM_{10} is more stringent classifications for air pollutant levels with corresponding health implications (Table 49). Each day the highest API (AQI) is reported for the primary pollutant (API>50), and almost every day the primary pollutant is PM_{10} in Beijing, especially in March and April. I calculated daily average PM_{10} concentrations using the API (AQI) values on days when PM_{10} was the primary pollutant (Table 50), which was the final service indicator. Air quality shortfall is the difference between daily average PM_{10} (derived using the API/AQI values) and the Grade II endpoint (150 $\mu g\ m^{-3}$ – legal limit for urban residents).

TABLE 49. Air Pollution Index (API) and new Air Quality Index (AQI) with corresponding daily average PM_{10} concentrations and defined health implications.

API (AQI)	Daily average PM_{10} ($\mu g\ m^{-3}$)	API Categories (MEP 2008)		AQI Categories (MEP 2012)	
		Air pollution level	Health implications	Air pollution level	Health implications
50	50	Excellent	None	Good	Satisfactory air quality.
100	150	Good	None	Moderate	Acceptable air quality.
150	250	N/A	N/A	Unhealthy for sensitive groups	Members of sensitive groups may experience health effects; general public likely unaffected.
200	350	Lightly polluted	Slight irritations may occur, individuals with breathing or heart problems should reduce outdoor exercise.	Unhealthy	Everyone may experience health effects; members of sensitive groups may experience more serious health effects.
300	420	Moderately polluted	People with breathing or heart problems, and elderly should remain indoors and restrict activities.	Very unhealthy	Health warnings of emergency conditions; entire population is likely to be affected.
400	500	Severely polluted	General public may experience strong irritations and symptoms. Elderly and children should remain indoors and avoid outdoor exercise.	Hazardous	Health alert; everyone may experience more serious health effects.
500	600		General public should avoid outdoor activities.	Hazardous	

TABLE 50. Equations to determine daily average PM_{10} using API (AQI) values.

API (AQI)	PM_{10} Equations ($\mu g\ m^{-3}$)
0-51	API
51-200	(API - 25)*2
201-300	(API + 300)/1.429
301-400	(API + 225)/1.25
401-500	API + 100

For 2009-2010 and 2012-2013, daily API (AQI) data were obtained from 9 BEP stations (Fig. 58). Stations were selected at different distances from the Yongding Corridor: (1) less than 5 km, (2) 10 km, (3) 20 km, and (4) 50 km. Stations less than 5 km are: (a) Longquan (Mentougou district), (b) Gucheng (Shijingshan district), (c) Yungang (Fengtai district), and (d) Huayuan (Fengtai district). Stations 10 km away are: (a) Huangcun (Daxing district), (b) Zhiwuyuan (Haidain district), and (c) Liangxiang (Fangshan district). Local PM_{10} was the average daily PM_{10} using the four stations (Longquan, Gucheng, Yungang, and Huayuan) located in the urban section. Regional PM_{10} was the average daily PM_{10} using six stations (Longquan, Gucheng, Yungang, Huayuan, Huangcun, and Liangxiang) located in the urban and outerurban sections. Two additional stations were selected to compare PM_{10} levels near the Yongding Corridor to general PM_{10} levels in Beijing, representing the city center (Guanyuan (Xicheng district)) and furthest eastern edge of the city approximately 50 km away (Tongzhou (Tongzhou district)).

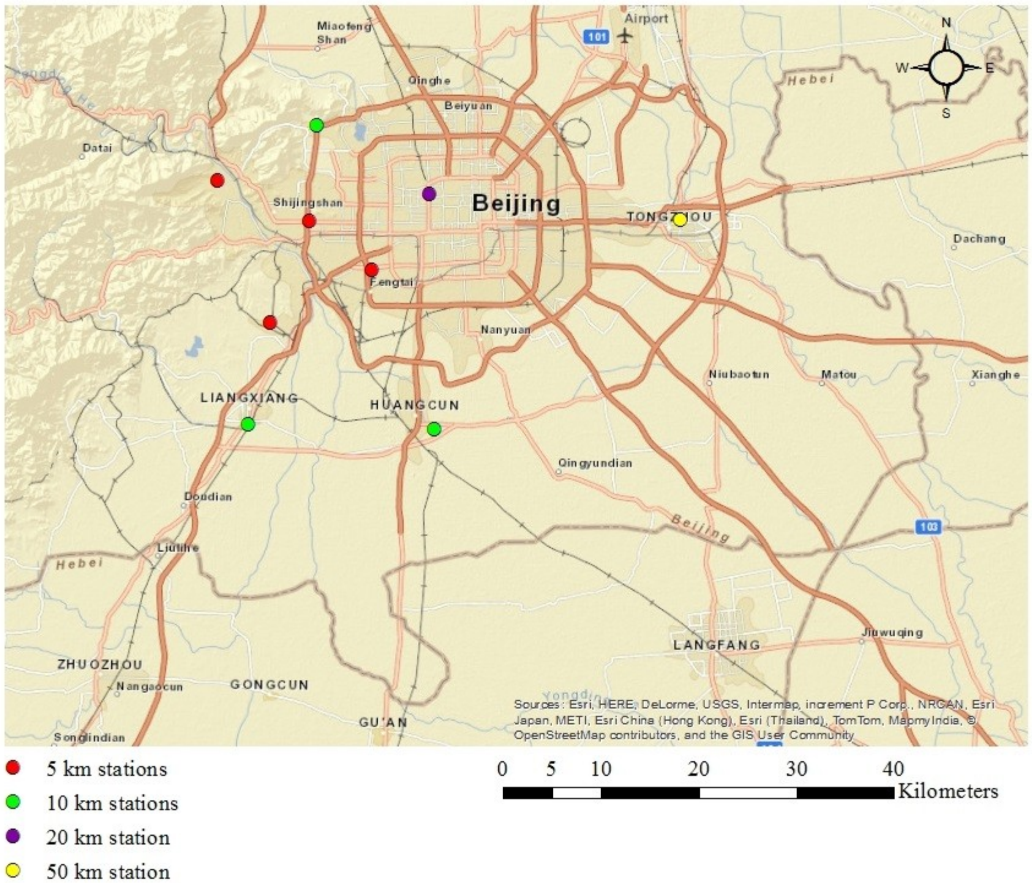


FIG. 58. Air quality stations to compare daily average PM_{10} near Yongding Corridor (5 km and 10 km) to city center (20 km) and furthest eastern edge of the city (50 km).

Yongding River wind erosion equations

Scientists often estimate sand flux either using empirical models (Gillette et al. 2004) or direct measurements. The wind speed at which sand particle suspension occurs (i.e., threshold wind velocity) is strongly controlled by water content and vegetation cover. During spring, the soil moisture content is low (1.0–1.26%) on the Yongding River because of low precipitation (near zero in March and April). Yue (2004) and Yue et al. (2006b) measured the amount of coarse sand (0.10-0.25 mm) (i.e., dust) transported from different land cover types on the Yongding River in Beijing from March to May

2002-2004. For different wind speeds they measured different sand flux rates for different land cover types (Yue et al. 2006a). Yue (2004) and Yue et al. (2006b) found an exponential relationship between sand flux rate and wind speed during spring months. Based on their field measurements, they calculated empirical equations relating wind speed (x) to sand flux (y) for each land cover type (Table 51). All empirical equations were statistically significant with high R^2 (greater than 0.90). I used the empirical wind erosion equations in Table 51 to estimate total sand flux rates by aggregating across four land cover classes (water class assumed to have zero sand flux; urban land cover is excluded). I modeled total daily sand flux rates for the Yongding River in pre- and post-Corridor periods during peak dust months. My analysis does not account for: (1) soil moisture, (2) wind direction, and (3) maximum wind speeds since I use daily average wind speeds.

TABLE 51. Yongding River empirical wind erosion equations per land cover type.

Yongding River Wind Erosion Equations (Yue 2004, Yue et al. 2006b)	
LULC Class	Sand flux equations (g day^{-1} cm^{-2})
Deciduous trees	$y = 0.576x^{2.2981}$
Grass	$y = 0.00576x^{4.57}$
Cropland	$y = 0.01008x^{5.5325}$
Bare soil	$y = 0.144x^{4.4677}$

Note y = sand flux rate (g day^{-1} cm^{-2}) and x = wind speed ms^{-1}.

I used wind speed data to parameterize the wind erosion equations then multiplied the sand flux per area values to the total area for each land cover class. Daily average wind speed was obtained from the Mentougou Meteorological Bureau for the pre- and post-Corridor periods. Landsat remote sensing images for September 30, 2009 (pre-Corridor) and September 1, 2013 (post-Corridor) were classified into seven LULC classes (see Appendix A). The total area for each LULC was calculated at the local and regional scales for pre- and post-Corridor periods (Table 52). In March and April 2013, the lakes/wetlands experienced significant drying, which increased bare soil area. The September 2013 bare soil area is an underestimate of the water area for the lakes/wetlands in March and April 2013. Hence the VIC model was used to simulate lake/wetland area in March and April 2013 (see Appendix B). VIC modeled lake/wetland area is presented in Table 53 for March and April 2013. The mean reduction in lake/wetland area was estimated to be 59 ha. For the post-Corridor period two sand flux estimates were generated: (1) lakes/wetlands at full extent using September 2013 LULC data and (2) lakes/wetlands experiencing drying in March and April 2013 (bare soil area increases by 59 ha) (Table 52).

TABLE 52. Total area (ha) for the LULC classes for the pre- and post-Corridor periods at local and regional scales.

Pre-Corridor (ha)			
LULC	Local	Regional	
	Lakes/Wetlands	Urban	Outerurban
Water	57	118	13
Deciduous trees	97	6,659	8,867
Grass	1186	6,625	3,518
Cropland	0	3,442	21,773
Urban	193	14,108	3,060
Bare soil	423	3,556	2,054

Post-Corridor (ha)			
LULC	Local	Regional	
	Lakes/Wetlands	Urban	Outerurban
Water/Wetland (Full extent)	652	733	33
Water/Wetland (Drying)	593	674	33
Deciduous trees	409	9,890	10,466
Grass	546	1,725	1,658
Cropland	0	1,657	16,450
Urban	256	18,517	7,980
Bare soil (Full extent)	95	2,011	2,699
Bare soil (Drying)	154	2,165	2,699

TABLE 53. Modeled lake/wetland area for March and April 2013 using the VIC model.

Variable Infiltration Capacity (VIC) Model Simulated Lake/Wetland Area		
Lakes/Wetlands	March 2013 Mean Area (ha)	April 2013 Mean Area (ha)
Mencheng Lake	30	25
Wetlands	35	5
Lianshi Lake	51	59
Garden Expo Lake	214	207
Xiaoyue Lake	21	22
Wanping Lake	33	29
Daning Reservoir	222	232
Total	606	579
March and April Average	593	

Ecological production functions

PM_{10} was found to have a linear relationship with sand flux (Gillette et al. 2004) during dust events, thus ecological production functions using OLS regression models were created using Stata 12.1 (see Appendix C). All models were tested for their explanatory power using the Ramsey RESET test, link test, and variance inflation factor. Ecological production functions were created to assess dust control relating sand flux to local and regional PM_{10} for the pre- and post-Corridor periods:

$$PM_{10} = \beta_0 + \beta_1 Sand + \varepsilon \quad (16)$$

where β_0 is the constant (y intercept), β_1 is marginal effects of sand flux on PM_{10}, *Sand* is sand flux (g day^{-1}), PM_{10} is daily average PM_{10} concentrations ($\mu g\ m^{-3}$), and ε is the error term.

Spatial mapping

ArcGIS was used to locate PM_{10} hotspots and assess the spatial distribution of air pollution and dust control. Maps were created using kriging and inverse distance weighted spatial interpolation to display: (1) PM_{10} air quality, (2) number of PM_{10} shortfalls, (3) PM_{10} shortfall amounts, and (4) dust reduction.

RESULTS

Climate conditions

Wind speed was similar between the pre- and post-Corridor periods, however over the entire time-series precipitation was greater in the post-Corridor period because of large summer rainfall events. For the pre-Corridor period, the highest max mean daily wind speed was in March (5.9 m/s) then April (4.3 m/s). For the post-Corridor period, the highest max mean daily wind speed was in April (4.9 m/s) then September and November (4.4 m/s) (Table 54). Mean monthly wind speed was 2.2 m/s for March and April 2010, and mean monthly wind speed was 1.6 m/s for March 2013 and 2.2 m/s for April 2013. Mean monthly wind speed was significantly different at $P<0.05$ level between the pre- and post-Corridor periods for: January, June, July, and October (Fig. 59). Annual precipitation was higher in the post-Corridor period because of large precipitation peaks in June and July 2013 (Fig. 60).

TABLE 54. Monthly mean wind speed and max wind speed.

Month	Pre-Corridor			Post-Corridor		
	Mean	Std. Dev.	Max	Mean	Std. Dev.	Max
January	2.0	1.1	3.9	1.1	0.8	3.3
February	1.5	0.5	2.6	1.5	0.9	4.1
March	2.2	1.3	5.9	1.6	0.7	2.9
April	2.2	0.9	4.3	2.2	1.0	4.9
May	1.7	0.7	3.5	1.6	0.7	3.9
June	1.6	0.4	3.4	1.2	0.5	2.3
July	1.4	0.3	2.4	1.2	0.4	1.9
August	1.2	0.4	2.0	1.2	0.4	1.8
September	1.2	0.6	2.8	1.4	0.9	4.4
October	1.5	0.7	3.3	1.2	0.7	2.8
November	1.5	0.8	4.1	1.7	1.2	4.4
December	1.8	1.1	3.6	1.5	1.1	3.5

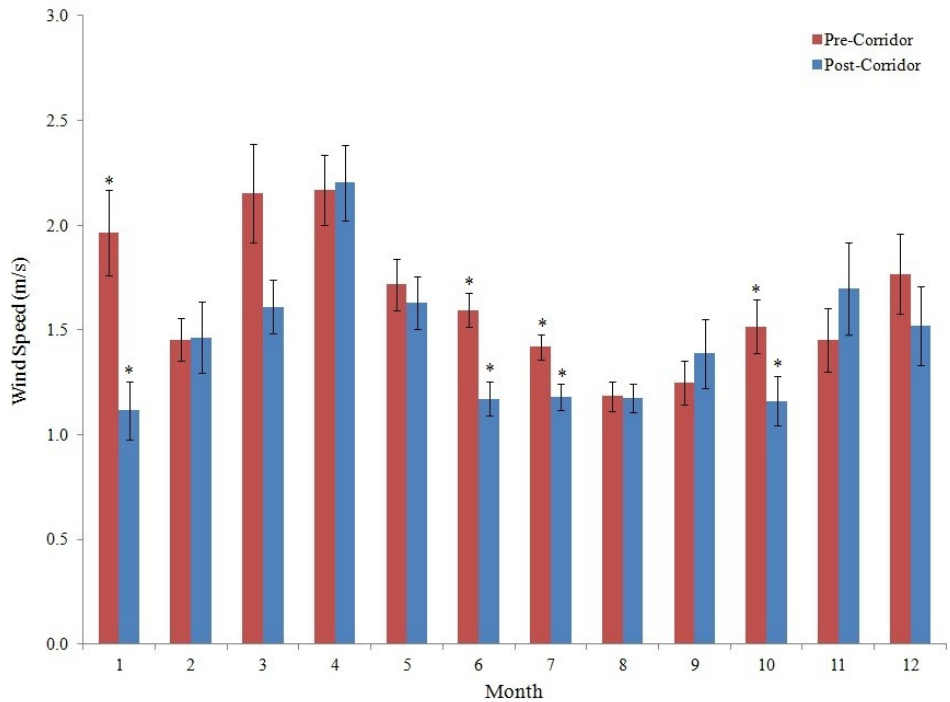


FIG. 59. Average monthly wind speed (m/s) with standard error bars; * statistically significant at P<0.05 level between pre- and post-Corridor.

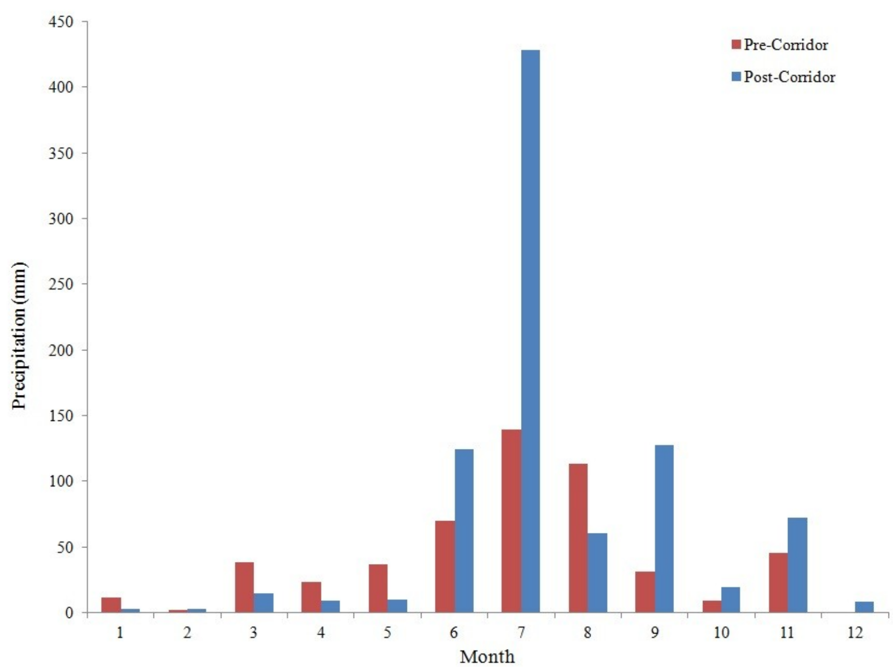


FIG.60. Monthly precipitation (mm) for pre- and post-Corridor periods.

Air quality

Mean daily PM_{10} was higher than the Grade II standard for the pre- and post-Corridor periods, and PM_{10} concentrations were not significantly different for March and April between both periods (Fig. 61). Averaged over the entire time-series, the mean daily PM_{10} was 151 μg m^{-3} in the pre-Corridor period and 183 μg m^{-3} in the post-Corridor period. Mean daily PM_{10} was significantly different at $P<0.05$ level between the pre- and post-Corridor periods for: January, February, June, July, and September (Fig. 61). PM_{10} maps using March and April mean values show hotspots in Fangshan and Fengtai districts, and lowest levels near the city center (Figs. 62-63). Despite similar spatial patterns, the regional PM_{10} levels were on average higher in the post-Corridor with a 50% increase for March and 20% increase for April.

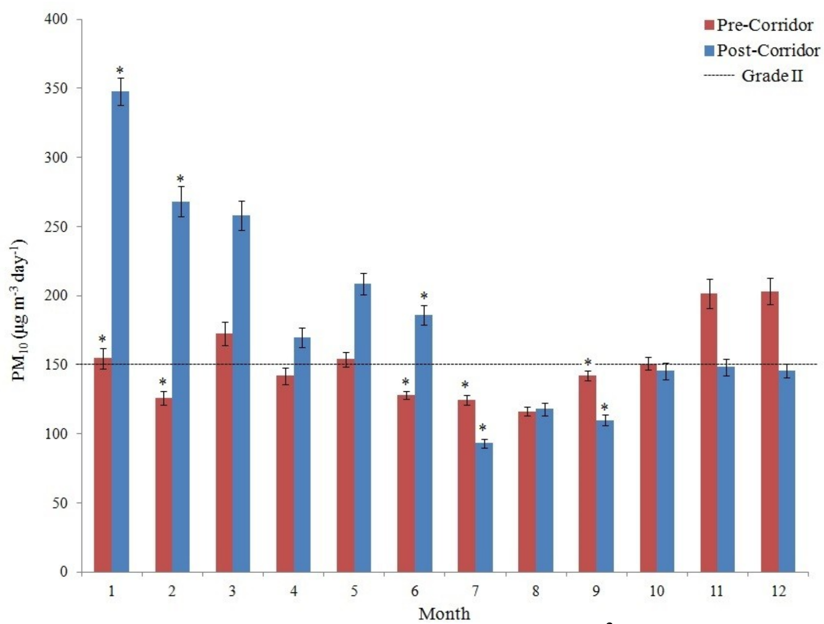


FIG. 61. Regional daily average PM_{10} concentrations (μg m^{-3}) per month with standard error bars; * statistically significant at $P<0.05$ level between pre- and post-Corridor.

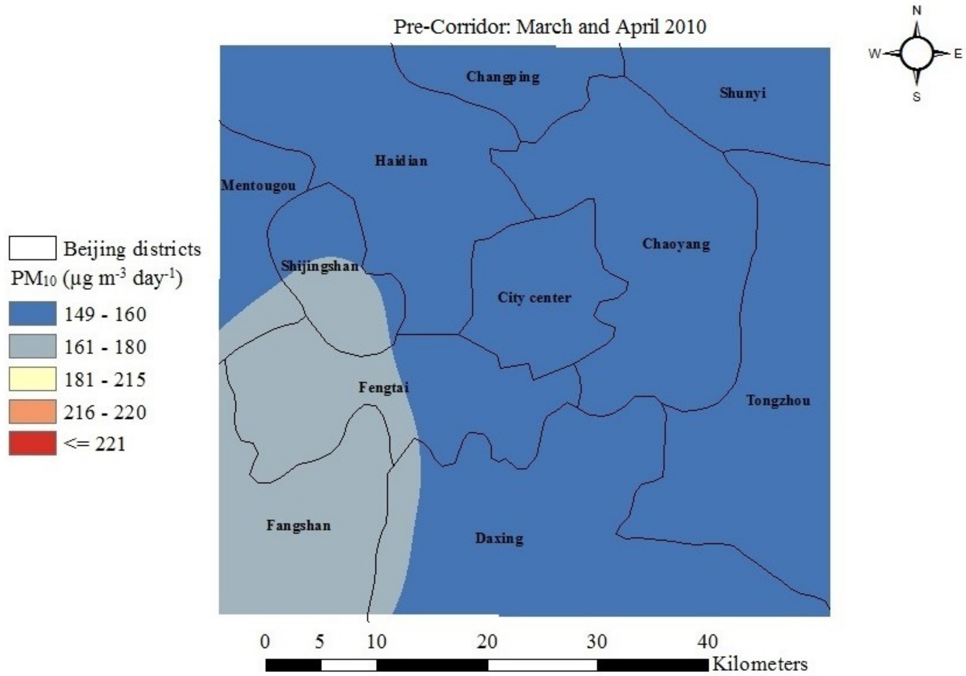


FIG.62. Mean daily PM_{10} for March and April 2010 in Beijing.

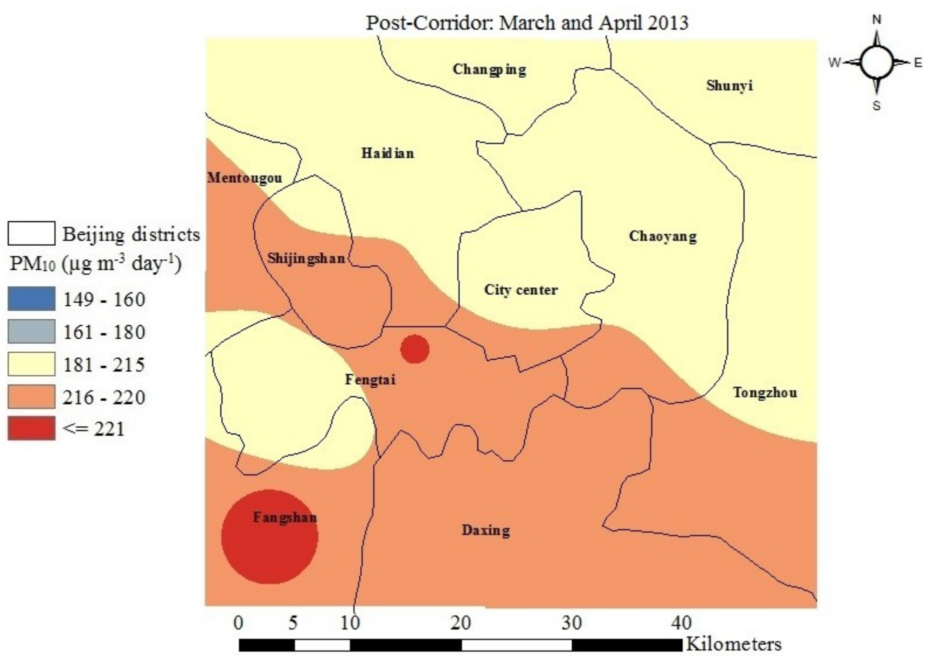


FIG. 63. Mean daily PM_{10} for March and April 2013 in Beijing.

PM_{10} shortfalls

During the post-Corridor period, PM_{10} levels were slightly elevated compared to the pre-Corridor period, however the mean shortfall amount (i.e., concentration over Grade II) was similar in both periods at local and regional scales (Table 55). For March, the number of shortfalls was 12 (local) and 12 (regional) in the pre-Corridor period, and 14 (local) and 18 (regional) in the post-Corridor period. For April, the number of shortfalls was 8 (local) and 8 (regional) in the pre-Corridor period, and 9 (local) and 10 (regional) in post-Corridor. Between the pre- and post-Corridor periods, the majority of the increase in the number of shortfalls was in March. The largest shortfalls in terms of frequency and amount where located in Fangshan and Fengtai districts and lowest near the city center and Haidian district. In the post-Corridor period the highest shortfall amounts were in Tongzhou district (Figs. 64-67).

TABLE 55. Local and regional PM_{10} shortfalls: Mean total number of shortfalls and mean shortfall amount for March and April for pre- and post-Corridor periods.

Local Shortfalls						
	Pre-Corridor			Post-Corridor		
Month	#	Mean	Std. Dev.	#	Mean	Std. Dev.
March	12	115	176	14	256	131
April	8	102	144	9	167	84
March and April	20	103	100	23	148	95
Regional Shortfalls						
	Pre-Corridor			Post-Corridor		
Month	#	Mean	Std. Dev.	#	Mean	Std. Dev.
March	12	177	109	18	258	131
April	8	144	74	10	170	84
March and April	20	106	99	28	147	97

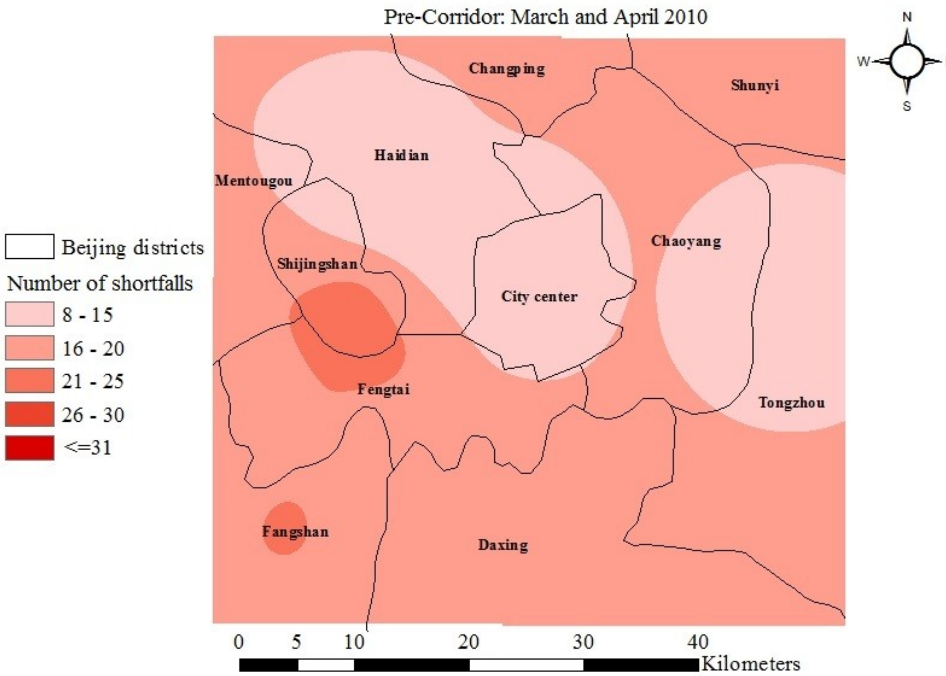


FIG.64. Total number of PM_{10} shortfalls for March and April 2010 in Beijing.

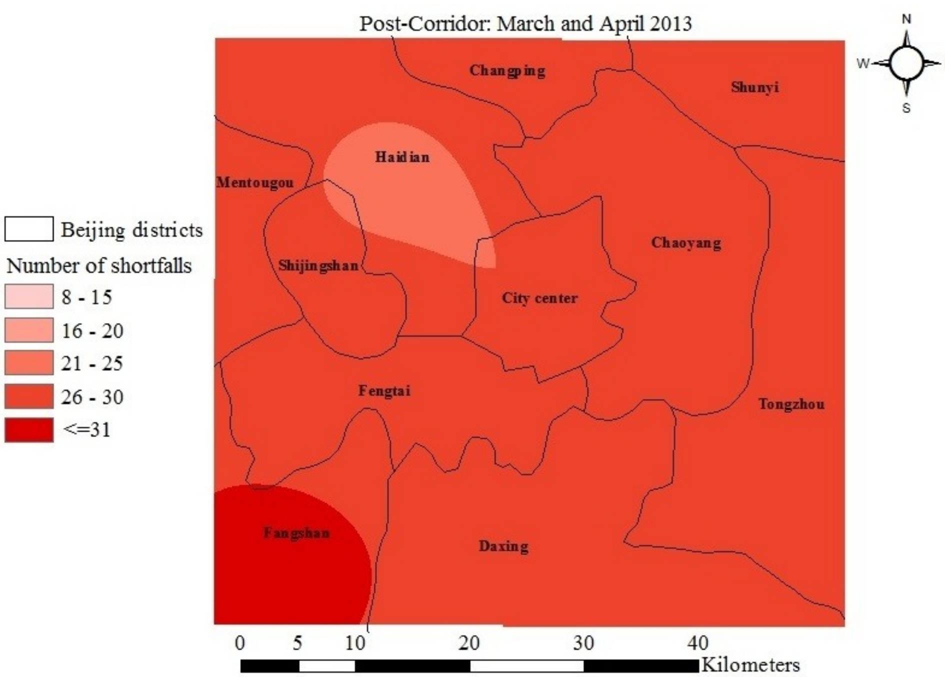


FIG.65. Total number of PM_{10} shortfalls for March and April 2013 in Beijing.

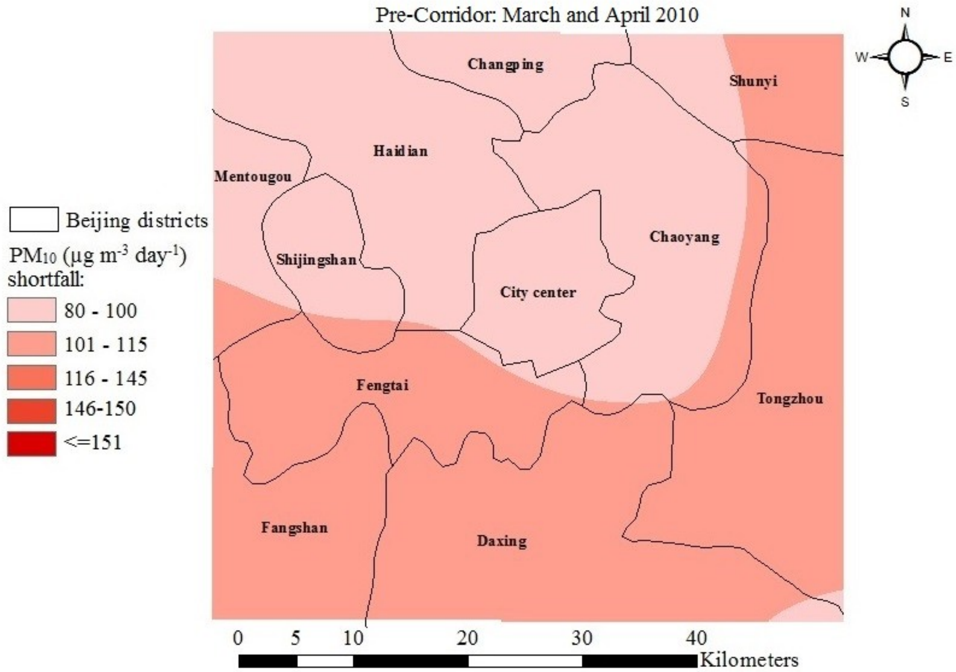


FIG. 66. Mean PM_{10} shortfall concentration for March and April 2010 in Beijing.

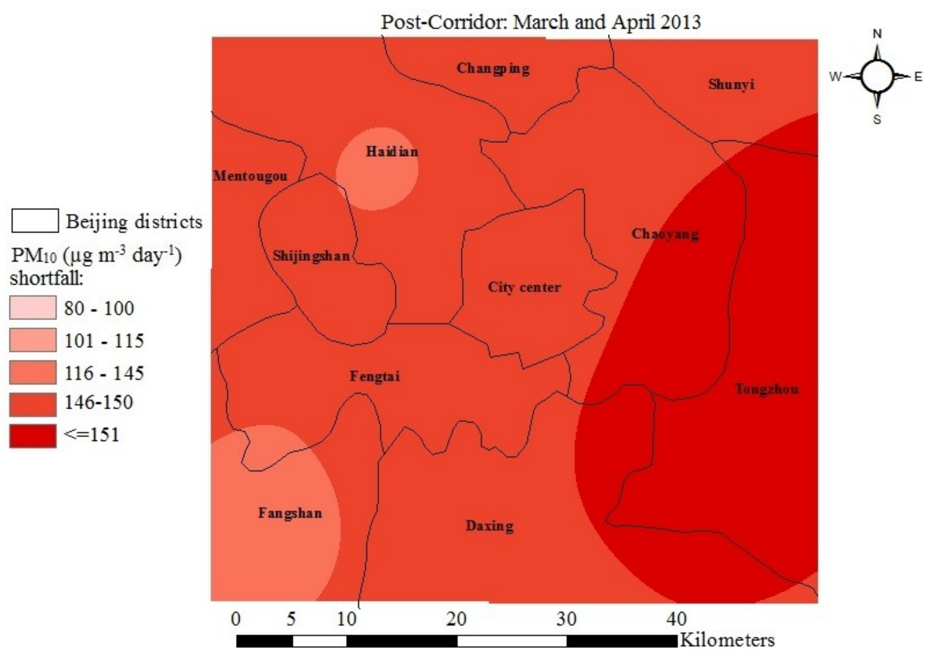


FIG. 67. Mean PM_{10} shortfall concentration for March and April 2013 in Beijing.

Modeled sand flux

Modeled mean sand flux rates were 29.1 g cm^{-2} day^{-1} (local) and 37.6 g cm^{-2} day^{-1} (regional) in March and April 2010, and 13.6 g cm^{-2} day^{-1} (local) and 16.4 g cm^{-2} day^{-1} in March and April 2013 (Table 56). Slightly higher wind speeds in the pre-Corridor period likely led to higher average sand flux rates compared to the post-Corridor period. Local sand flux rates represent three land cover types: (1) deciduous trees, (2) grass, and (3) bare soil. Regional sand flux rates represent four land cover types: (1) deciduous trees, (2) grass, (3) cropland, and (4) bare soil. The modeling only examined potential changes in sand flux from changes in the above land cover classes.

Modeled sand flux rates were compared to literature values to assess their validity and magnitude relative to other wind erosion/PM_{10} studies. Owens Lake is the single largest source of particulate matter in the United States covering 285 km^2. During a dust event, Gillette et al. (2004) estimated sand fluxes from 168 – 2,832 g cm^{-2} day^{-1} with PM_{10} levels ranging from 32 – 2,452 μg m^{-3}. These large sand fluxes occur under wind speeds greater than 17.0 m/s, which are significantly higher than wind speeds in the pre- and post-Corridor periods on the Yongding River. Under medium wind speeds, Yue et al. (2006a) measured sand flux rates from 79.68 –17.52 g cm^{-2} day^{-1} for wind speeds ranging from 7.45 – 6.9 m/s on the Yongding River. Under low wind speeds, Nickling and Gillies (1993) measured sand flux rates from 6.05 x 10^{-8} – 0.022 g cm^{-2} day^{-1} for wind speeds ranging from 0.1 – 1.0 m/s from the Niger River in Mali. Modeled sand flux rates for the pre- and post-Corridor periods seem reasonable since mean daily wind speeds ranged from 1.6 – 4.9 m/s.

TABLE 56. Modeled sand flux rates (g cm^{-2} day^{-1}) for the pre and post-Corridor periods at local and regional scales.

Pre-Corridor: Sand Flux Rate (g cm^{-2} day^{-1})				
Month	Local		Regional	
	Mean	Std. Dev.	Mean	Std. Dev.
March	39.95	102.79	53.30	143.08
April	17.96	27.45	21.44	34.43
Average	29.13	75.96	37.64	105.20
Post-Corridor: Sand Flux Rate (g cm^{-2} day^{-1})				
Month	Local		Regional	
	Mean	Std. Dev.	Mean	Std. Dev.
March	5.75	7.48	6.39	8.61
April	21.50	41.26	26.32	54.05
Average	13.62	30.45	16.36	39.67

Local is based on three land cover types: (1) deciduous trees, (2) grass, and (3) bare soil.
Regional is based on four land cover types: (1) deciduous trees, (2) grass, (3) cropland, and (4) bare soil.

Mean monthly sand flux decreased from the pre-Corridor period to the post-Corridor period (Table 57). In the pre-Corridor period, mean sand flux for March and April was 0.004 g $month^{-1}$ (local) (Fig. 68) and 0.131 g $month^{-1}$ (regional) (Fig. 69). In the post-Corridor period, mean sand flux for March and April was 0.001 g $month^{-1}$ (local) (Fig. 68) and 0.050 g day^{-1} (regional) (Fig. 69). There was no difference in sand flux emissions when lakes/wetlands were modeled as full extent or drying. There was more percent sand flux reduction at the local scale (67%) compared to the regional scale (50%) because the outerurban section consists of cropland with patches of bare soil area.

TABLE 57. Modeled sand flux for March and April for the pre- and post-Corridor periods at local and regional scales.

Pre-Corridor: Sand Flux Emissions (g month^{-1})		
Month	Local	Regional
March	0.005	0.192
April	0.002	0.070
Average	0.004	0.131

Post-Corridor (Full Extent): Sand Flux Emissions (g month^{-1})		
Month	Local	Regional
March	0.000	0.022
April	0.001	0.078
Average	0.001	0.050

Post-Corridor (Drying): Sand Flux Emissions (g month^{-1})		
Month	Local	Regional
March	0.000	0.022
April	0.001	0.078
Average	0.001	0.050

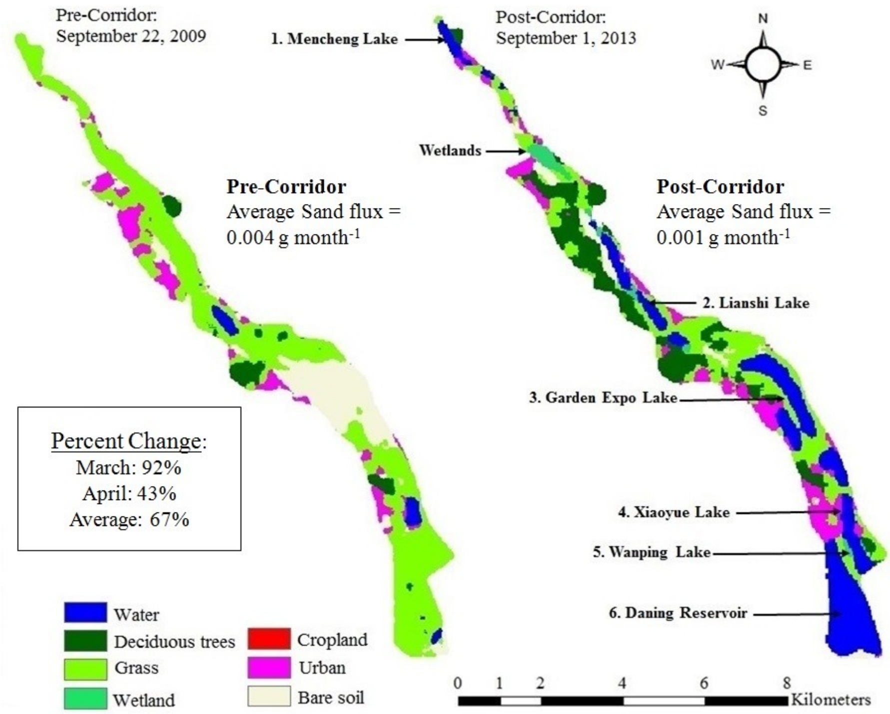


FIG.68. Percent sand flux reduction due to land cover changes, comparing pre- and post-Corridor modeled sand flux at local scale.

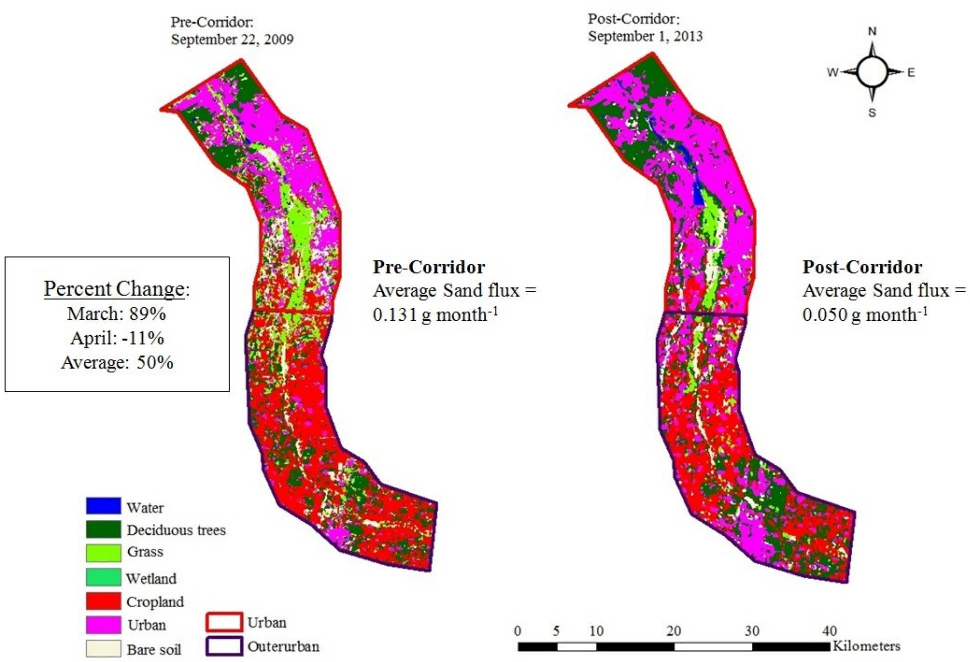


FIG.69. Percent sand flux reduction due to land cover changes, comparing pre- and post-Corridor modeled sand flux at regional scale. Note the negative percent change for April indicates higher average sand flux in April 2010 than April 2013.

Ecological production functions: Sand flux rates to PM_{10}

Local and regional sand flux emissions were unable to explain variations in PM_{10} for the pre-Corridor and post-Corridor periods (Table 58). The R^2 for the pre-Corridor and post-Corridor production functions were low (0.06-0.18) and root mean square errors (RMSE) were high (86.01-118.69) suggesting the modeled Yongding River sand flux was unable to explain the majority of variation in PM_{10} during March and April. Sand flux coefficients were insignificant in the pre-Corridor period. Sand flux coefficients were significant in the post-Corridor period, however the coefficients suggest increases in sand flux result in increases in PM_{10}. The modeled sand flux must be highly correlated to another variable(s), which is driving the non-interpretable results in the post-Corridor period. The lack of a significant and interpretable relationship between sand flux and PM_{10} for both periods is likely due to: (1) poor accuracy of modeled sand flux values, (2) other dust sources and/or (3) wind conditions.

TABLE 58. Regression statistics for pre-Corridor and post-corridor dust control production functions.

Pre-Corridor: Sand Flux to Air Quality					
	Sand Flux Coefficient (Marginal Effect)	P-Value	95% CI	R^2	RMSE
PM_{10} (Local)	120780 (75681)	0.12	-30888 to 272449	0.18	87.32
PM_{10} (Regional)	3101 (1892)	0.11	-690 to 6892	0.18	86.01
Post-Corridor: Sand Flux to Air Quality					
	Sand Flux Coefficient (Marginal Effect)	P-Value	95% CI	R^2	RMSE
PM_{10} (Local)	-763251 (370057)	0.04	-1505492 to -21009	0.07	118.12
PM_{10} (Regional)	-8355 (4011)	0.04	-16401 to -309	0.06	118.69

R^2 is coefficient of determination, the standard errors are reported in parentheses to coefficients
CI is confidence interval
RMSE is root mean squared error

DISCUSSION

PM_{10} shortfalls

The mean daily PM_{10} was higher than the Grade II national standard in the pre- and post-Corridor periods, however there were no statistically significant differences in mean daily PM_{10} for March and April between both periods. Averaged across the entire year, mean daily PM_{10} was 151 μg m^{-3} (standard deviation of 29 μg m^{-3}) for the pre-Corridor period and 183 μg m^{-3} (standard deviation of 75 μg m^{-3}) for the post-Corridor period. However regional daily mean PM_{10} levels for March increased from 174 μg m^{-3} (pre-Corridor; standard deviation of 105 μg m^{-3}) to 258 μg m^{-3} (post-Corridor; standard deviation of 131μg m^{-3}). The lack of a statistically significant difference in regional daily mean PM_{10} for March is likely because of the large standard deviations. The number of PM_{10} shortfalls was slightly larger in the post-Corridor period, however the mean shortfall amount was similar in both periods at local and regional scales. There were noticeable hotspots of PM_{10} in frequency and magnitude of shortfalls in Fangshan and Fengtai districts near the Yongding Corridor compared to the city center in both periods.

Despite reported PM_{10} shortfalls, the mean daily PM_{10} concentrations were lower than those recorded during past spring dust events in Beijing. Wang et al. (2006) calculated a mean daily PM_{10} of 374 μg m^{-3}on blowing dust days compared to mean daily PM_{10} of 162 μg m^{-3} on non-blowing dust days. In 2000 PM_{10} concentrations during April dust events were as high as 720 μg m^{-3} and 898 μg m^{-3} in Beijing (Xie et al. 2005). Wind speeds greatly influence the magnitude of a dust event, and wind speeds greater than 5.0 – 7.0 m/s are needed for large sand fluxes for most land cover classes on the

Yongding River (Yue et al. 2006a). For March and April there were no days with wind speeds greater than 5.0 m/s in the pre-and post-Corridor periods. In Beijing a blowing dust day often represents local dust suspension. The Mentougou Meteorological Bureau reported one blowing dust day in the pre-Corridor period on March 20, 2010 (600 µg m^{-3}), and two blowing dust days in the post-Corridor period on February 28, 2013 (400 µg m^{-3}) and March 18, 2013 (80 µg m^{-3}; likely reporting error). The low number of blowing dust days and lower mean daily PM_{10} levels compared to dust events, suggest the pre- and post-Corridor periods had low dust seasons.

Dust control

Modeled sand flux emissions were low in the pre- and post-Corridor periods suggesting there are other important dust sources leading to PM_{10} shortfalls in March and April in both periods. It was estimated that mean sand flux was 0.004 g $month^{-1}$ (local) and 0.131 g $month^{-1}$ (regional) in pre-Corridor period, and 0.001 g $month^{-1}$ and 0.050 g $month^{-1}$ in post-Corridor period. Despite the low dust emissions in both periods there was an estimated percent dust reduction of 67% (local) and 50% (regional). There were no statistically significant differences in mean daily wind speeds for March and April between the pre- and post-Corridor periods. Mean sand flux rates were 29.1 g cm^{-2} day^{-1} (local) and 37.6 g cm^{-2} day^{-1} in pre-Corridor period, and 13.6 g cm^{-2} day^{-1} and 16.4 g cm^{-2} day^{-1} in post-Corridor period. The higher mean sand flux rates and greater variance for the pre-Corridor period suggest the slightly higher wind speeds in the pre-Corridor period contributed to the differences in sand flux emissions between both periods. The Beijing government implemented substantial afforestation efforts on the Yongding River prior to the Yongding Corridor evident in the high deciduous trees and grass area in the pre-Corridor period. The result suggests the deciduous trees and grasses were providing dust control, and the new ecosystems are providing similar dust control under low to medium wind speeds.

The lack of a significant and interpretable relationship between sand flux and PM_{10} in the pre- and post-Corridor periods is likely because: (1) poor accuracy of modeled sand flux rates, (2) other dust sources are larger PM_{10} contributors, and/or (3) wind conditions during this study did not represent dust events. During the spring, dust is deposited from local (e.g., Yongding River), regional (e.g., Hebei and Inner Mongolia), and distance sources (e.g., Gobi Desert) (Xie et al. 2005). Zhu et al. (2011) indicated that high PM_{10} pollution occurs when regional and distant dust sources bring sand located 1,000 – 2,000 km northwest of Beijing at wind speeds greater than 7.0 m/s. They evaluated the sand flux pathways causing high PM_{10} in Beijing during the winter and spring, and concluded that sand from southern Mongolia and western Inner Mongolia and anthropogenic sources in Shanxi and Hebei had significant impacts on PM_{10} in Beijing. Second, during this analysis there was significant construction surrounding the Yongding Corridor in the post-Corridor period, which can increase local PM_{10}. No sand flux emissions resulting from the urban land cover change was calculated, which is likely another important PM factor. Lastly the short time-scale of this analysis likely influenced the lack of a significant and interpretable relationship between sand flux and PM_{10}. There is high inter-annual variability in the contribution of sand flux to PM_{10} in Beijing since sand flux was estimated to be responsible for 14%, 15%, 60%, and 45% of severe PM_{10}

pollution from 1995-2000 in Beijing. In this study, only two years were evaluated and neither represented high dust seasons since mean daily wind speeds were between 1.6 – 4.9 m/s. Gillette et al. (2004) determined a linear relationship between sand flux and PM_{10} for high dust events.

Management

Despite the lack of a significant relationship between modeled sand flux and PM_{10}, the modeled sand flux values suggest management was able to obtain their goal of near zero dust emissions from the Yongding River. Using simple empirical equations, the new ecosystems seem to have low dust emissions under low to medium wind speeds. A decade ago, the Yongding River was mainly sand dunes and exposed sand pits. Thus the increased water area and vegetation area are likely providing dust control compared to past conditions when the Yongding River was mainly bare soils. The drying of the lakes/wetlands in March and April 2013 seemed to have no difference on modeled sand flux emissions compared to the lakes/wetlands at full extent. However the limited temporal data led to no assessment of how dust emissions may change under high wind speeds, which will be the ultimate test of dust control from the new ecosystems.

CONCLUSION

In summary I conducted a simple analysis to evaluate dust control from the new ecosystems on the Yongding Corridor, however I found no significant relationship between modeled sand flux rates and PM_{10} levels at local and regional scales. Likely my analysis was too crude to provide an accurate measure of dust control from the new ecosystems on the Yongding River. Based on the LULC data, the amount of regional bare soil area on the Yongding River in the pre-Corridor period was 5,610 ha (small in comparison to other regions suffering desertification known to cause high PM_{10} levels like Owens Lake (28,500 ha)). The total reduction in bare soil area from the new ecosystems was calculated to be 900 ha, which suggests there was a reduction in the amount of easily erodible land on the Yongding River. The new ecosystems on the Yongding River are likely providing some dust control simply because new ecosystems have reduced the amount of bare soil area. However there was no noticeable change in PM_{10} levels in the pre- and post-Corridor periods (both were higher than the Grade II standard considered suitable for urban residents), and PM_{10} levels were slightly higher in the post-Corridor period. Currently management and scientists assume the Yongding River is a large contributor to local PM_{10} levels during peak dust months. The utility of a simple analysis was to quickly assess the strength of the relationship between Yongding River sand flux emissions and PM_{10}. My analysis suggests scientists need to conduct a more accurate assessment of dust control to credibly determine the relationship between bare soil area on the Yongding River and local PM_{10}.

The key findings from this chapter are:

- Mean daily PM_{10} was higher than the Grade II standard leading to air quality shortfalls of 20 days in pre-Corridor and 28 days in post-Corridor.
- Modeled sand flux emissions were: 0.004 g $month^{-1}$ (local) and 0.131 g $month^{-1}$ (regional) in pre-Corridor, and 0.001 g $month^{-1}$ (local) and 0.050 g $month^{-1}$ (regional) in post-Corridor.
- Mean percent reduction in sand flux emissions was estimated to be 67% (local) and 50% (regional).
- Ecological production functions indicated no significant and interpretable relationship between sand flux and PM_{10}.
- A more accurate analysis is needed to evaluate the relationship between sand flux from the Yongding River and PM_{10} levels in Beijing.

CHAPTER 8

VISITOR PREFERENCES AND LANDSCAPE AESTHETICS

ABSTRACT

Green space is highly valued for cultural services like landscape aesthetics, recreation, and heritage preservation. In Beijing green space is considered critical to improving landscape aesthetics to enhance district-level economies. Visitor surveys were conducted from April 2013 to September 2013 on the Yongding River Ecological Corridor to evaluate: (1) visitor preferences for different ecosystem services and (2) the relationship between perceived environmental quality (i.e., Chapters 5-7) and perceived landscape aesthetics. Demographics of the surveyed population suggest the Yongding Corridor attracts a diverse spectrum of Chinese citizens in terms of gender, age, education level, occupation, and income level. Most visits to the Yongding Corridor were for relaxation (61%) and recreation (32%). The top five ecosystem services selected by visitors reported as social values were: (1) leisure and travel (61%), (2) air quality (44%), (3) landscape preservation (20%), (4) recreation (17%), and (5) cooling (17%). The top problems reported as current dissatisfactions and future concerns were water pollution and water storage. The majority of surveyed visitors scored landscape aesthetics as 'beautiful' (46%) or 'very beautiful' (36%); only 19% of respondents gave a score below these final service levels. Lastly, I created an ecological production function using an ordinal logistic regression model, which showed that the probability of visitors ranking the Yongding Corridor as 'very beautiful' was significantly more likely when air quality and water quality were seen as 'very healthy' and climate was seen as 'cold.'

INTRODUCTION

Green spaces (e.g., parks, greenways, ecological corridors, etc.) are defined as vegetation or water landscapes set apart for recreational, aesthetic, and/or heritage purposes in an urban environment (Fabos 1995, Searns 1995, Wendel et al. 2012). Typically cities are located a significant distance away from undeveloped ecosystems or wilderness areas, and thus many urban residents increasingly feel psychologically and culturally separate from the natural environment. Green spaces provide an important cultural function allowing people to interact with nature while offering an escape from the noise, traffic, and crowds of urban life (Chiesura 2004, Zhang and Yang 2014). Matsuoka and Kaplan (2008) conducted a literature review on studies that examine how people interact with the urban environment. They identified three types of human needs: (1) contact with nature, (2) aesthetics like scenic beauty and cleanliness, and (3) recreation. Also they identified three interaction needs associated with green spaces: (1) social interaction, (2) citizen participation in the design process, and (3) a sense of community identity.

Green spaces provide many important cultural services defined as the "nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences" (MA 2005). In cities green spaces are valuable amenities because they increase the attractiveness of neighborhoods often leading to economic benefits, such as tourism and higher property values (Tyrvainen 1997, Geoghegan 2002, Kong et al. 2007), which increase tax revenues for municipalities (Chiesura 2004). This phenomenon is exemplified by popular urban parks like Central Park in New York City (35 million visitors per year) and Hyde Park in London (37 million visitors per year). People enjoy natural landscapes for their scenic beauty and relaxing atmosphere, which have been shown to improve mental health (Maas et al. 2006). Barton and Pretty (2010) conducted a meta-analysis on the impact of parks on self-esteem and mood in the United Kingdom. They found that exposure to green spaces improved self-esteem and mood irrespective of duration, intensity, location, gender, age, and health status. Green spaces in conjunction with facilities (i.e., built infrastructure: basketball courts, tennis courts, bike paths, etc.) provide another highly valued ecosystem service, which is recreational opportunities (Bolund 1999). The scenic beauty of green spaces has shown to promote healthier communities by encouraging people to engage in physical activities like walking, running, and biking (Barton and Pretty 2010).

Nowhere is the challenge of obtaining and maintaining green spaces for cultural services as difficult as China because of rapid urbanization, dramatic ecosystem losses, shifting social demographics, and a large population. During the initial phase of China's urbanization, green spaces were often replaced with artificial surfaces and altered to provide for other land uses. Since the 1990s, heightened awareness of cultural services and the alarming decline of green spaces in China resulted in new urban policies to conserve existing sites and develop new parks (Jim and Chen 2006). Chinese citizens increasingly want green spaces since there is a growing demand to live in proximity to parks to connect to nature (Yin et al. 2007). For centuries, Chinese people lived in communal settings where households were linked through shared garden courtyards, however modernization is quickly replacing traditional communal living (i.e., hutongs) with individualized apartment units (Zhang 2006). Today public parks provide an important social function in Chinese culture as the modern communal courtyard where residents gather daily to maintain a sense of community identity in natural settings. In response to growing interests for preserving China's garden heritage, the State Council of the People's Republic of China created an official designation to protect green spaces in cities known as the "national garden city." From 1992 to 2011, the Ministry of Housing and Rural Urban Development designated 214 national garden cities (or districts) across China. Citizens however are becoming increasingly concerned about the distribution and accessibility of green spaces to all Chinese people. The massive rural to urban migration occurring across China has led to informal settlements and significant disparities among social classes where migrants and the urban poor have limited access to green spaces. Municipalities are trying to create eco-cities by designing green spaces for cultural services (aesthetics, recreation, and heritage values) and ecosystem functionality while trying to reduce the unequal distribution of environmental amenities (Jim and Chen 2006).

The gardens and parks of Beijing are the most distinguishing features of the city, which represent its long history as the political and cultural capital of China (Shi 1998). The gardens and temples of China's imperial rulers are critical to the identity of Beijing. The Beijing government is working to protect these cultural treasures while making them available to the public for recreation and tourism. Every year millions of residents and tourists visit Beijing's parks to connect with the past (e.g., Temple of Heaven), enjoy nature (e.g., Kunming Lake), and socialize (e.g., Houhai). Green spaces are integral to urban planning in Beijing where the long-term goal is to make Beijing an eco-city using a network of connected parks and ecological corridors (Li et al. 2005). Currently officials are focusing their efforts on creating new green spaces in peri-urban districts to improve urban livability in these less developed areas. Parks are considered a means of enhancing tourism and leisure industries to advance district-level economies.

The Beijing government is currently creating its largest public park known as the Yongding River Ecological Corridor, and the cultural services are driving many of the investment decisions supporting this expensive greening project. The Yongding River is famous in Beijing since it was the city's largest river known commonly as the "Mother River." Centuries ago it was a major transportation artery linking trade and commerce through the Taihang Mountains to the North China Plain. The Yongding River is home to the oldest stone bridge in northern China, known as the Marco Polo Bridge, which was designated a national cultural heritage site (Fig.70). The English name comes from Marco Polo who first introduced this important bridge to Europeans during his travels through China. This location also carries great significance to many Chinese since the first battle of the Sino-Japanese War (1937-1945) started on the Marco Polo Bridge marking the beginning of the Chinese resistance movement against the Japanese invasion during World War II. Domestic and foreign tourists visit the Marco Polo Bridge every year, however the environmental degradation along the Yongding River was compromising the scenic beauty and visitor experience. Since 2010 designers began working on beautifying the Yongding River using ecosystems, artwork, and iconic cultural structures (e.g., pagodas, temples, etc.) (Fig. 71). Landscape architects chose to construct new lakes and wetlands since water landscapes have proven effective at improving landscape aesthetics to foster land development and recreation (Stevens 2009, Barton and Pretty 2010). It has been well known for millennia that people enjoy oceans, lakes, streams, and ponds. Over the past 30 years empirical investigations have simply supported this relationship between people and water landscapes (Nassauer et al. 2001). In 2011 the Yongding Corridor officially opened to the public as a network of four parks: Mencheng Lake, Lianshi Lake, Xiaoyue Lake, and Wanping Lake. Unlike past development efforts, the Beijing government is trying to incorporate historical and cultural features of the Yongding River into the Yongding Corridor to maintain a sense of local heritage within the landscape (Fig. 70). In the past three years, the Yongding Corridor has become a popular destination among Beijingers for leisure and recreational activities (Fig. 72).

FIG.70. Photos of the cultural heritage features along the banks of the Yongding Corridor: (A) new Mencheng Lake pagoda, (B) wooden boats honoring the historical importance of the Yongding River as an ancient transportation artery, (C) statues signifying important historical and traditional figures, (D) Marco Polo Bridge – a national cultural heritage site, (E) garden features encouraging environmentalism, and (F) a new national museum on gardens and parks to educate the public about the value of green spaces.

FIG. 71. Photos of the landscape aesthetic features (combination of natural and built infrastructure) to create a sense of scenic beauty: (A) waterfall and fountain at Mencheng Lake, (B) wetlands with curved pathway at Wanping Lake, (C) water lily pads, and (D) flowers and trees planted along the banks of the Yongding Corridor.

FIG. 72. Photos of the diversity of leisure and recreational activities: (A) camping and picnicking, (B) fishing, (C) ribbon dancing, (D) kite flying, (E) basketball, (F) biking, (G) tai chi, and (H) celebrations (e.g., wedding photos).

Much of the success of the Yongding Corridor will depend on visitor perceptions of its environmental quality. Human expectations direct the way we interact with landscapes since our preferences – what we like, what we want, and what we think others find acceptable – shape our assumptions of beauty and naturalness (Nassauer et al. 2001). For the Yongding Corridor, people will likely travel or choose to live nearby if they find the parks beautiful, clean, safe, and accessible. Developers are investing billions of dollars into real estate projects believing the improved ecosystem services will help entice people to move to southwest Beijing. Thus understanding visitor opinions on Yongding Corridor ecosystem services could help management and developers better serve its users.

Landscape aesthetics is the interaction between biophysical features of the landscape and the perceptual and judgmental processes of the human viewer (Daniel 2001). To assess landscape aesthetics one cannot simply use environmental monitoring (i.e., biophysical measurements); one has to consider how people perceive environmental quality and its influence on their perceptions of scenic beauty. In previous chapters, I evaluated the influence of the new ecosystems on four aspects of environmental quality (other management priorities): (1) water storage (i.e., water landscape), (2) local climate regulation (i.e., cooling effect), (3) water purification (i.e., water quality), and (4) dust control (i.e., air quality). In this chapter, I evaluate the impact of perceived environmental quality on perceived landscape aesthetics to link the environmental targets to management's end goal.

A critical area of ecosystem service research is advancing scientific and management understanding on how environmental conditions influence people's experience on the landscape (Fig. 73). Social scientists have conducted empirical studies consistently showing that perceived "poor" or "bad" environmental quality shapes people's experiences of parks (House 1991, Nassauer et al. 2001). For instance Steinwender et al. (2008) examined the association between water quality and visitor experiences of urban waterfronts. Visitor perceptions of the landscape improved when water quality, water area, and wetland area improved. Hipp and Ogunseitan (2011) developed a methodology relating objective measures and subjective perceptions of environmental quality to visitor feelings of relaxation at coastal parks in Southern California. The novelty of Hipp and Ogunseitan (2011) study is that they created ecological production functions relating air quality, water quality, and physical comfort to the leisure experiences of visitors. Overall they found that environmental quality significantly influenced people's feelings of rest and relaxation. Lastly, the majority of public preference studies on the environment are conducted in North America and Europe. There have been very few studies assessing public opinions on environmental quality, environmental amenities or ecosystem services in China (Yu 1995, Chen et al. 2009). Hence there is little information available to managers on how to incorporate public preferences into management schemes on ecosystem services in China.

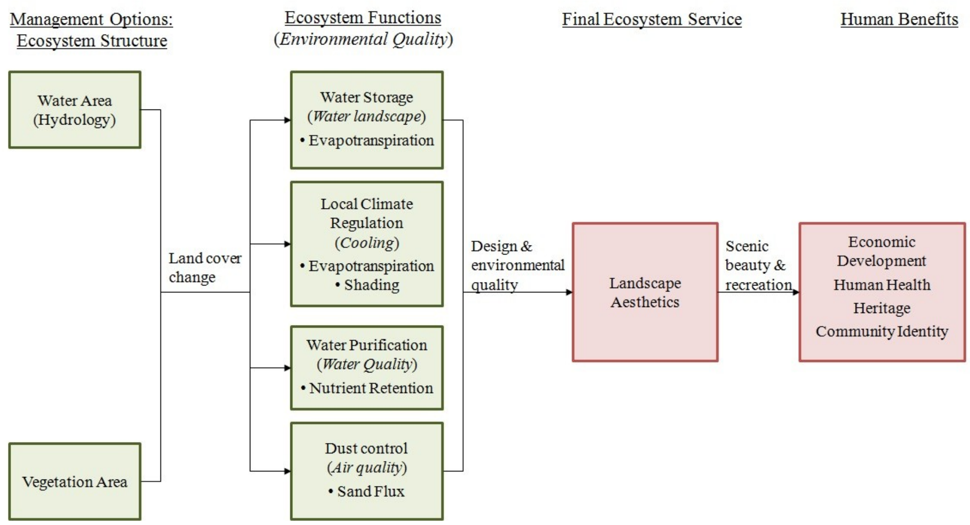


FIG.73. Conceptual diagram linking management options as changes in ecosystem structure to ecosystem functions to the final ecosystem service and human benefits. In this chapter "design" refers to water storage (i.e., maintaining the water landscape).

In this chapter I evaluate public opinion of the Yongding Corridor using a visitor survey to assess: (1) visitor preferences for different ecosystem services and (2) the relationship between perceived environmental quality (air quality, water quality, and climate) and perceived landscape aesthetics. To assess landscape aesthetics, I selected final services using a scoring system for scenic beauty. Second surveys were conducted to assess public opinion on ecosystem services from April 2013 to September 2013. Third I evaluated the demographics and distribution (i.e., residence) of park users. Fourth I assessed public preferences on management endpoints to compare visitor priorities with management priorities. Lastly, I created an ecological production function linking perceived environmental quality to perceived landscape aesthetics using an ordinal logistic regression. Chapter objectives are to estimate: (1) park accessibility, (2) public preferences for different ecosystem services, (3) landscape aesthetic shortfalls, and (4) marginal effects of perceived environmental quality on perceived landscape aesthetics.

METHODS

My measurement approach consists of six general steps outlined in Fig. 74. I determined visitor opinions on landscape aesthetics using surveys conducted from April 2013 to September 2013. In this chapter I evaluate two aspects of park experiences: (1) visitor preferences for different ecosystem services; (2) the relationship between perceived environmental quality of the Yongding Corridor and perceived landscape aesthetics to evaluate the potential contribution of the regulating ecosystem services (i.e., Chapters 5-7) to scenic beauty. My objective is to assess how the ecosystem services explored in previous chapters link to management's end goal of scenic beauty.

To evaluate visitor preferences, I first evaluated the frequency of visits, purpose of visits, and the demographics of park users. Second I assessed visitor preferences for different ecosystem services to compare visitor priorities to management priorities. Third I mapped the spatial distribution of park users. To assess the contribution of the regulating services to landscape aesthetics, I selected final services for scenic beauty then measured the final service indicator using visitor surveys to determine service shortfalls. Next I summarized the biophysical measurements representing environmental conditions on the date the surveys were conducted. I compared biophysical measurements of environmental quality to survey responses on air quality, water quality, and climate. Lastly, I created an ecological production function using an ordinal logistic regression to link perceived environmental quality (air quality, water quality, and climate) to perceived landscape aesthetics.

In summary I evaluated the contribution of the new ecosystems to landscape aesthetics by: (1) comparing biophysical measurements to perceived environmental quality and (2) relating perceived environmental quality to perceived landscape aesthetics (Table 59). In Table 60, I outline the data collected and methods used to determine the biophysical measurements, perceived landscape aesthetics, perceived environmental quality, park accessibility, and visitor preferences for different ecosystem services. The methodological steps are explained in detail in the following subsections.

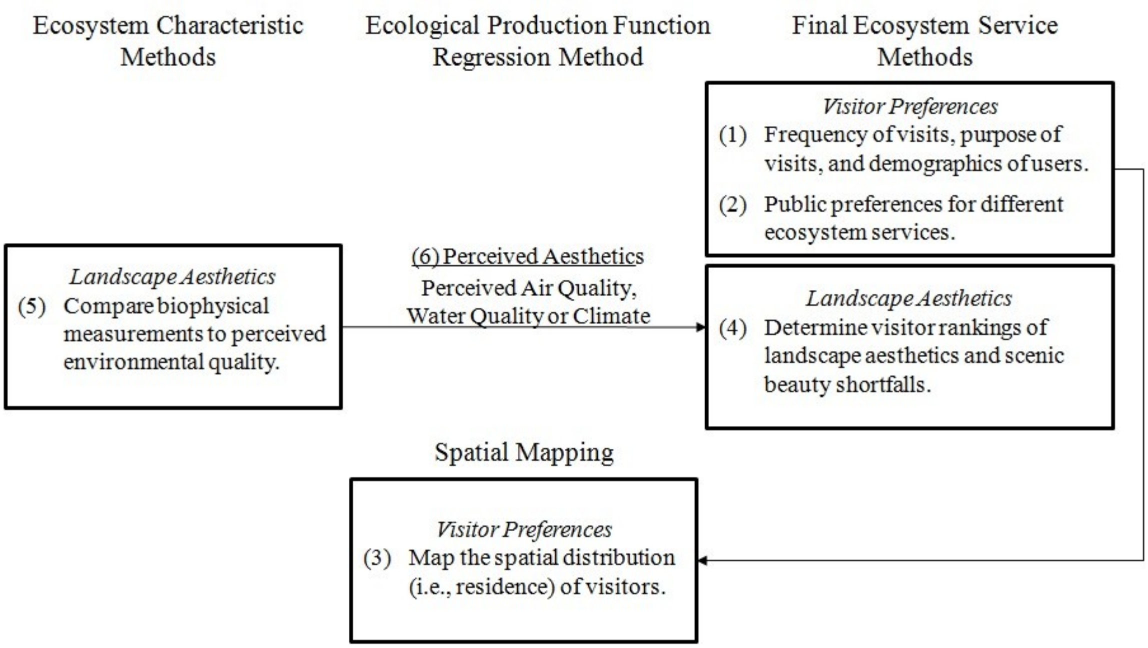


FIG. 74. General methodological steps to evaluate visitor preferences for different ecosystem services and estimate the contributions of the regulating services (i.e., other management priorities) to landscape aesthetics on the Yongding River Ecological Corridor.

TABLE 59. Description of the main measurement steps to evaluate ecosystem contributions to landscape aesthetics from the Yongding River Ecological Corridor.

Ecosystem Service Measurement Steps	Landscape Aesthetics
Relating Management Options to Ecosystem Functions	Compare biophysical measurements of environmental conditions to perceived environmental quality.
Relating Final Service to Potential Beneficiaries	Determine park accessibility using demographic and distribution (i.e., residence) data on park users.
Relating Ecosystem Functions to Final service	Determine marginal effects of perceived environmental quality on perceived landscape aesthetics.

TABLE 60. Data to measure landscape aesthetics and visitor preferences.

Data to Measure Landscape Aesthetics							
Category	Aesthetics Indicator	Biophysical Measurements			Perceived Environmental Quality	Park Accessibility	Public Preferences
Data type	Survey	Air quality index	Total nitrogen & Total phosphorus	Temperature & Humidity	Survey	Survey	Survey
Data sources	Field collection	Beijing Environmental Protection Bureau	Field collection	Field collection & Mentougou Meteorological Bureau	Field collection	Field collection	Field collection
Purpose	Scenic beauty.	Link environmental quality to landscape aesthetics to estimate the contribution of the ecosystems to the cultural service.				Demographics & distribution of park users.	Social legitimacy of selected ecosystem services.

Study area

The study area consisted of two popular public parks (Mencheng Lake and Wanping Lake) on the Yongding Corridor with similar accessibility, and landscape and cultural features (Fig. 75). Mencheng Lake marks the beginning of the Yongding Corridor located in Mentougou and Shijingshan districts. At Mencheng Lake the study boundaries consisted mainly of the large water body (i.e., the lake) and a rest area consisting of statues and a fountain, which is approximately 3 km long (Fig. 76). Homes and a roadway run along the banks of Mencheng Lake making it an accessible park. Alternatively Wanping Lake marks the end of the Yongding Corridor located in Fengtai district. At Wanping Lake the study boundaries covered the entire bank running from the entrance to the end of the lake, which is approximately 1 km long (Fig. 77). Wanping Lake has a large parking lot making it accessible for people with vehicles. Both parks have a similar design where the focus is an expansive water landscape surrounded by pathways and docks. The main differences are: (1) Mencheng Lake is a longer lake, (2) Wanping Lake has an open space for people to fly kites and dance, and (3) Wanping Lake has more trees with canopy cover, thus it is the main location for family picnics and camping. At both parks there are currently no entrance and parking fees.

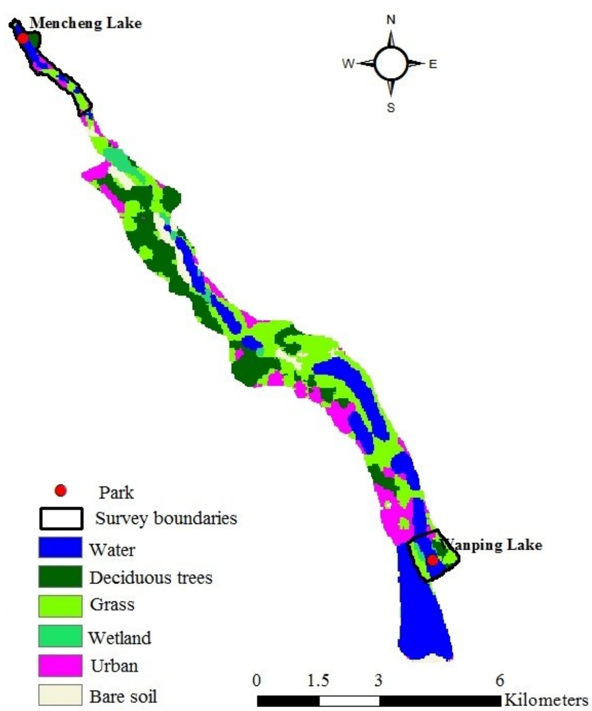


FIG.75. Visitor surveys were conducted at two public parks on the Yongding River Ecological Corridor from April 2013 to September 2013.

FIG.76. Mencheng Lake: (A) northern section is the largest continuous water body in the park, frequently visited because it is an expansive water landscape, (B) docks and pathways line the lake shore with mini-pavilions for people to experience the lake, (C) play area with shallow water area for children, and (D-E) below the large water body the channel narrows into meandering streams with cultural features (i.e., statues, water fountain, etc.).

FIG.77. Wanping Lake: (A) a shorter lake than Mencheng Lake visited frequently because it is an expansive water body, (B) entrance to Wanping Lake, (C) curved pathways allow visitors to experience the lake and wetlands, (D) docks and pathways on lake shore, and (E) families commonly picnic and set tents under the trees.

Social survey

I worked with students at the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences (RCEES-CAS) to conduct a questionnaire-based survey to assess the: (1) demographics and distribution of park users, (2) frequency of visits and reasons for visiting, (3) public preferences for different ecosystem services, and (4) public perceptions of environmental quality and landscape aesthetics (see Appendix D). The questionnaire was used to gauge public opinion on ecosystem services from the Yongding Corridor, and evaluate the influence of perceived environmental quality on visitor experiences. Arizona State University's Institutional Review Board approved all materials, methods, and questions (see Appendix D).

From April 2013 to September 2013, a team of students visited one park each month to survey visitors. We conducted the surveys in the morning and afternoon (before 6pm) at Mencheng Lake for April, June, July, and August 2013. For May 2013, we conducted the surveys in the afternoon (before 6pm) at Wanping Lake. For September 2013, we conducted the surveys in the evening (after 6pm) at Mencheng Lake. In China, peak park usage is commonly in the summer and fall on the weekends, and in the nighttime on weekdays and weekends because most families visit the parks after dinner. For each month, the survey dates were selected at random covering weekdays and weekends. The objective of our methodology was to obtain a representative sample of visitors spanning seasons, weekdays/weekends, and daytime and nighttime. Each survey visit included at least two research surveyors over a period of 2-4 hours. Surveyors approached all visitors appearing to be over the age of 12 years old and asked for their voluntary participation. Those who agreed to participate were given the option of completing the questionnaire as self-administered or surveyor-administered. Participants who chose surveyor-administered listened to questions read in Chinese by the surveyors who offered no guidance on questions to participants. A total of 193 respondents participated in the population survey. We did not collect any information on those who declined and/or reasons why they declined, and no information on groups (i.e., visiting the park with others). For each respondent, we collected information on gender, age, education level, occupation, income level, duration of stay, purpose of visit, frequency of visits to the location (pre- and post-Corridor), and place of residence in terms of district and/or province.

Visitor opinions of different ecosystem services from the Yongding Corridor were determined by having participants: (1) select ecosystem services of value to them, (2) select current dissatisfactions and future concerns, and (3) state reasons for choosing the park they visited. First participants were asked "What is the most important value to them from the Yongding Corridor," respondents could select multiple ecosystem service values listed below (or included others in an "open ended" section): 'air quality improvements' (1), 'cooling effects' (2), 'increase water supply' (3), 'water quality improvements' (4), 'place for leisure and travel' (5), 'recreation opportunities' (6), 'heritage value for future generations' (7), and 'landscape preservation' (8). Second participants were asked "What aspects of the Yongding Corridor are you dissatisfied with," respondents could select multiple values ranging from 1 to 5 and provide any additional areas of dissatisfaction not listed: 'water quality' (1), 'water level' (2), 'air quality' (3), 'climate' (4), and ‘environment’ (5). Third participants were asked two open-ended questions: “There are many parks near the Yongding River, such as Mencheng Lake, Xiaoyue Lake, and Wanping Lake. Today why did you choose this park over other parks?”; “What is your biggest concern about the future of the Yongding River?”

Final services and final service indicators

The questionnaire was used to solicit information on people’s perceptions of environmental quality and landscape aesthetics. Respondents were first asked to score the landscape aesthetics then asked to score environmental quality and overall trip satisfaction (Table 61). The order in which questions were presented was important to minimize bias in answers since participants were asked to evaluate landscape aesthetics (the dependent variable) prior to evaluating environmental quality (the independent variables). The final service levels for landscape aesthetics were visitor scores of ‘beautiful’ (4) or ‘very beautiful’ (5). Final service shortfalls were the difference between surveyed visitor values and final service levels.

Biophysical measurements: environmental conditions

Data were collected in the field and obtained from municipal monitoring stations for air quality, water quality, and climate on the dates when the surveys were conducted (Table 60). Air quality index (AQI) values were obtained from the Beijing Environmental Protection Bureau Longquan station in Mentougou district. Water samples were collected in the field when surveys were conducted, and samples were analyzed for total nitrogen

(TN) and total phosphorus (TP). Air temperature and relative humidity Hobo data loggers were placed at Mencheng Lake and Wanping Lake to determine mean daily air temperature and relative humidity for survey dates from April 2013 to July 2013. For August 2013 and September 2013, the mean daily air temperature and relative humidity were obtained from the Mentougou Meteorological Bureau because the field crew removed the data loggers in the end of July 2013. Mean daily air temperature and relative humidity were used to calculate heat stress index values (HI).

TABLE 61. Survey questions used to assess public perceptions on landscape aesthetics and environmental quality on the Yongding River Ecological Corridor.

No.	Question	Value	Score Description
1 (Aesthetics)	You think the Yongding River Ecological Corridor is:	1	Very unattractive
		2	Unattractive
		3	Okay
		4	Beautiful
		5	Very beautiful
2 (Air Quality)	During your trip today, the air quality on the Yongding River Ecological Corridor was:	1	Very unhealthy
		2	Unhealthy
		3	Moderate
		4	Healthy
		5	Very healthy
3 (Water Quality)	During your trip today, the water quality on the Yongding River Ecological Corridor was:	1	Very unhealthy
		2	Unhealthy
		3	Moderate
		4	Healthy
		5	Very healthy
4 (Climate)	During your trip today, the weather on the Yongding River Ecological Corridor was:	1	Very hot
		2	Hot
		3	Warm
		4	Cool
		5	Cold
5 (Trip Satisfaction)	Overall, did you enjoy your trip today:	1	Very unpleasant
		2	Unpleasant
		3	Okay
		4	Enjoyable
		5	Very enjoyable

Ecological production function: ordinal logistic regression model

The success of the Yongding Corridor will depend heavily on how people perceive the landscape aesthetics, which can be influenced by environmental quality (i.e., the other management priorities representing the four services in Chapters 5-7). The government and developers created the new ecosystems to improve environmental conditions. The goal is to get people to find beauty and enjoyment in the area to motivate tourism, new businesses, and housing purchases. The public is the primary user of concern to investors, thus understanding visitor preferences is critical to making the Yongding Corridor relevant to its users. First, I summarize the biophysical measurements of environmental quality measured on the same dates as when the surveys were conducted. Second, I compare the biophysical measurements to perceived environmental quality to assess how actual environmental conditions match people's perceptions. People were asked to score environmental quality and aesthetics for their current trip, however many of the survey respondents are local residents. Thus visitor perceptions of environmental quality are likely influenced by several interactions with the landscape that extend beyond the immediate environmental conditions. Third I create an ecological production function using an ordinal logistic regression model to link perceived environmental quality to perceived landscape aesthetics.

In the social sciences many of the variables from surveys are ordinal (i.e., 1st, 2nd, 3rd, etc.) since individuals often are asked to rank values where the distance between categories is unknown. For example, people commonly perceive environmental quality on scales of 'healthy' or 'unhealthy', thus social scientists assign values to these qualitative descriptions to analyze people's opinions, perceptions, and values. Social scientists commonly evaluate ordinal categorical variables using ordinal logistic regression models – a specialized case of the general linear model. Unlike ordinary least square (OLS) regressions logistic models use the standard logistic probability distribution. An ordinal logistic regression model allows one to estimate a set of regression coefficients to predict the probability of the outcome of interest. The common form of a simple ordinal logistic regression model is:

$$ln\left(\frac{prob(event)}{(1\text{-}prob(event))}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k \tag{17}$$

I evaluated the potential contributions of the ecosystems to landscape aesthetics using an ordinal logistic regression model to link visitor scores of environmental quality to scores of aesthetics. The general model is shown below:

$$ln\left(\frac{prob(Aesthetics)}{(1\text{-}prob(Aesthetics))}\right) = \beta_0 + \beta_1 Air + \beta_2 Water + \beta_3 Cooling + \beta_4 Enjoyment + \varepsilon \tag{18}$$

where *Aesthetics* is visitor scores of scenic beauty (Table 61). As Daniel (2001) defines landscape aesthetics is the interaction between biophysical features of the landscape and the perceptual and judgmental processes of the human viewer. I selected four explanatory variables representing: (a) biophysical conditions - three regulating ecosystem services (e.g., dust control, water purification, and local climate regulation) and (b) judgmental processes - personal satisfaction with the trip. The *Air* variable is visitor scores on air quality, *Water* variable is visitor scores on water quality, the *Cooling* variable is visitor scores on climate conditions, and the *Enjoyment* variable is visitor scores on overall trip experience. I chose to include the Enjoyment variable because trip satisfaction (i.e., enjoyment) is influenced by an individual's mood, social interactions with others, etc. that are not related to the environmental conditions. Therefore people's feelings of their trip can impact their judgment of the landscape's beauty. When creating a regression model one tries to balance efficiency using few explanatory variables while not minimizing precision, and reducing multicollinearity. I chose these explanatory variables because landscape aesthetics are influenced by both biophysical attributes and human feelings of their experience. Also these four variables created the most robust model.

As standard practice the regression coefficients (i.e., marginal effects) from an ordinal logistic regression model are presented as: (1) proportional odds ratios, (2) percent changes in the odds, and (3) predicted probabilities. An assumption of an ordinal logistic regression is that the relationship between the independent variables and the response variable is the same for all groups. For instance, the ordinal logistic regression assumes the coefficients that describe the relationship between the lowest versus all higher score classes of the response variable are the same as those that describe the relationship between the next lowest score classes and all higher score classes. This is called the proportional odds assumption or parallel regression assumption. All statistical analyses were conducted using Stata 12.1 to generate the ordinal logistic regression model (see Appendix C). I tested the proportional odds assumption using the omodel test in Stata. Also I assessed goodness of fit metrics to evaluate the suitability of the model (see Appendix C).

RESULTS

Descriptive statistics of surveyed population

The total number of surveys completed was 193 with 152 completed between 10:00 am and 5:00 pm (day time) and 41 completed after 6pm (night time). The majority of the responses were from Mencheng Lake (N = 138) compared to Wanping Lake (N = 55). Also we obtained fewer responses in June 2013 (N = 3) compared to other months (April = 19; May = 55; July = 29; August = 46; September = 41) because there were few visitors present on that given day.

Demographic information on surveyed visitors

The survey respondents represented a diverse spectrum of Beijing citizens in terms of gender, age, education level, occupation, and income level. The surveyed population was 43% female and 57% male, representing a range of ages: '21-30' (19%), '31-40' (26%), '41-50' (17%), '51-60' (20%), and 'above 60' (14%) (Fig.78). The education levels of survey respondents were also mixed: 57% having a high school or less education, 36% having college or equivalent education, and 3% having a master's or higher education (Fig. 79). The main occupations were 'government' (20%), 'retired' (19%), 'commercial, service personnel' (15%), 'self-employed' (10%), 'agriculture' (6%), and 'professional, technical personnel' (6%) (Table 62). The surveyed population represented various personal monthly income levels: poor (<2,000 yuan), low income (<5,000 yuan), middle income (5,001-8,000 yuan), and upper middle income (>8,000 yuan). In 2013, the average monthly per capita income in Beijing was 5,973 yuan ($ 927

USD). The majority of respondents had personal monthly income levels below Beijing's average per capita monthly income level. Out of the 193 respondents: 17% had no income (this category is likely misleading since many of the individuals were stay at home parents or retired), 62% were poor to low income, 10% were middle income, and 8% were upper middle income (Table 63). The income levels reported were monthly personal income not household income levels, which can skew the reported social classifications. Other members of a household could contribute a higher or lower proportion to the overall household income, which is not evaluated in these survey results.

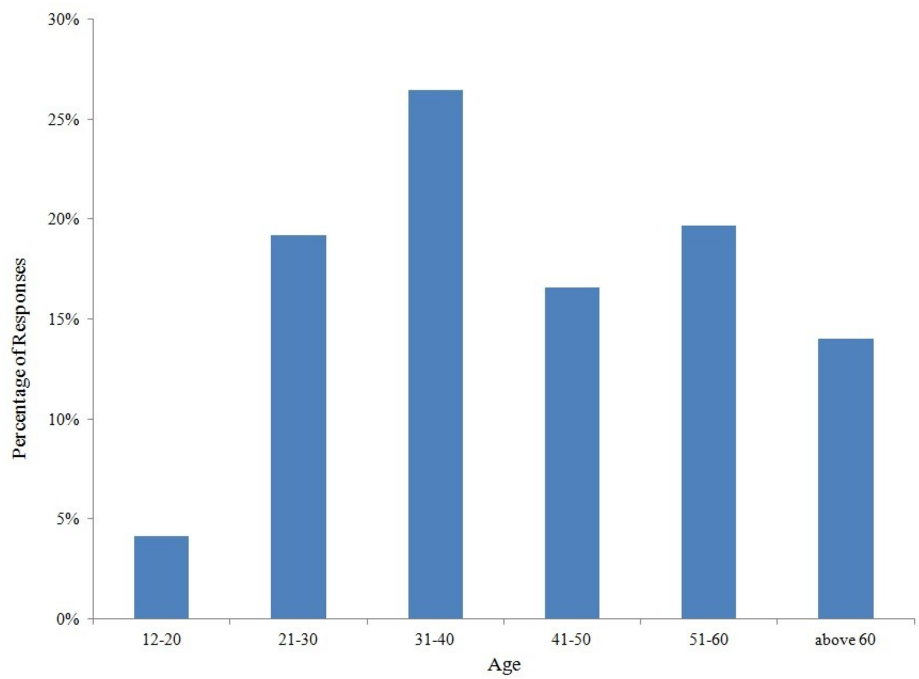


FIG. 78. Age profile of the surveyed population.

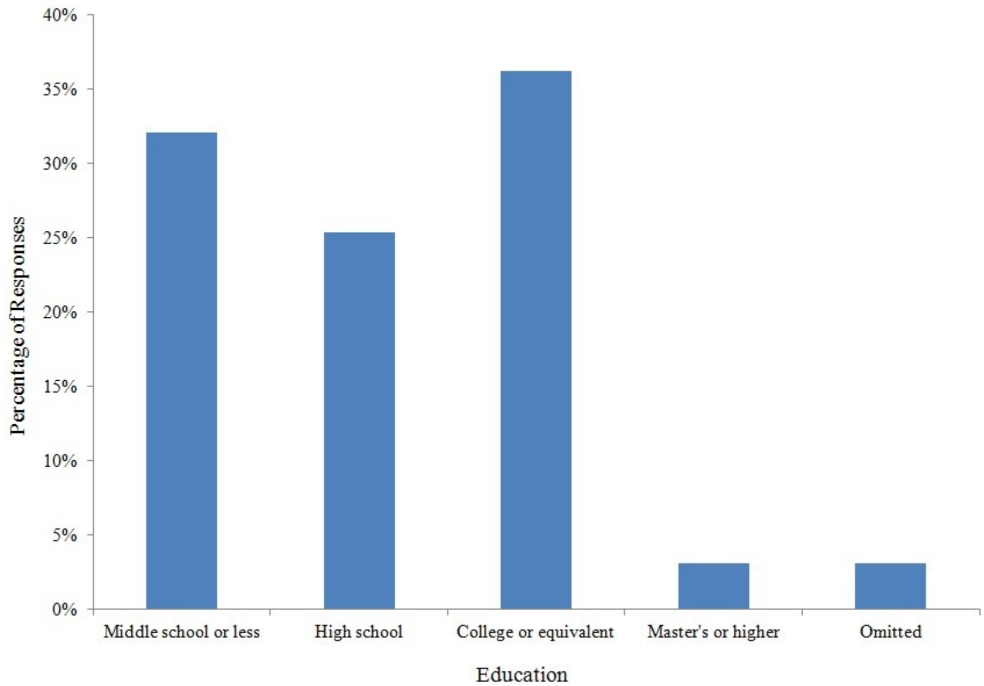


FIG.79. Education levels of the surveyed population.

TABLE 62. Occupations of the surveyed population.

Occupation	N	%
Student	10	5%
Teacher	7	4%
Researcher	2	1%
Military	4	2%
Government	38	20%
Commercial, service personnel	29	15%
Professional, technical personnel	12	6%
Farming, Forestry, Animal Husbandry and/or Fisheries	11	6%
Self-employed	20	10%
Retired	37	19%
Unemployed	14	7%
Other	6	3%
Omitted	3	2%

TABLE 63. Personal monthly income levels of the surveyed population.

Income	N	%
No income	33	17%
<2,000 yuan (<$325 USD)	27	14%
2,001-5,000 yuan ($325-815 USD)	93	48%
5,001-8,000 yuan ($815-1,303 USD)	20	10%
8,001-15,000 yuan ($1,303-2,443 USD)	11	6%
>15,000 yuan (>$2,443 USD)	4	2%
Omitted	5	3%

Distribution of park visitors

The demographics of the surveyed population were diverse since the Yongding Corridor attracts both local residents and leisure tourists from around Beijing and other provinces. The majority of parks visitors were local residents from districts surrounding Mencheng Lake (Mentougou and Shijingshan districts) and Wanping Lake (Fengtai district) (Fig. 80). We conducted the majority of surveys at Mencheng Lake, thus 69% of the surveyed population were from nearby Mentougou and Shijingshan districts. However there were visitors who traveled from as far as Chaoyang and Changping districts (Fig. 80), which suggests Beijingers outside of nearby districts are aware of the Yongding Corridor, and are willing to travel to southwest Beijing for leisure and recreation activities. Also there were a few visitors from neighboring Hebei and Shandong Provinces (Fig. 81). This result suggests there is potential for the Yongding Corridor to capture a share of Beijing's tourism market. The new subway line opened in May 2013, and free parking is likely making the Yongding Corridor more accessible to visitors beyond nearby districts.

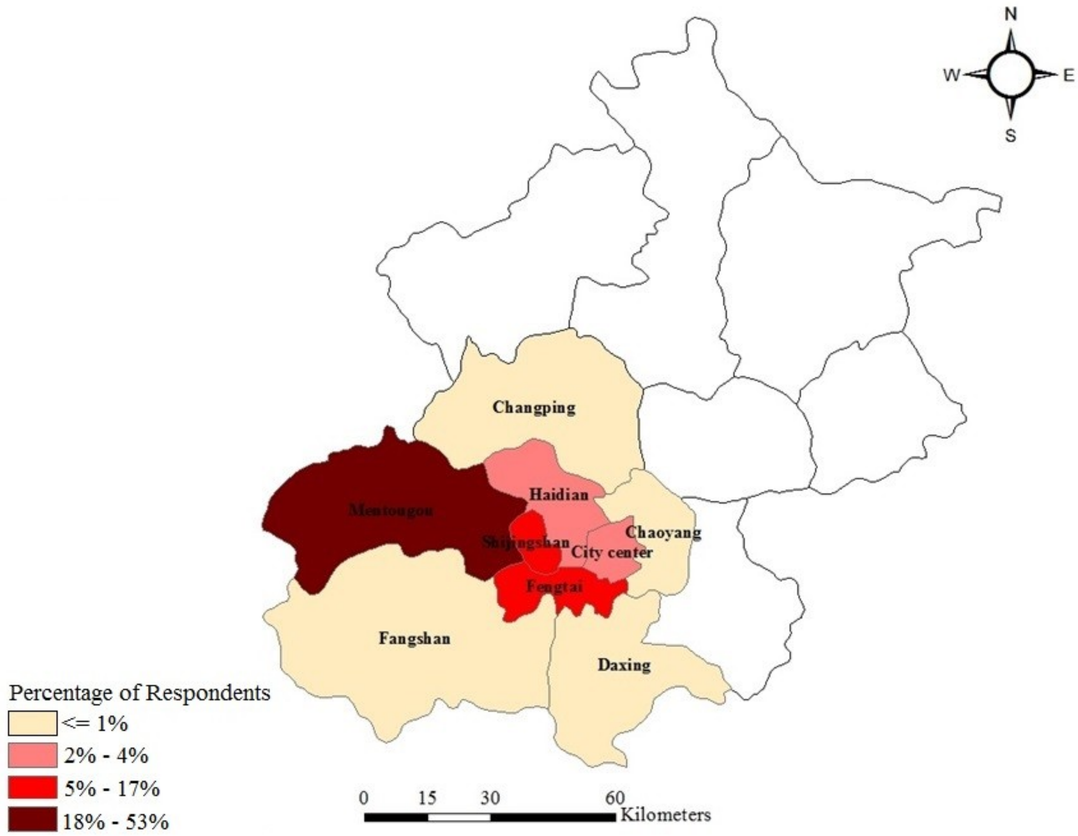


FIG.80. Place of residence of leisure and recreation beneficiaries (i.e., visitors) by district in Beijing municipality.

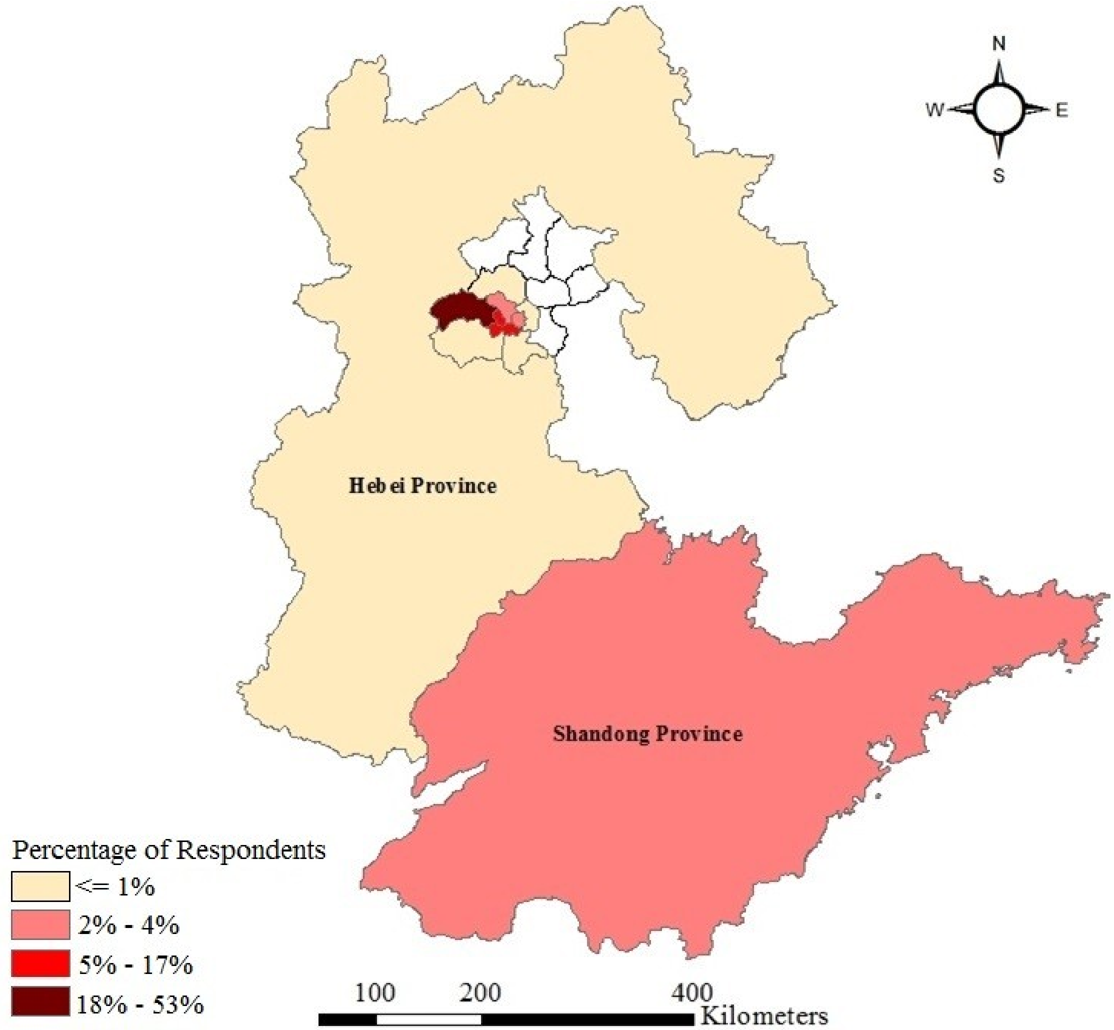


FIG. 81. Place of residence of leisure and recreation beneficiaries (i.e., park visitors) by province and Beijing municipality (not labeled but surrounded by Hebei Province).

Visitor preferences on ecosystem services: social legitimacy of management endpoints

Visitor preferences for different ecosystem services were assessed to determine the social legitimacy of management endpoints (i.e., final services), and understand visitor interests to help management prioritize actions on multiple services. The Beijing Water Authority (BWA) selected five primary ecosystem services from the Yongding Corridor: (1) water storage (water supply), (2) local climate regulation (cooling), (3) water purification (water quality), (4) dust control (air quality), and (5) landscape aesthetics (leisure, recreation, heritage). From BWA planning documents, the ultimate goal for management is to improve the cultural services by enhancing the environmental quality of the Yongding River. However after discussing with managers, they were interested in ways to prioritize the five ecosystem services. Responses from the surveyed population provide a possible way to rank different ecosystem services from the Yongding Corridor shown in Table 64. From the Yongding Corridor, the top five ecosystem services selected by visitors in terms of their social values were: (1) 'leisure and travel' (61%), (2) 'air quality' (44%), (3) 'landscape preservation' (20%), (4) 'recreation' (17%), and (5) 'cooling' (17%). It is important to note that the questionnaire considered 'air quality' as the potential of the Yongding Corridor to reduce all air pollutants, not only local dust.

TABLE 64. Most important ecosystem services to visitors.

Surveyed Population Preferences for Ecosystem Services		
Social Values (Ecosystem Services)	N	%*
Leisure and travel (cultural)	117	61%
Air quality (dust control and air pollution control†)	85	44%
Landscape preservation (cultural and biodiversity)	38	20%
Recreation (cultural)	32	17%
Cooling (local climate regulation)	33	17%
Water quality (nutrient retention)	26	13%
Heritage value for future generations (cultural)	27	14%
Water supply (water storage)	12	6%
Other (wetland biodiversity^)	1	1%

* Individuals were asked to select the most important ecosystem services to them from the Yongding River Ecological Corridor, thus the percentages are out of 193 responses; will not add up to 100%.
† Public perceptions of air quality are likely not only impacted by sand flux, but other air pollution sources like nitrous oxide, ozone, etc.
^One respondent filled the other blank as wetland biodiversity.

The surveyed population identified two main problems impacting the Yongding Corridor, which were water pollution and water storage (Tables 65-66). When visitors were asked about current dissatisfactions the main selections were: (1) ‘other’ such as traffic, litter, few shade trees, and few restrooms, (2) ‘water quality’, and (3) ‘water level’ (Table 65). In 2013, there were few public restrooms on the Yongding Corridor and few shade trees. In the summer people congregate under bridges because the covered pavilions are too small for families, and many of the trees are too young to provide sufficient shade for large groups. When respondents were asked an open-ended question of “What is your biggest concern about the future of the Yongding River,” the top reported concerns were grouped into five categories: (1) water pollution (25%), (2) water storage (13%), (3) management and maintenance (12%), (4) litter (9%), and (5) ecosystem protection (5%). Many visitors articulated water pollution as a concern, but local residents provided important observations on the source of the problem. For example, local residents wrote statements, such as: (1) “a need for residents to maintain the water quality by controlling sewage discharge,” (2) “few districts have ways to remove sewage; sewage discharge is a concern,” and (3) “pollution outfall is near water bodies.” Furthermore, frequent visitors were concerned about “water scarcity” and “lake drying,” which they felt were causing poor water quality. Lastly, visitors showed an interest in the sustainability of the Yongding Corridor by articulating their biggest concern as: (1) “maintaining the current environmental condition,” (2) “coordination between surrounding buildings and scenic beauty to maintain the landscape conditions,” (3) “ability to ensure long-term maintenance,” and (4) “after completion, the ability to remain in good condition.”

TABLE 65. Visitors were asked about current dissatisfactions with the Yongding River Ecological Corridor.

Areas for Improvement		
Dissatisfactions	N	%
Other (traffic, littering, few shade trees, and few restrooms)	71	37%
Water quality	69	36%
Water level	22	11%
Air quality	12	6%
Climate	4	2%
Environment	24	12%

TABLE 66. Visitors were asked to state their biggest concerns about the future of the Yongding River.

Future Concerns		
Topic	N	%*
Omitted	53	27%
Water pollution	49	25%
None	25	13%
Water storage	25	13%
Management and maintenance	24	12%
Litter	18	9%
Ecosystem Protection	9	5%
Overuse	9	5%
Lack of Facilities (restrooms, handicap accessible, bus stop, shops, and hotels)	7	4%
Floods	5	3%
Safety	5	3%
Surrounding development	4	2%
Restrictions (fishing, and fees)	2	1%

* Individuals were asked to select the most important ecosystem services to them from the Yongding River Ecological Corridor, thus the percentages are out of 193 responses.

Landscape aesthetics shortfalls

The majority of surveyed visitors considered the landscape aesthetics of the Yongding Corridor ‘beautiful’ or ‘very beautiful’, thus from the surveyed population there were few people who experienced shortfalls. Out of the 193 people who participated in the survey, 36% considered the Yongding Corridor ‘very beautiful’ and 46% considered the Yongding Corridor ‘beautiful’ (Fig. 82). There were 18% that considered the Yongding Corridor ‘okay’, 1% considered the Yongding Corridor ‘unattractive’, and 0% considered the Yongding Corridor ‘very unattractive.’ Hence only 19% of participants in the survey graded the Yongding Corridor below the final service levels.

Furthermore, the majority of respondents were satisfied with their overall trips to the Yongding Corridor since 59% reported their trip as 'enjoyable' and 32% reported their trip as 'very enjoyable.' Only 6% of the respondents felt their trip was 'okay' and 1% as 'unpleasant.' In general the survey participants gave the Yongding Corridor high scores for scenic beauty and trip satisfaction.

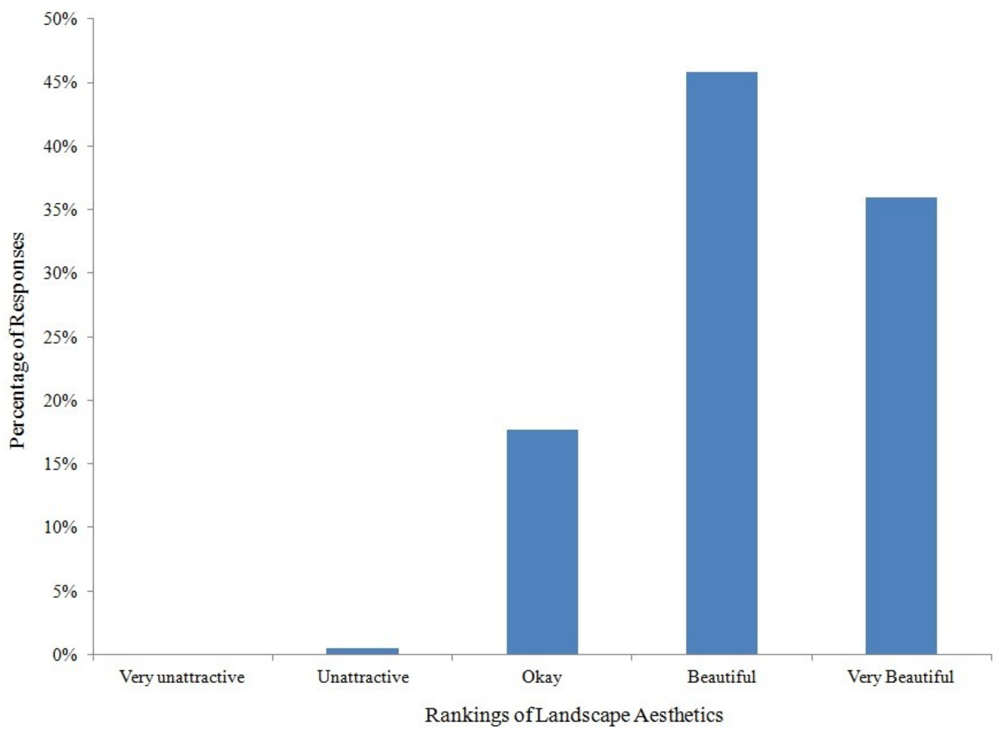


FIG.82. Percent of responses of surveyed population on landscape aesthetics; final services are rankings of 'beautiful' and 'very beautiful.'

The frequency of visits to the Yongding River was significantly higher in the post-Corridor period compared to the pre-Corridor period, and during a visit the average time spent on the Yongding Corridor was just above 2 hours (Table 67). For the pre-Corridor period (before 2010), the mean number of visits was just below 4 visits and in the post-Corridor period (after 2010) the mean number of visits was 5 visits. During the survey period, 36% of participants spent between 1-2 hours and 34% spent between 2-4 hours on the Yongding Corridor (Fig. 83). During the survey period, 61% of participants stated the purpose of their visit was ‘relaxation’ and 32% stated the purpose of their visit was ‘exercise’ (Fig. 84). Visitors gave individual statements on their reasons for their park selection, which were grouped into 8 different categories: (1) proximity and accessibility, (2) aesthetics, (3) environmental quality, (4) quiet, (5) recreation, (6) free, (7) have not visited other parks on the Yongding Corridor, and (8) omitted. 62% of participants stated they chose their park based on proximity and accessibility from their home and parking lots (Fig. 85). The next two most popular responses were aesthetics where people stated “beautiful water landscapes,” and environmental quality where people stated “good air quality” and “cool environment.”

TABLE 67. Summary statistics for frequency of visits (pre- and post-Corridor), duration of visit, and purpose of visit.

Variable	Mean	Std. Dev.
Pre-Corridor visits[a]	3.7*	3.1
Post-Corridor visits[a]	6.0*	2.0
Time spent at park[b]	3.2	1.0
Purpose of visit[c]	1.7	0.5

* Statistically significant difference between pre- and post-Corridor mean visits at $P < 0.01$ level.
[a] Ordinal variable (number of visits): 1 = 0; 2 = 1; 3 = 2; 4 = 3; 5 = 4; 6 = 5; 7 = 6-10; 8 = > 10.
[b] Ordinal variable (time spent): 1 = <30 minutes; 2 = 31-60 minutes; 3 = 1-2 hours; 4 = 2-4 hours; 5 = 1 day.
[c] Ordinal variable (purpose): 1 = exercise, recreation; 2 = relaxation; 3 = tourism; 4 = other.

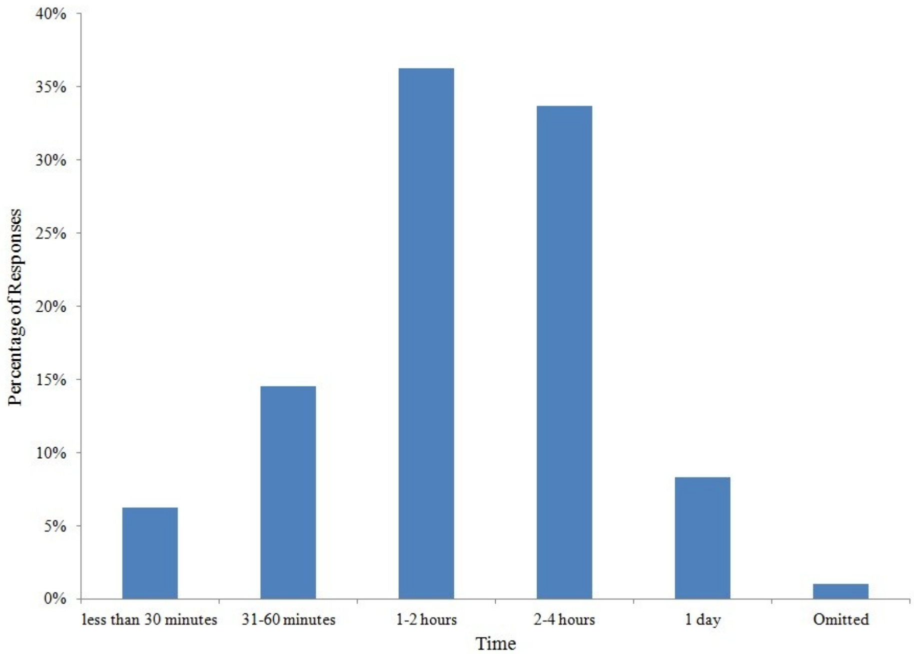


FIG. 83. Percent of responses of surveyed population on the duration of visit to the Yongding River Ecological Corridor.

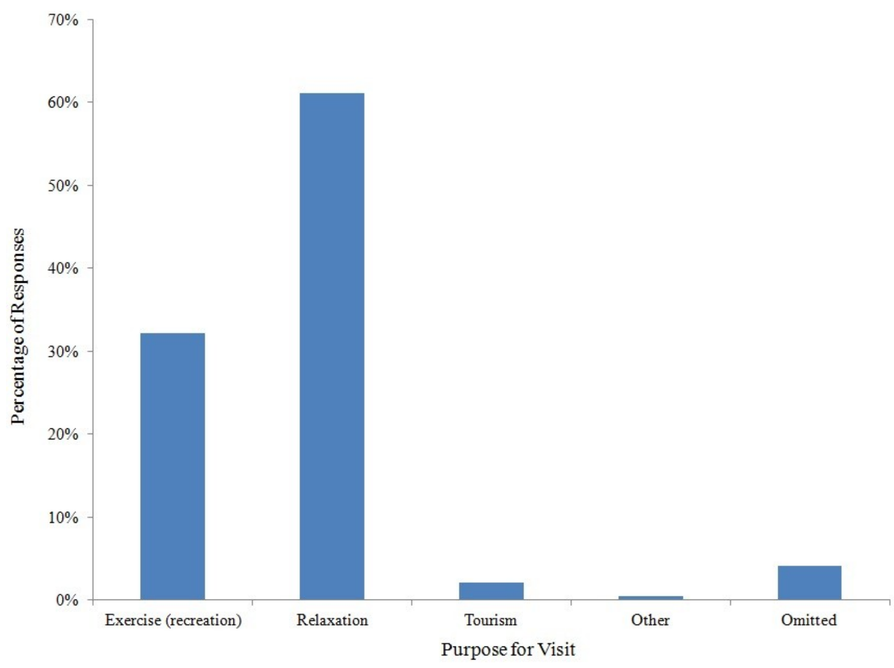


FIG.84. Percent of responses of surveyed population on the purpose of the visit to the Yongding River Ecological Corridor.

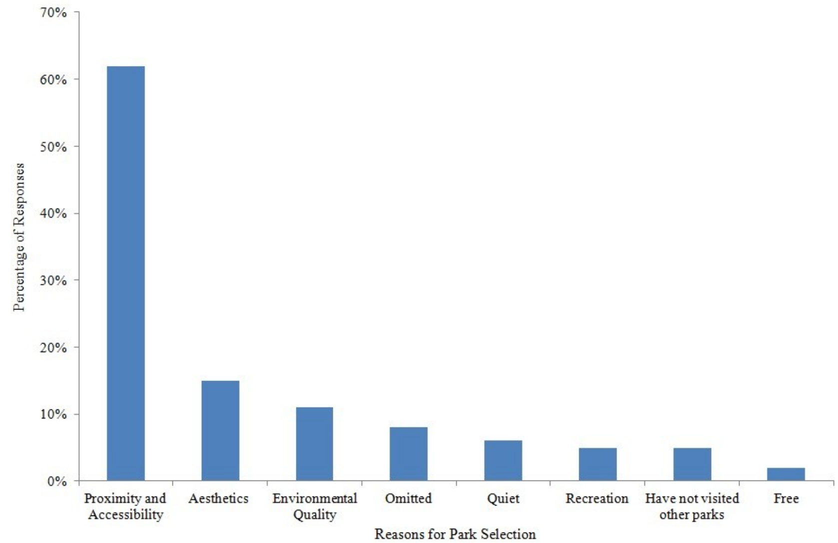


FIG.85. Percent of responses of surveyed population on different reasons for park selection on the Yongding River Ecological Corridor.

Environmental quality: Biophysical measurements and public perceptions

On the same date when the surveys were conducted in June 2013 and July 2013 both air quality and water quality were poor, and climate conditions were near sultry (Table 68). For June 2013 and July 2013, survey participants gave the lowest average ratings for aesthetics, trip enjoyment, air quality, water quality, and climate compared to other months (Table 69). For June 2013, the mean score on: perceived aesthetics was 4.0 (equivalent to 'beautiful'), perceived trip enjoyment was 3.7 (just below 'enjoyable'), perceived air quality was 3.7 (just below 'healthy'), perceived water quality was 2.7 (just below 'moderate'), perceived climate was 4.0 (equivalent to 'cool'). When the survey was conducted in June 2013 the mean daily AQI was 132 ('unhealthy for sensitive groups'), TN was 3.14 mg/L (unsuitable for any human uses), TP was 0.12 mg/L (suitable for drinking water), and mean daily air temperature was 26.7 °C, relative humidity was 66%, and HI was 25 (below sultry).

For July 2013, the mean score on perceived aesthetics was 3.9 (just below 'beautiful'), the mean score: on perceived trip enjoyment was 4.1 (just above 'enjoyable'), perceived air quality was 3.6 (below 'healthy'), perceived water quality was 3.2 (just above 'moderate'), and perceived climate was 3.1 (just above 'warm'). When the survey was conducted in July 2013 the mean daily AQI was 190 ('unhealthy'), TN was 3.32 mg/L (unsuitable for any human uses), TP was 0.07 mg/L (suitable for nature reserves), and mean daily air temperature was 27.2 °C, relative humidity was 72%, and HI was 25 (below sultry). Lower visitor scores in June 2013 and July 2013 matched the objective monitoring data indicating poor environmental quality, suggesting environmental quality could potentially influence visitor experiences.

TABLE 68. Environmental quality data describing the environmental conditions on the same date when the surveys were conducted.

Biophysical Measurements									
Month	AQI Value	AQI Grade	TN (mg/L)	TN Grade	TP (mg/L)	TP Grade	Temp. (° C)	RH (%)	HI
April 2013	53	Moderate	1.62	5	0.05	1	11.11	25	13
May 2013	81	Moderate	0.91	3	0.07	1	25.12	23	21
June 2013	132	Unhealthy for sensitive groups	3.14	6	0.12	2	26.96	66	25
July 2013	190	Unhealthy	3.32	6	0.07	1	27.16	72	25
August 2013	127	Unhealthy for sensitive groups	1.49	3	0.05	1	27.53	70	25
September 2013	---	---	---	---	---	---	---	---	---

Standard deviations are shown in parentheses; AQI = China's air quality index; TN = total nitrogen (mg/L); TN Grade = China's TN water quality standard; TP = total phosphorus (mg/L); TP Grade = China's TP water quality standard; Temp. = air temperature (° C); RH = relative humidity (%); HI = China's heat index.
No environmental measurements were taken in September 2013.

TABLE 69. Perceived environmental quality, aesthetics, and trip satisfaction; mean monthly scores and standard errors for each variable.

Surveyed Population Perceptions of Trip Experience					
Month	Aesthetics[a]	Air Quality[b]	Water Quality[c]	Climate[d]	Enjoyment[e]
April 2013	4.05 (0.71)	3.89 (0.66)	3.21 (0.63)	3.68 (0.48)	4.11 (0.68)
May 2013	4.16 (0.66)	3.69 (0.50)	3.24 (0.47)	3.76 (0.58)	4.11 (0.60)
June 2013	4.00 (1.00)	3.67 (0.58)	2.67 (0.58)	4.00 (0.00)	3.67 (0.58)
July 2013	3.90 (0.77)	3.59 (0.63)	3.18 (0.86)	3.10 (0.98)	4.07 (0.65)
August 2013	4.20 (0.82)	4.15 (0.66)	3.10 (0.79)	3.70 (0.65)	4.43 (0.50)
September 2013†	4.38 (0.67)	4.03 (0.74)	3.08 (0.69)	4.00 (0.00)	4.46 (0.60)

Standard deviations shown in parentheses.

† September 2013 surveys were taken after 6pm for April 2013 - August 2013 surveys were taken before 6pm.

[a] Aesthetics are rankings for scenic beauty: 1 = very unattractive; 2 = unattractive; 3 = okay; 4 = beautiful; 5 = very beautiful.
[b] Air quality: 1 = very unhealthy; 2 = unhealthy; 3 = moderate; 4 = healthy; 5 = very healthy.
[c] Water quality: 1 = very unhealthy; 2 = unhealthy; 3 = moderate; 4 = healthy; 5 = very healthy.
[d] Climate: 1 = very hot; 2 = hot; 3 = warm; 4 = cool; 5 = cold.
[e] Enjoyment are rankings for trip satisfaction: 1 = very unpleasant; 2 = unpleasant; 3 = ok; 4 = enjoyable; 5 = very enjoyable.

Ecological production function: Perceived environmental quality to perceived aesthetics

The final step of the analysis is linking visitor perceptions of environmental quality to perceptions of landscape aesthetics to assess the potential influence of environmental quality of the new ecosystems on scenic beauty. An ecological production function was created using an ordinal logistic regression model to assess the potential relationship between perceived environmental quality and landscape aesthetics. The model has four explanatory variables (air quality, water quality, climate, and trip enjoyment) and one response variable (aesthetics) using surveys from April 2013 to September 2013. The summary statistics of the five variables are reported in Table 70.

TABLE 70. Summary statistics of the variables used in the ecological production function linking perceived environmental quality to landscape aesthetics.

Variable	N	Mean	Std. Dev.	Min	Max
Aesthetics	192	4.17	0.73	2	5
Air Quality	190	3.87	0.65	3	5
Water Quality	189	3.18	0.71	1	5
Climate	192	3.67	0.69	1	4
Enjoyment	189	4.24	0.61	2	5

First I summarize the full model using the cumulative regression coefficients, which were evaluated using proportional odds ratios and percent changes in the odds (the full report on regression statistics are listed in Appendix C). The regression coefficients for water quality, climate, and enjoyment were statistically significant, however the regression coefficients for air quality was not statistically significant (Table 71). When interpreting regression coefficients of ordinal logistic models, social scientists prefer to use proportional odds ratios and percent changes in odds because they are easier to understand. Therefore these metrics were used to interpret the statistically significant regression coefficients. For a unit increase in the water quality score, the odds of having a high visitor score of aesthetics compared to middle or low scores increases by a factor of 1.86 or 86%, holding other variables constant. For a unit increase in the climate score, the odds of having a high visitor score of aesthetics compared to middle or low scores increases by a factor of 1.75 or 75%, holding other variables constant. For a unit increase in the trip enjoyment score, the odds of having a high visitor score of aesthetics compared to middle or low scores increases by a factor of 2.60 or 160%, holding other variables constant. Water quality had a slightly higher influence compared to climate, but trip enjoyment had the greatest influence on average aesthetic scores.

TABLE 71. Regression coefficients proportional odds ratios and percent changes in odds.

Variable	Proportional odds ratio	Percent change (%)
Air Quality	1.22 (1.14)	22.2 (14.0)
Water Quality	1.86 (1.54)*	86.5 (54.5)*
Climate	1.75 (1.46)*	75.0 (45.7)*
Enjoyment	2.60 (1.80)*	159.7 (80.1)*

*P<0.05 and standard deviations shown in parentheses.

Second I used predicted probabilities to compute predictions of changes in explanatory variables at the final service level of ‘very beautiful,’ which is useful for understanding the potential contribution of each variable in obtaining the highest ranking for landscape aesthetics. Predicted probabilities allow one to analyze the potential probability of getting a desired outcome for individual score classes of each explanatory variable. I summarize the highest probabilities of obtaining an aesthetics score of ‘very beautiful' for each explanatory variable, however all predicted probabilities are shown in Table 72. When air quality is perceived as 'very healthy', holding other variables at their means, the probability of visitors scoring the aesthetics as 'very beautiful' is 38% (statistically significant at P<0.05) (Fig. 86). When water quality is perceived as 'very healthy', holding other variables at their means, the probability of visitors scoring the aesthetics as 'very beautiful' is 61% (statistically significant at P<0.05) (Fig. 87). When climate is perceived as 'cold', holding other variables at their means, the probability of visitors scoring the aesthetics as 'very beautiful' is 51% (statistically significant at P<0.05) (Fig. 88). When trip enjoyment is perceived as 'very enjoyable', holding other variables at their means, the probability of visitors scoring the aesthetics as 'very beautiful' is 51% (statistically significant at P<0.05) (Fig. 89). A high water quality ranking had the highest predicted probability of visitors scoring the aesthetics at the final service level of 'very beautiful.'

TABLE 72. Predicted probabilities of getting the final service level of aesthetics = 5 (very beautiful) for each explanatory variable, holding other variables at their means.

Aesthetics = 5 (Very Beautiful)								
Score Class	Air Quality	95% CI	Water Quality	95% CI	Climate	95% CI	Enjoyment	95%CI
1	0.22 (0.13)	-0.04-0.48	0.11 (0.05)*	0.01-0.22	0.10 (0.06)	-0.01-0.21	0.02 (0.02)	-0.02-0.06
2	0.25 (0.10)*	0.06-0.45	0.19 (0.05)*	0.09-0.29	0.16 (0.06)*	0.05-0.27	0.05 (0.03)	-0.01-0.12
3	0.29 (0.06)*	0.18-0.41	0.31 (0.04)*	0.24-0.38	0.25 (0.04)*	0.17-0.34	0.13 (0.04)*	0.04-0.22
4	0.34(0.04)*	0.26-0.41	0.46 (0.06)*	0.33-0.58	0.37 (0.04)*	0.29-0.46	0.28 (0.04)*	0.21-0.36
5	0.38 (0.08)*	0.22-0.55	0.61 (0.11)*	0.40-0.82	0.51 (0.08)*	0.35-0.67	0.51 (0.06)*	0.38-0.63

*P<0.05 in parenthesis below coefficient is the standard error.

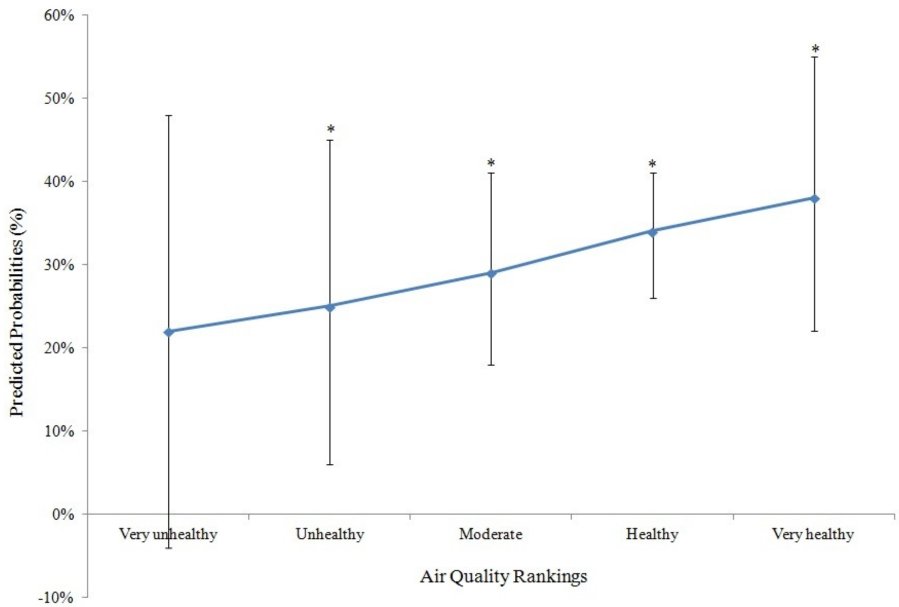


FIG.86. Predicted probabilities for aesthetics = ‘very beautiful’ at each score class of air quality holding all other variables at their means; predicted probabilities are shown with 95% confidence intervals; * statistically significant at P<0.05.

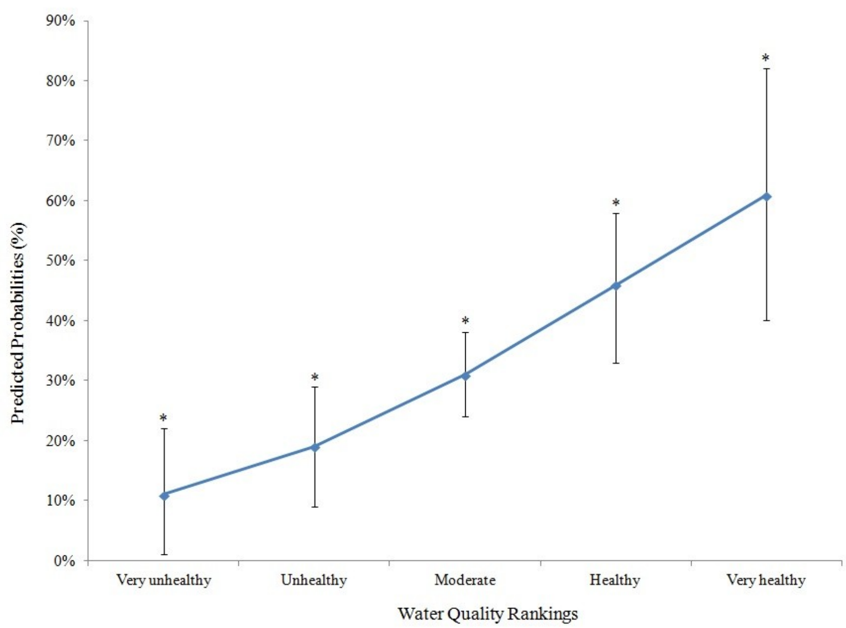


FIG.87. Predicted probabilities for aesthetics = ‘very beautiful’ at each score class of water quality holding all other variables at their means; predicted probabilities are shown with 95% confidence intervals; * statistically significant at P<0.05.

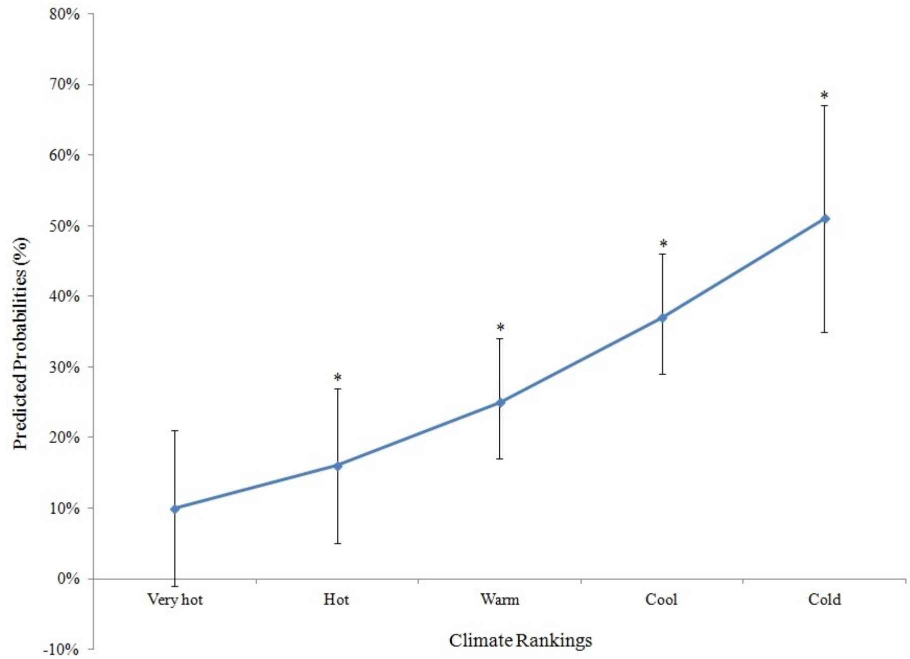


FIG.88. Predicted probabilities for aesthetics = 'very beautiful' at each score class of climate holding all other variables at their means; predicted probabilities are shown with 95% confidence intervals; * statistically significant at P<0.05.

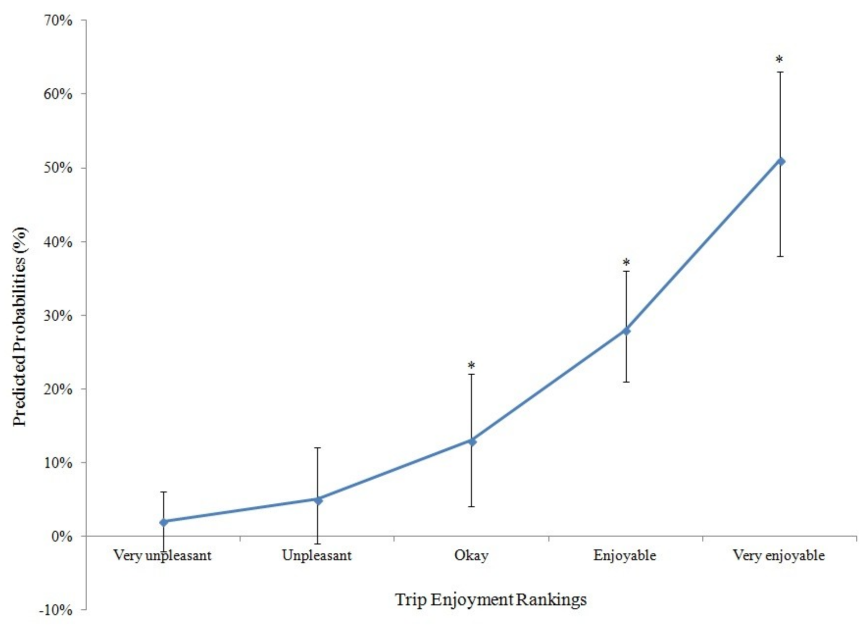


FIG.89. Predicted probabilities for aesthetics = 'very beautiful' at each score class of trip enjoyment holding all other variables at their means; predicted probabilities are shown with 95% confidence intervals; * statistically significant at P<0.05.

DISCUSSION

Park accessibility

The five districts spanning the Yongding Corridor in southwest Beijing are some of the poorest districts in Beijing, thus the major motivation of the project is to enhance economic conditions in southwest Beijing to advance livelihoods. The five southwest districts are home to 4.4 million people and account for 30% of Beijing's land area. In 2009, the districts contributed only 12% to annual GDP (115 billion yuan) and 5% to annual municipal revenues (10.3 billion yuan) (BWA 2009). There are significant social and economic disparities between different districts in Beijing, and the southwest districts are lagging far behind others in terms of development. The government is attempting to reduce socio-economic disparities using the Yongding Corridor as a means of increasing financial investment to improve employment rates and living standards in this underdeveloped region. Unlike past housing developments, the Changxindian eco-city on the Yongding River is mandated to have 15% of total housing units as economically affordable and government-subsidized housing, and in-situ redevelopment instead of relocating villagers (Yip 2008). Lastly, the government has chosen to make the Yongding Corridor a free public park to make it accessible to residents, which is rare among Beijing parks. However management is discussing possible fees to fund maintenance and management efforts at the district-level.

Park accessibility is an interesting piece of the Yongding Corridor story since it reflects a shift in government attitudes towards providing environmental amenities to a segment of Beijing's population who for many years had limited access to green spaces. The demographic composition of the survey respondents suggest the Yongding Corridor is attracting a diverse spectrum of Chinese citizens in terms of gender, age, education level, occupation, and income level. There are young adults, families with children, and seniors who visit the parks on the Yongding Corridor. The income levels span from poor and low income individuals to upper middle income individuals. The majority of the respondents' personal monthly income was lower than Beijing's average per capita monthly income. The majority of the visitors were local residents from Mentougou, Shijingshan, and Fengtai districts. Also there were visitors as far as Chaoyang and Changping districts, and neighboring Hebei and Shandong Provinces. The demographics of survey participants suggest the Yongding Corridor is both a neighborhood park and tourist destination.

Landscape aesthetics shortfalls

Results from the questionnaire-based survey suggest the Yongding Corridor is providing a 'beautiful' or 'very beautiful' environment, which is influenced by both natural and cultural features. The majority of respondents scored the Yongding Corridor as 'beautiful' (46%) or 'very beautiful' (36%). Only 19% of respondents scored the Yongding Corridor below these final service levels. People gave high scores for trip satisfaction (i.e., the score for trip experience) likely influenced by their individual moods and scenic beauty: 59% of respondents scored their trip as 'enjoyable' and 32% as 'very enjoyable.' If people feel they had a positive trip (includes factors beyond environmental conditions or recreational facilities) they will likely score the landscape aesthetics higher, and the inverse relationship is true as well (i.e., the higher the score for landscape aesthetics the likely higher score for trip satisfaction). Based on the survey results, the Yongding Corridor seems to be meeting final service levels on landscape aesthetics. Answers to the open-ended questions offer insight into aspects of landscape aesthetics that visitors favor and are concerned with.

First when visitors were asked about their reasons for selecting the park they were visiting the most common response was proximity to their home and accessibility from the roadway, but the second most common response was the "beauty of the environment." When describing the landscape aesthetics of the Yongding Corridor, people articulated scenic beauty as the presence of water and vegetation, and landscape quality in terms of air quality, water quality (clarity and smell), and cool temperatures. In addition to proximity and accessibility, landscape aesthetics and environmental quality were mentioned more frequently as factors motivating park choices compared to other reasons like recreation facilities. This makes sense because the majority of respondents selected relaxation as the main purpose of their visit to the Yongding Corridor. The challenge for management is balancing potential tradeoffs between aesthetic quality and other ecosystem services.

Second when visitors were asked to comment on current dissatisfactions and future concerns about the Yongding Corridor, the two main problems were water pollution and water storage. The majority of visitors felt poor water quality and water losses could undermine the long-term aesthetic quality of the Yongding Corridor. The number one reported concern was water pollution. In the surveyed population, local residents commented on the need to reduce the amount of domestic sewage entering directly into the Yongding Corridor. Some individuals felt local residences need to help maintain water quality by controlling the discharge of domestic waste, but another individual noted the lack of available options for residences to remove household waste (i.e., infrastructure). Furthermore about 12% of all respondents were concerned about management and maintenance efforts. The survey results match the biophysical analysis in Chapter 5 (water storage) and Chapter 6 (water purification), which showed there are current challenges in: (1) regulating water storage to prevent lake drying, and (2) nutrient loading relative to wetland nutrient retention to improve water quality. The survey responses further illustrate the importance of addressing these challenges to maintain the currently favorable public perception of landscape aesthetics on the Yongding Corridor.

Perceived environmental quality and perceived aesthetics

Perceived environmental quality had a statistically significant influence on perceived landscape aesthetics, specifically on the probability of getting the highest ranking of ‘very beautiful. The ecological production function results show the probabilities of perceived air quality, water quality, and climate at different score classes have a statistically significant influence on perceived aesthetics at the final service level of ‘very beautiful.’ Water quality had the highest probability, such that when water quality is perceived as ‘very healthy,’ holding other variables at their means, the probability of visitors ranking aesthetics as ‘very beautiful’ is 61%.

Management

Visitor preferences for different ecosystem services were evaluated to compare visitor needs to management priorities to help management prioritize its efforts on multiple services. Based on my discussions with the Beijing Water Science and Technology Institute (BWSTI) staff, management is interested in ways to prioritize different ecosystem services. I proposed using visitor surveys to elicit public opinion on different ecosystem services to understand how to better serve the users of the Yongding Corridor. Management then could compare management priorities to visitor interests to evaluate a pathway forward. Everyone was supportive of this approach, and the results suggest that the top five ecosystem services in terms of their social values (in order of importance) are: (1) leisure and travel, (2) air quality, (3) landscape preservation, (4) recreation, and (5) cooling. Leisure and travel is the top ecosystem service selected by both surveyed visitors and management, which depends on landscape aesthetics. However my results suggest that landscape aesthetics is significantly influenced by how people perceive the air quality, water quality, and climate on the Yongding Corridor. Furthermore, visitors showed current dissatisfactions and future concerns about water pollution and water storage problems. This suggests that the functionality of the ecosystems is important to maintaining the aesthetic quality of the landscape.

CONCLUSION

In summary the Yongding Corridor, based on 193 visitor surveys, seems to be meeting final service levels on landscape aesthetics since the majority of visitors scored the Yongding Corridor as 'beautiful' and 'very beautiful.' However visitors were concerned about water pollution and water storage, and the impact of these problems on the long-term aesthetic quality of the Yongding Corridor. Furthermore I found perceived air quality, water quality, and climate were important variables in determining perceived aesthetic quality. Therefore the regulating ecosystem services explored in Chapters 5-7 (i.e., other management priorities) are likely important in maintaining the aesthetic quality on the Yongding Corridor. The key findings from this chapter are:

- Majority of surveyed visitors considered the landscape aesthetics as 'beautiful' (46%) or 'very beautiful' (36%).
- Only 19% of respondents gave a score below these final service levels.
- Demographics of the surveyed population suggest a diverse spectrum of Chinese citizens (gender, age, education level, occupation, and income level) visit the Yongding Corridor.
- Top five ecosystem services selected by visitors reported as social values were: (1) leisure and travel (61%), (2) air quality (44%), (3) landscape preservation (20%), (4) recreation (17%), and (5) cooling (17%).
- Water quality had the highest probability of influencing perceived aesthetics; when water quality is perceived as 'very healthy,' holding other variables at their means, the probability of visitors ranking aesthetics as 'very beautiful' is 61%.

CHAPTER 9

MANAGEMENT

EVALUATION: THE FIVE ECOSYSTEM SERVICES

First I compare the outcomes of the five ecosystem services (Chapters 5-8) to summarize their general trends then determine potential synergies and tradeoffs. Based on my assessment, the Yongding Corridor is meeting the final service levels for landscape aesthetics, but is falling short on meeting final service levels for water storage, local climate regulation, water purification, and dust control (Table 73). In 2012-2013, the water levels of the new ecosystems were unable to be sustained across different seasons in Beijing because of inconsistent inflows, which led to shallower lakes. Shallower lakes simply are more vulnerable to lake drying especially in Beijing's semi-arid climate. Also in June 2013, there were a high number of sultry events, and my model results suggest the ecosystems are likely providing evaporative cooling; however the cooling effect from the lakes/wetlands is low. Furthermore I determined that the new ecosystems provided high nutrient retention from 2012-2013, however nutrient loading is greater than the wetland water purification capacity, resulting in water quality shortfalls. I was unable to determine a statistically significant relationship between sand flux from the Yongding River and PM_{10} levels. However there were PM_{10} shortfalls for areas along the Yongding River in both the pre- and post-Corridor periods. The Yongding Corridor is meeting final service levels for landscape aesthetics, and my results indicate that visitor perceptions of a 'very beautiful' landscape are significantly influenced by positive perceptions of air quality, water quality, and climate.

Table 73. Summary of the results of all five ecosystem services.

Ecosystem Service	Water Storage	Local Climate Regulation	Water Purification	Dust Control	Landscape Aesthetics
Ecosystem Status	Dry Lakes (low water levels)	Low Evaporative Cooling	High Nutrient Retention	Reduction in Sand Flux (no relationship to PM_{10})	High Scenic Beauty
Final Services	**Water Storage Shortfalls (Water Inefficiency)**	**Human Comfort Shortfalls (Sultry Events)**	**Water Quality Shortfalls (Poor Water Quality)**	**Air Quality Shortfalls (Poor Air Quality)**	**Meeting Target**
Problems	Inconsistent Inflow Shallow Lakes (vulnerable to drying)	Lack of Shade Trees	High Water Pollution (domestic sewage)	Urbanization Distant Dust Sources	Poor Environmental Quality

Next I summarize the synergies and tradeoffs among ecosystem services to determine feasible management options. I used the marginal changes for each service from the ecological production functions to describe the possible magnitude of changes in the ecosystems needed to reduce the shortfalls. This allowed me to visualize the different relationships between the services, and rank the management options in terms of their likelihood (Table 74).

There is a tradeoff between reducing water loss to improve water storage and increasing water loss to improve human comfort. For water levels to consistently meet the desired engineered specifications, I calculated it would likely require an 18% reduction in the total water area: lake volume ratio of the lakes/wetlands to get the necessary 55% reduction in total annual water loss that managers want. Management could likely achieve this change in lake dimensions, if they maintain consistent inflows across all seasons and/or make the lakes deeper. However for the ecosystems to likely have any substantial impact on reducing sultry events (i.e., reducing the heat index value by 1 unit) there would potentially need to be a 10,000% increase in water loss (i.e., evapotranspiration). This quantity of water loss from ET is impossible given the current size of the lakes/wetlands. Even though a biophysical tradeoff exists, the quantity of ET needed to improve human comfort makes it an unrealistic consideration for management. This finding is important because it offers direction to management on how to focus their efforts on creating comfortable 'cool' environments. The most feasible options are to plant shade trees and construct shaded infrastructure (i.e., pavilions). These options will likely have a greater impact on reducing local temperatures in the summer than relying on evaporative cooling from the lakes/wetlands. However managers must weigh the additional water demands of planting shade trees to improve human comfort.

Managers believe the poor water storage is the primary driver causing the poor water quality on the Yongding Corridor. Low water levels reduce the dilution capacity of the lakes, which makes the nutrient concentrations higher. From my assessment, I determined that the wetlands are providing high nutrient retention, but the nutrient loading is simply greater than the wetland capacity to purify the effluent to final service levels. The reduction in water levels is likely exacerbating the main problem – high nutrient concentrations entering the system as domestic sewage from shoreline homes. Therefore only improving water storage will not solve the main problem. Nutrient loading needs to be addressed in addition to water storage.

My results suggest a 50% increase in wetland area would be needed to obtain the required total phosphorus level, and a 75% reduction in the concentration of nutrients entering the system to obtain the required total nitrogen level. Given space limitations, it is likely not feasible to increase wetland area by 50% from its current size. The most productive avenue is controlling domestic sewage entering the Yongding Corridor.

Table 74. Synergies and tradeoffs among ecosystem services using marginal changes presented as ways to reduce shortfalls, management options, and the possibility of the options.

Reduce Shortfall (Concern)	Management Options	Possibility
Maintain Lakes/Wetlands (Prevent the Drying of Lakes)	↓ **18%** Water Area: Lake Volume → ↓ **55%** Water Loss (Evapotranspiration)	Possible
Improve Human Comfort (Reduce Sultry Events)	↑ **10,000%** Evapotranspiration → ↓ **1 Unit** Heat Index	Unlikely
Improve Water Quality (Increase Water Purification)	↑ **50%** Wetland Area → ↓ **0.4 mg/L** Total Phosphorus	Unlikely
Improve Water Quality (Reduce Nutrient Loading)	↓ **75%** Nutrient Load → ↓ **7 mg/L** Total Nitrogen	Possible
Improve Air Quality (Dust Control)	No statistically significant relationship between sand flux and PM_{10}	Uncertain (Probably Unlikely)
Maintain Landscape Aesthetics (Environmental Quality)	'Very Healthy' Air Quality 'Very Healthy' Water Quality 'Cold' Climate → ↑ **38%, 61% or 51%** 'Very Beautiful' Landscape Aesthetics	Possible (Water Quality and Climate)

I was unable to determine a relationship between sand flux (i.e., bare soil area) and PM_{10} levels near the Yongding Corridor. However I believe the Yongding Corridor likely has limited potential to reduce PM_{10} levels in Beijing. I base this conclusion on: (1) the lack of a significant relationship between modeled sand flux and PM_{10}, (2) high PM_{10} levels in the pre- and post-Corridor period, and (3) small bare soil area on the Yongding

River. However additional analysis is needed to generate credible estimates of sand flux to understand how bare soil area on the Yongding River relates to PM_{10} levels in Beijing.

Lastly, I determined synergistic relationships between how people perceive air quality, water quality, climate, and landscape aesthetics. Based on visitor surveys, I determined that when air quality is perceived as 'very healthy,' 'water quality' is perceived as 'very healthy,' or climate is perceived as 'cold' there is a 38%, 61%, or 51% probability that visitors will score the landscape aesthetics as 'very beautiful.' Managers on average are currently meeting the final service levels for landscape aesthetics. But my results (ecological production function and visitor statements on dissatisfactions/future concerns) suggest maintaining favorable ratings of scenic beauty will likely require managing the environmental quality in particular the water quality.

Stakeholder concerns: The public and management

Next I summarize stakeholder needs and concerns, which I will use to compare against the synergies and tradeoffs (i.e., biophysical results) in an attempt to generate useful recommendations for management. My final services were selected in consultation with management, however understanding how to address the tradeoffs requires understanding both public and management priorities. The public (i.e., local residents and tourists) are the users of the Yongding Corridor while management is responsible for the construction and ongoing maintenance of the system. To my knowledge there has been no discussion between management and the public to foster shared understanding on priorities to protect the environmental conditions on the Yongding Corridor.

I surveyed visitors to determine public preferences for different ecosystem services (Table 75) and concerns (Table 77). In addition to my surveys, the State Key Laboratory of Urban and Regional Ecology (SKLURE) surveyed 10 managers and scientists working at the Beijing Water Science and Technology Institute (BWSTI). The management surveys were designed to elicit information on management preferences for different ecosystem services (Table 76), and their perspectives on the biggest management challenges (Table 78). Visitors and managers selected similar ecosystem services of value to them, and both groups selected leisure and travel as the most important value. Based on the stakeholder responses, I generated a simple ranking of the top five ecosystem services presented in Table 79 to help clarify shared priorities.

Visitors and managers selected water pollution and water storage as top challenges, but visitors ranked water pollution as their number one concern while managers ranked water scarcity as their number one management challenge. This reveals the difficulty managers associate with maintaining lake volumes, which is critical because the lake and wetland hydrology underpins the entire system. I use the ecosystem service results and stakeholder priorities to make a few recommendations in the next section.

Table 75. Most important ecosystem services from the Yongding Corridor to visitors.

Surveyed Population Preferences for Ecosystem Services		
Social Values (Ecosystem Services)	N	%*
Leisure and travel (cultural)	117	61%
Air quality (dust control and air pollution control†)	85	44%
Landscape preservation (cultural and biodiversity)	38	20%
Recreation (cultural)	32	17%
Cooling (local climate regulation)	33	17%
Water quality (nutrient retention)	26	13%
Heritage value for future generations (cultural)	27	14%
Water supply (water storage)	12	6%
Other (wetland biodiversity^)	1	1%

* Individuals were asked to select the most important ecosystem services to them from the Yongding River Ecological Corridor, thus the percentages are out of 193 responses.

† Public perceptions of air quality are likely not only impacted by sand flux, but other air pollution sources like nitrous oxide, ozone, etc.

^One respondent filled the other blank as wetland biodiversity.

TABLE 76. Most important ecosystem services from the Yongding Corridor to management.

Management Preferences for Ecosystem Services		
Social Values (Ecosystem Services)	N	%*
Leisure and travel (cultural)	8	80%
Recreation (cultural)	4	40%
Air Quality (dust control)	3	30%
Cooling (local climate regulation)	1	10%
Water quality (water purification)	1	10%
Water supply (water storage)	1	10%
Heritage value for future generations (cultural)	1	10%
Other (Real Estate Development)	1	10%

* Individuals were asked to select the most important ecosystem services to them from the Yongding River Ecological Corridor, thus the percentages are out of 10 responses.

TABLE 77. Visitor concerns about the Yongding Corridor.

What aspects of the Yongding River Ecological Corridor are you dissatisfied with?		
Dissatisfactions	N	%
Other (traffic, littering, few shade trees, and few restrooms)	71	37%
Water quality	69	36%
Water level	22	11%
Air quality	12	6%
Climate	4	2%
Environment	24	12%

TABLE 78. Management challenges on improving the Yongding River.

Which do you think is the biggest challenge for improving and managing the Yongding River?		
Challenge	N	%
Water scarcity	6	60%
Water pollution	4	40%
Insufficient funding	0	0%
Other (managing water resources)	1	10%

TABLE 79. Stakeholder ranking of ecosystem services and top challenges.

Ranking of Ecosystem Services
(1) Leisure and Travel: Landscape Aesthetics
(2) Air Quality: Dust Control
(3) Cooling: Local Climate Regulation
(4) Water Quality: Water Purification
(5) Water Supply: Water Storage
Top Challenges
(1) Water Pollution
(2) Water Storage

RECOMMENDATIONS

Organizing priorities

I combine the biophysical tradeoffs with stakeholder needs to suggest top priorities for management. The most important ecosystem service to visitors and managers is landscape aesthetics for leisure and travel purposes (Table 80). Next air quality was considered a high priority for stakeholders. However I believe the Yongding Corridor likely has limited potential to reduce PM_{10} levels in Beijing. I base this conclusion on: (1) the lack of a significant relationship between modeled sand flux and PM_{10} (high uncertainty), (2) high PM_{10} levels in the pre- and post-Corridor period, and (3) small bare soil area on the Yongding River.

In a world of limited resources, I suggest management focus on: water quality, water supply, and cooling. The end goal for stakeholders is landscape aesthetics, however I found that water purification, water storage, and local climate regulation are critical to maintaining a high aesthetic quality (Fig. 90). Lake drying threatens the condition of the water landscape (key feature driving visitor experiences). Poor water quality (i.e., algal blooms, odors, etc.) was shown to reduce the probability of visitors giving high landscape aesthetic scores. Lastly, hot environments make it uncomfortable for people to relax in the parks, which visitors expressed as dissatisfactions in survey responses. A common misconception is that one has to sacrifice ecosystem functionality for landscape aesthetics in park design. I found framing ecosystem functionality around human welfare makes it easier to see how functionality supports scenic beauty- the direct environmental benefit most people experience when visiting the Yongding Corridor (Fig. 90).

TABLE 80. Suggested ecosystem service priorities for management.

Priorities
(1) Leisure and Travel (Landscape Aesthetics)
(2) Water Quality (Water Purification) and Water Supply (Water Storage)
(3) Cooling: Local Climate Regulation

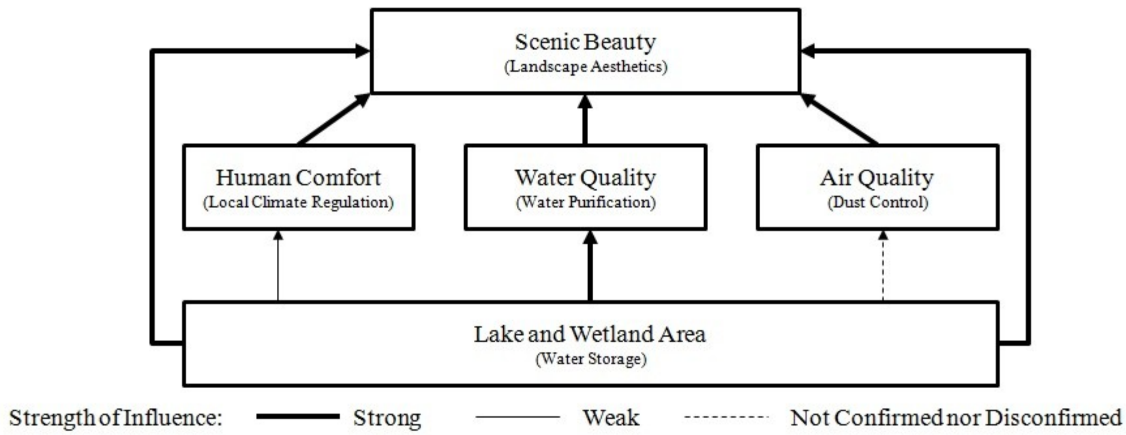


FIG.90. Stakeholders indicated that the most important value from the Yongding Corridor is scenic beauty, and my analysis suggests this final service depends on the other ecosystem services. The top row arrows depict the relationships between environmental quality and landscape aesthetics determined using the visitor surveys. The bottom row arrows depict the biophysical relationships between the ecosystems (lakes and wetlands) and the final services. My objective is to illustrate the interrelationships among management goals using social values and ecosystem processes.

Synergistic actions

I use the term synergistic actions because “synergy” refers to the combination of multiple ingredients producing a result greater than the sum of individual parts. It is the consideration of the “whole system” and the connections between pieces to generate holistic solutions. The objective of an ecosystem services assessment is to make tradeoffs among ecosystem services explicit to aspire towards more synergistic actions. However synergistic actions may still involve difficult tradeoffs. I use this term to refer to a process of thinking when making decisions. It is generating actions that consider the system and its interacting parts to clarify how to strategically address multiple goals and threats that could undermine the stability of the system. The generation of synergistic actions requires us to move beyond fragmented thinking (one problem at a time) towards systems thinking where understanding the system causes the manager or scientist to focus on relationships among components, not just individual components. Mastering the relationships is essential to building the necessary craft (science and policies) to tackle the complex social-environmental problems currently confronting our institutions.

I recommend possible synergistic actions to address the priorities listed above in a manner where actions work together to reduce shortfalls. I suggest three main actions shown in Table 81: (1) maintain consistent inflow and/or make the lakes deeper, (2) reduce the nutrient load, and (3) plant shade trees and/or construct shade structures. These three actions are synergistic because each addresses a specific problem, but together they have the potential to address the main challenge, which is maintaining and/or enhancing the overall environmental quality to sustain the scenic beauty over time. For instance, only improving the water storage will likely not reduce the water pollution or human discomfort problems. The current assumption is that low water levels are causing poor water pollution and low evaporative cooling. My assessment suggests the most useful action in addressing water pollution is reducing domestic waste entering the Yongding Corridor. To address human discomfort I believe the most useful action is planting shade trees as suggested by visitors, however managers need to consider the additional water demands of shade trees.

TABLE 81. Suggested actions to address stakeholder priorities while reducing shortfalls.

Actions	Reasons
Consistent Inflow and/or Deeper Lakes	Improve Water Storage
Reduce Nutrient Load (Domestic Sewage)	Improve Water Quality
Plant Shade Trees	Improve Human Comfort and Landscape Aesthetics

Practical steps

Lastly I suggest a few practical steps management can take to enhance its capacity to sustain the Yongding Corridor over time (Table 82). Currently the Beijing Water Authority is monitoring water quality every month at 8 sites. However these 8 sites were not selected with a consideration of nutrient loading and wetland nutrient retention. Using my water quality results I recommend 8 water sampling sites to help management track lake water quality, nutrient loading, and wetland nutrient retention. These 8 sites can help management improve its water quality monitoring program without increasing its current effort. It simply represents a shift in thinking from only tracking lake water quality in terms of meeting the Grade III standard (i.e., the final service level) to using the monitoring data to also guide efforts on reducing the water pollution source and improving wetland functionality.

Also I was able to identify the main location where nutrients are entering the Yongding Corridor, which is a stormwater channel between Mencheng Lake and Lianshi Lake. The stormwater channel likely is bringing domestic waste from shoreline homes into the Yongding Corridor.

To address this problem management will need to engage with local residents to identify feasible solutions to reduce the amount of sewage discharged from homes. A current problem is the lack of proper infrastructure in these neighborhoods (i.e., sewer systems). Managers need to work with local communities to identify feasible alternatives like septic tanks or treatment wetlands (outside the Yongding Corridor). If local residents are not provided useful alternatives then they have no choice but to dump their waste directly into channels. Lastly management cannot be everywhere all the time. Community engagement could help maintenance efforts by making residents feel they have a vested interest in protecting the Yongding Corridor. Public participation has shown to reduce costs while increasing effectiveness of management efforts in green infrastructure projects in other countries. The current positive opinion of the Yongding Corridor and statements of concern expressed by visitors suggests local residents value the new parks, and want them to be successful. If managed properly local residents could be a valuable asset for management in reducing costs and enhancing the overall effectiveness of maintaining the ecosystems over time.

TABLE 82. Suggestions of practical steps for management.

Practical Steps	Explanation
Water Quality Monitoring Program	I recommend 8 water sampling sites to help management track: lake water quality, nutrient loading, and wetland nutrient retention.
Reduce Domestic Sewage from Shoreline Homes	I recommend addressing a primary water pollution source on the Yongding Corridor.
Community Engagement	To address the water pollution problem will require management to engage with local residences to identify feasible solutions for handling domestic waste. Also local residences could help in monitoring and maintaining the Yongding Corridor.

Scientific Analysis

Next I make a few recommendations on ways to improve the analysis of ecosystem services from the Yongding Corridor. If possible I would recommend scientists place water gauges at the lakes to monitor water levels to help warn management when water storage is getting low before massive drying occurs. Also information on water levels can help scientists accurately estimate water loss rates to improve water efficiency in the system. Second is to continue monitoring water quality to evaluate the effectiveness of management actions (i.e., construction of subsurface treatment wetlands, regulation of the dumping of waste etc.). Next if management decides to plant shade trees or construct shade structures, I would recommend scientists continue the climate monitoring using the air temperature data loggers (placing them under shade trees and non-vegetated areas). I also would continue the visitor surveys to assess how public opinion changes if the identified maintenance challenges are not resolved. Lastly, I did not conduct any analysis of the biodiversity, however I observed an increase in the number of species and abundance of birds during my assessment compared to the pre-Corridor period. The Yongding Corridor may be providing new habitats for wildlife, thus it would be useful if scientists monitored changes in biodiversity because of the lakes/wetlands.

The main data inconsistencies that I experienced when conducting my assessment were the: (1) difficulty of generating accurate estimates of sand flux using simple models, and (2) the short temporal scale of my analysis. I recommend scientists conduct the necessary analysis relating bare soil area to PM_{10} and $PM_{2.5}$ on the Yongding River.

SKLURE has a mobile truck to monitor PM_{10} and $PM_{2.5}$ throughout Beijing at various locations. I would recommend adding a few sites near the Yongding River to actually measure the amount of PM generated from bare soil areas on the Yongding River. The simple models and government datasets are too crude to unravel the relationship between bare soil area and PM_{10} on the Yongding River. Another inconsistency was the varying time frames of my analysis of different ecosystem services because of time limitations. I used government datasets to make an annual comparison between pre- and post-Corridor conditions. For the field data, however, I was only able to monitor climate, water quality, and visitor experiences for less than six months. The short time frame of the field data makes it difficult to generate robust conclusions on each ecosystem service, thus I was only able to make general recommendations. For future analysis, I would recommend long-term monitoring, which does not require additional field sites, but consistent tracking of key variables at selected sites over time.

Usually when one conducts environmental monitoring surprises arise, which requires adaptive thinking; however the challenge when monitoring multiple ecosystem services is adapting the analysis for several variables not just one. During my assessment, I confronted many surprises because this was the first year of operation of a complex, engineered set of ecosystems. I had to juggle generating an assessment modeling water storage of lakes/wetlands that underwent unexpected drying, which made it impossible to place the necessary water temperature data loggers to confirm VIC model outputs. Furthermore, managers had planned to complete the subsurface wetlands, but during my assessment they were incomplete thus I had to design a water quality monitoring program not knowing if and/or where excess nutrients were directly entering the Yongding Corridor. Also I had expected all the lakes to be complete, but the timeline of construction of the ecosystems kept changing, which made it difficult to have air temperature data loggers at all the lakes/wetlands. The challenge was using the surprises as valuable learning opportunities – the variation actually helped me learn more about the new ecosystems that management is creating.

CONCLUDING THOUGHTS

I was given a rare chance to encounter the types of sustainability challenges currently confronting government leaders in Beijing. From my time in China, I have come to see China's efforts as an extension of the U.S. and European experience. Chinese decision-makers are creating policies that attempt to unify issues often managed separately in the West like natural disasters, climate change, pollution, biodiversity, and leisure/tourism. The Beijing government engineered ecosystems on the Yongding River for ecosystem services to improve environmental quality to get high scenic beauty. Managers and landscape architects are working to make the Yongding Corridor a park that advances both form and function to generate efficient solutions on: groundwater recharge, comfortable environments, water quality, air quality, and leisure/recreation. For decades, scholars have recommended that governments create holistic policies that work to bridge disciplinary and societal divides to transition societies towards sustainability. The Chinese are utilizing the lessons from the West, and are attempting to unify issues to implement sustainability concepts. Necessity is driving political will, however the

Chinese are confronting limits to their ambitions because of the human capital challenges of implementing holistic frameworks like the ecosystem services approach.

The main challenge is building the capacity to know how to handle multiple problems at once. Focusing our knowledge and governance systems around relationships not single issues is a dramatic shift, but is a shift that must occur. It is daunting because we cannot simply abandon the past. We have to work through our existing knowledge systems searching for ways to unify fragmented ways of thinking. This requires spending the time to locate connections among disciplines, policies, and societal sectors.

Much of the knowledge task falls on the shoulders of scientists to gather the necessary ecological and social data to relate ecosystems to human welfare. The relationships between ecosystem processes (e.g., nutrient retention, wind erosion), environmental quality (e.g., water quality, air quality), and human benefits (e.g., drinking water, scenic beauty) are complicated. Over the course of my dissertation, however, I learned it is possible to analyze these relationships using ecological data, endpoints, and social surveys. During my assessment, the most challenging aspect was conceptualizing how to organize different types of data. Once I created a conceptual framework connecting the data types then collecting the data to create ecological production functions became easier.

Overall my methodology is simple; I use basic ecological data (e.g., evapotranspiration, air temperature, nutrient concentrations) and visitor survey data (air quality, water quality, climate, and aesthetics scores) to create simple regression models. For four ecosystem services, I was able to identify statistically significant relationships among ecosystems (environmental quality) and human welfare (endpoints). After creating the ecological production functions, I learned of their utility as a simple method to interpret basic relationships between environmental and social variables, which we often presume have causal associations. However the current lack of empirical information is simply making it difficult for scientists and decision-makers to make judgments about these associations.

Natural resources are becoming increasingly limited, which is creating more complex social-ecological problems than the past. Traditional approaches that only focus on individual problems or separate environmental issues from social issues are insufficient to help us think through the interconnected challenges currently confronting our institutions. The strength of the ecosystem services approach is offering people a way to process multiple connections to put holistic thinking into practice. In a world of limited resources, governments are realizing they need ways to rationally evaluate multiple goals and problems to strategically address priorities while minimizing tradeoffs (i.e., unintended consequences). Difficult decisions require both leadership and thoughtfulness. Leadership requires responsibility, and thoughtfulness requires clear and considerate thinking. Thoughtfulness in part requires good tools to help us improve our chances at clearly managing multiple tasks without underestimating the complexity of the issues we face. From my experience, I have come to see holistic frameworks less as an option and more as a necessity because decision-makers, scientists, and the public seriously need ways to process the daunting complexity of interconnected issues that define our world today.

REFERENCES

An, X. Q., Q. Hou, N. Li, and S. X. Zhai. 2013. Assessment of human exposure level to PM_{10} in China. Atmospheric Environment **70**:376-386.

Andersson, E., S. Barthel, S. Borgström, J. Colding, T. Elmqvist, C. Folke, and Å. Gren. 2014. Reconnecting cities to the biosphere: stewardship of green infrastructure and urban ecosystem services. Ambio **43**:445-453.

Andrews, S.Q. 2008. Inconsistencies in air quality metrics: 'Blue sky' days and PM_{10} concentrations in Beijing. Environmental Research Letters **3:** doi:10.1088/1748-9326/3/3/034009.

Arheimer, B., and H. B. Wittgren. 2002. Modelling nitrogen removal in potential wetlands at the catchment scale. Ecological Engineering **19**:63-80.

Ayanu, Y. Z., C. Conrad, T. Nauss, M. Wegmann, and T. Koellner. 2012. Quantifying and mapping ecosystem services supplies and demands: a review of remote sensing applications. Environmental Science and Technology **46**:8529-8541.

Bagstad, K. J., D. J. Semmens, S. Waage, and R. Winthrop. 2013. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. Ecosystem Services **5**:27-39.

Bai, X. 2003. The process and mechanism of urban environmental change: an evolutionary view. International Journal of Environment and Pollution **19**:528-541.

Bai, X. 2007. Integrating global environmental concerns into urban management: the scale and readiness arguments. Journal of Industrial Ecology **11**:15-29.

Baker, J., W. R. Sheate, P. Phillips, and R. Eales. 2013. Ecosystem services in environmental assessment - Help or hindrance? Environmental Impact Assessment Review **40**:3-13.

Barbier, E. B. 2007. Valuing ecosystem services as productive inputs. Economic Policy **49:**178-229.

Barton, J., and J. Pretty. 2010. What is the best dose of nature and green exercise for improving mental health? A multi-study analysis. Environmental Science & Technology **44:** 3947-3955.

Bavor, H.J., D.J. Roser, S.A. McKersie, and P. Breen. 1988. Treatment of Secondary Effluent. Report to Sydney Water Board, Sydney, NSW, Australia.

BWA (Beijing Water Authority). 2009. The green Yongding River: construction plan for an ecological corridor. Beijing Water Authority, Beijing, China (in Chinese).

Beldring, S. 2002. Multi-criteria validation of a precipitation-runoff model. Journal of Hydrology **257**:189-211.

Bennett, E. M., G. D. Peterson, and L. J. Gordon. 2009. Understanding relationships among multiple ecosystem services. Ecology Letters **12**:1394-1404.

Bernhardt, E. S. and M. A. Palmer. 2007. Restoring streams in an urbanizing world. Freshwater Biology **52**:738-751.

Bolund, P. and S. Hunhammar. 1999. Ecosystem services in urban areas. Ecological Economics **29**:293-301.

Bowling, L. C. and D. P. Lettenmaier. 2010. Modeling the Effects of Lakes and Wetlands on the Water Balance of Arctic Environments. Journal of Hydrometeorology **11**:276-295.

Boyd, J. 2007. The endpoint problem. Resources: 26-28.

Boyd, J. and S. Banzhaf. 2007. What are ecosystem services? The need for standardized environmental accounting units. Ecological Economics **63**:616-626.

Brander, L. M., I. Brauer, H. Gerdes, A. Ghermandi, O. Kuik, A. Markandya, S. Navrud, P. Nunes, M. Schaafsma, H. Vos, and A. Wagtendonk. 2012. Using meta-analysis and GIS for value transfer and scaling up: valuing climate change induced losses of European wetlands. Environmental and Resource Economics **52**:395-413.

Bras, R. F. 1990. Hydrology: an introduction to hydrologic science. Addison-Wesley, Reading, Massachusetts, USA.

Brauman, K. A., G. C. Daily, T. K. Duarte, and H. A. Mooney. 2007. The nature and value of ecosystem services: An overview highlighting hydrologic services. Annual Review of Environment and Resources **32**:67-98.

Burkhard, B., I. Petrosillo, and R. Costanza. 2010. Ecosystem services - bridging ecology, economy and social sciences. Ecological Complexity **7:**257-259.

Burkhard, B., F. Kroll, S. Nedkov, and F. Muller. 2012. Mapping ecosystem service supply, demand and budgets. Ecological Indicators **21**:17-29.

Caprotti, F. 2014. Critical research on eco-cities? A walk through the Sino-Singapore Tianjin Eco-City, China. Cities **36**:10-17.

Carpenter, S. R., N. F. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley, and V. H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications **8**:559-568.

Carpenter, S. R., H. A. Mooney, J. Agard, D. Capistrano, R. S. DeFries, S. Diaz, T. Dietz, A. K. Duraiappah, A. Oteng-Yeboah, H. M. Pereira, C. Perrings, W.V. Reid, J. Sarukhan, R. J. Scholes, and A. Whyte. 2009. Science for managing ecosystem services: beyond the Millennium Ecosystem Assessment. Proceedings of the National Academy of Sciences of the United States of America **106**:1305-1312.

Chan, C. K. and X. Yao. 2008. Air pollution in mega cities in China. Atmospheric Environment **42**:1-42.

Chan, K. M. A., M. R. Shaw, D. R. Cameron, E. C. Underwood, and G. C. Daily. 2006. Conservation planning for ecosystem services. PloS Biology **4**:2138-2152.

Chavan, P. V., and K. E. Dennett. 2008. Wetland simulation model for nitrogen, phosphorus, and sediments retention in constructed wetlands. Water , Air, and Soil Pollution **187**:109-118.

Chen, B., O. A. Adimo, and Z. Y. Bao. 2009. Assessment of aesthetic quality and multiple functions of urban green space from the users' perspective: The case of Hangzhou Flower Garden, China. Landscape and Urban Planning **93**:76-82.

Chiesura, A. 2004. The role of urban parks for the sustainable city. Landscape and Urban Planning **68**:129-138.

China Daily. 2005. Green belts may root out sandstorms. http://english.people.com.cn/200504/01/eng20050401_178991.html.

Claiborn, C., B. Lamb, A. Miller, J. Beseda, B. Clode, J. Vaughan, L. Kang, and C. Newvine. 1998. Regional measurements and modeling of windblown agricultural dust: The Columbia Plateau PM_{10} Program. Journal of Geophysical Research-Atmospheres **103**:19753-19767.

Cook, B. R., and C. J. Spray. 2012. Ecosystem services and integrated water resource management: Different paths to the same end? Journal of Environmental Management **109**:93-100.

Cooter, E. J., A. Rea, R. Bruins, D. Schwede, and R. Dennis. 2013. The role of the atmosphere in the provision of ecosystem services. Science of the Total Environment **448**:197-208.

Crossman, N. D., B. Burkhard, S. Nedkov, L. Willemen, K. Petz, I. Palomo, E. G. Drakou, B. Martín-Lopez, T. McPhearson, K. Boyanova, R. Alkemada, B. Egoh, M. B. Dunbar, and J. Maes. 2013. A blueprint for mapping and modelling ecosystem services. Ecosystem Services **4:** 4-14.

Cuddington, K., M. J. Fortin, L. R. Gerber, A. Hastings, A. Liebhold, M. O'Connor, and C. Ray. 2013. Process-based models are required to manage ecological systems in a changing world. Ecosphere **4**:1-12.

Cugurullo, F. 2013. How to build a sandcastle: an analysis of the genesis and development of Masdar City. Journal of Urban Technology **20**:23-37.

Daily, G. C., S. Polasky, J. Goldstein, P. M. Kareiva, H. A. Mooney, L. Pejchar, T.H. Ricketts, J. Salzman, and R. Shallenberger. 2009. Ecosystem services in decision making: time to deliver. Frontiers in Ecology and the Environment **7**: 21-28.

Daniel, T. C. 2001. Whither scenic beauty? Visual landscape quality assessment in the 21st century. Landscape and Urban Planning **54**:267-281.

De Groot, R.S. 2006. Function-analysis and valuation as a tool to assess land use conflicts in planning for sustainable, multi-functional landscapes. Landscape and Urban Planning **75**:175-186.

De Groot, R.S., B. Fisher, M. Christie, J. Aronson, L. Braat, R. Haines-Young, J. Gowdy, T. Killeen, E. Maltby, A. Neuville, S. Polasky, R. Portela, and I. Ring. 2010a. Integrating the ecological and economic dimensions in biodiversity and ecosystem service valuation. The Economics of Ecosystems and Biodiversity (TEEB). Earthscan, London, UK.

De Groot, R. S., R. Alkemade, L. Braat, L. Hein, and L. Willemen. 2010b. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecological Complexity **7**:260-272.

Dong, J. 2002. Sandstorms in Beijing: occurrence, protection and control (Master's Thesis). Royal Institute of Technology, Stockholm, Sweden.

Du, G.S., Y.M. Wu, Z.S. Yang, D.W. Wu and J. Liu. 2005. Analysis of water quality on urban rivers and lakes in Beijing. Journal of Lake Science, **17:** 373–377 (in Chinese).

Egoh, B., B. Reyers, M. Rouget, D. M. Richardson, D. C. Le Maitre, and A. S. van Jaarsveld. 2008. Mapping ecosystem services for planning and management. Agriculture Ecosystems & Environment **127**:135-140.

Eigenbrod, F., P. R. Armsworth, B. J. Anderson, A. Heinemeyer, S. Gillings, D. B. Roy, C. D. Thomas, and K. J. Gaston. 2010. The impact of proxy-based methods on mapping the distribution of ecosystem services. Journal of Applied Ecology **47**:377-385.

Fabos, J. G. 1995. Introduction and overview: the greenway movement, and potential uses of greenways. Landscape and Urban Planning **33:** 1-13.

Fisher, B., K. Turner, M. Zylstra, R. Brouwer, R. de Groot, S. Farber, P. Ferraro, R. Green, D. Hadley, J. Harlow, P. Jefferiss, C. Kirkby, P. Morling, S. Mowatt, R. Naidoo, J. Paavola, B. Strassburg, D. Yu, and A. Balmford. 2008. Ecosystem services and economic theory: integration for policy-relevant research. Ecological Applications **18**:2050-2067.

Fisher, B.K., R. K. Turner, and P. Morling. 2009. Defining and classifying ecosystem services for decision making. Ecological Economics **68**:643-653.

Fu, B. J., S. Wang, C. H. Su, and M. Forsius. 2013. Linking ecosystem processes and ecosystem services. Current Opinion in Environmental Sustainability **5**:4-10.

Gao, H., T. J. Bohn, E. Podest, K. C. McDonald, and D. P. Lettenmaier. 2011. On the causes of the shrinking of Lake Chad. Environmental Research Letters **6**: 1-7.

Gao, Q. 2012. The four lakes on the Yongding River in Beijing: initial analysis of the water circulation system. Beijing Water Authority **S277.1:** 46-48 (in Chinese).

Geoghegan, J. 2002. The value of open spaces in residential land use. Land Use Policy **19**:91-98.

Gillette, D., D. Ono, and K. Richmond. 2004. A combined modeling and measurement technique for estimating windblown dust emissions at Owens (dry) Lake, California. Journal of Geophysical Research-Earth Surface **109:** doi:10.1029/2003JF000025.

Gober, P., A. Brazel, R. Quay, S. Myint, S. Grossman-Clarke, A. Miller, and S. Rossi. 2010. Using watered landscapes to manipulate urban heat island effects: how much water will it take to cool Phoenix? Journal of the American Planning Association **76**:109-121.

Gu, C., X. Yuan, and J. Guo. 2010. China's master planning system in transition: case study of Beijing. 46th ISOCARP Congress, Hague, Netherlands.

Haines-Young, R.H., and M.B. Potschin. 2009. Methodologies for defining and assessing ecosystem services. Final Report, JNCC, Project Code C08-0170-0062, Nottingham, Nottinghamshire, UK.

Haines-Young, R.H., M.B. Potschin, and F. Kienast. 2012. Indicators of ecosystem service potential at European scales: Mapping marginal changes and trade-offs. Ecological Indicators **21**:39-53.

Haines-Young, R.H. and M.B. Potschin. 2013. Common International Classification of Ecosystem Services (CICES). EEA/IEA/09/003, Nottingham, Nottinghamshire, UK.

Hald, M. 2009. Sustainable urban development and the Chinese eco-city. Fridtjof Nansen Institute, Lysaker, Norway.

Hamby, D. M. 1994. A review of techniques for parameter sensitivity analysis of environmental models. Environmental Monitoring and Assessment **32**:135-154.

Hao, J. M. and L. T. Wang. 2005. Improving urban air quality in China: Beijing case study. Journal of the Air & Waste Management Association **55**:1298-1305.

Hipp, J. A. and O. A. Ogunseitan. 2011. Effect of environmental conditions on perceived psychological restorativeness of coastal parks. Journal of Environmental Psychology **31**:421-429.

House, M. A. and E.K. Sangster. 1991. Public perception of river-corridor management. Journal of the Chartered Institution of Water and Environmental Management **5:**312-317.

Huang, J. L., R. S. Wang, F. Li, W. R. Yang, C. B. Zhou, J. S. Jin, and Y. Shi. 2009. Simulation of thermal effects due to different amounts of urban vegetation within the built-up area of Beijing, China. International Journal of Sustainable Development and World Ecology **16**:67-76.

Irmak, S., I. Kabenge, D. Rudnick, S. Knezevic, D. Woodward, and M. Moravek. 2013. Evapotranspiration crop coefficients for mixed riparian plant community and transpiration crop coefficients for Common reed, Cottonwood and Peach-leaf willow in the Platte River Basin, Nebraska-USA. Journal of Hydrology **481**:177-190.

Jacques, M. 2009. When China rules the world: the rise of the middle kingdom and the end of the western world. Penguin Group, London, UK.

Jiang, B., C. P. Wong, F. Lu, Z. Ouyang, and Y. Wang. 2014. Drivers of drying on the Yongding River in Beijing. Journal of Hydrology **519, Part A**: 69-79.

Jim, C. Y. and W. Y. Chen. 2006. Perception and attitude of residents toward urban green spaces in Guangzhou (China). Environmental Management **38**:338-349.

Jing, H. W. 2006. An analysis of the causes and control methods for surface water pollution in Beijing. Urban Environment & Urban Ecology, **19:** 17–19 (in Chinese).

Kadlec, R.H. and R.L. Knight. 1996. Treatment wetlands. Lewis Publishers, Boca Raton, Florida, USA.

Kadlec, R. H. and K. R. Reddy. 2001. Temperature effects in treatment wetlands. Water Environment Research **73**:543-557.

Kadlec, R.H. and S.D. Wallace. 2009. Treatment wetlands 2nd edition. Lewis Publishers, Boca Raton, Florida, USA.

Keeler, B. L., S. Polasky, K. A. Brauman, K. A. Johnson, J. C. Finlay, A. O'Neill, K. Kovacs, and B. Dalzell. 2012. Linking water quality and well-being for improved assessment and valuation of ecosystem services. Proceedings of the National Academy of Sciences of the United States of America **109**:18619-18624.

Kennedy, J.F. 1963. Remarks of President John F. Kennedy at American University Commencement. Available at: http://www.jfklibrary.org/Asset-Viewer/BWC7I4C9QUmLG9J6I8oy8w.aspx. Last accessed 7 July 2014.

Kim, C. 2010. Place promotion and symbolic characterization of new Songdo City, South Korea. Cities **27**:13-19.

Kimball, J. S., S. W. Running, and R. Nemani. 1997. An improved method for estimating surface humidity from daily minimum temperature. Agricultural and Forest Meteorology **85**:87-98.

Kinzig, A. P., C. Perrings, F. S. Chapin, S. Polasky, V. K. Smith, D. Tilman, and B. L. Turner. 2011. Paying for Ecosystem Services-Promise and Peril. Science **334**:603-604.

Kong, F. H., H. W. Yin, and N. Nakagoshi. 2007. Using GIS and landscape metrics in the hedonic price modeling of the amenity value of urban green space: a case study in Jinan City, China. Landscape and Urban Planning **79**:240-252.

Kovats, R. S. and S. Hajat. 2008. Heat stress and public health: A critical review. Annual Review of Public Health **29**: 41-55.

Kremen, C. 2005. Managing ecosystem services: what do we need to know about their ecology? Ecology Letters **8**:468-479.

Kremen, C. and R. S. Ostfeld. 2005. A call to ecologists: measuring, analyzing, and managing ecosystem services. Frontiers in Ecology and the Environment **3**:540-548.

Landers, D.H., and A.M. Nahlik. 2013. Final ecosystem goods and services classification system (FEGS-CS). EPA/600/R-13/ORD-004914. United States Environmental Protection Agency, Office of Research and Development. Washington, DC, USA.

La Notte, A., J. Maes, B. Grizzetti, F. Bouraoui, and G. Zulian. 2012. Spatially explicit monetary valuation of water purification services in the Mediterranean bio-geographical region. International Journal of Biodiversity Science, Ecosystem Services and Management **8**:26-34.

Larocque, G. R., J. S. Bhatti, R. Boutin, and O. Chertov. 2008. Uncertainty analysis in carbon cycle models of forest ecosystems: Research needs and development of a theoretical framework to estimate error propagation. Ecological Modelling **219**:400-412.

Lee, K. N. 1993. Compass and gyroscope. Island Press, Washington, DC, USA.

Li, F., R. S. Wang, J. Paulussen, and X. S. Liu. 2005. Comprehensive concept planning of urban greening based on ecological principles: a case study in Beijing, China. Landscape and Urban Planning **72**:325-336.

Liang, M. Q., C. F. Zhang, C. L. Peng, Z. L. Lai, D. F. Chen, and Z. H. Chen. 2011. Plant growth, community structure, and nutrient removal in monoculture and mixed constructed wetlands. Ecological Engineering **37**:309-316.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges. 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. Journal of Geophysical Research-Atmospheres **99**:14415-14428.

Lillesand, T.M., R.W. Kiefer, and J.W. Chipman. 2008. Remote sensing and image interpretation, sixth edition. John Wiley & Sons, Inc. Hoboken, NJ, USA.

Liss, K. N., M. G. E. Mitchell, G. K. MacDonald, S. L. Mahajan, J. Methot, A. L. Jacob, D. Y. Maguire, G. S. Metson, C. Ziter, K. Dancose, K. Martins, M. Terrado, and E. M. Bennett. 2013. Variability in ecosystem service measurement: a pollination service case study. Frontiers in Ecology and the Environment **11**:414-422.

Liu, S., R. Costanza, S. Farber, and A. Troy. 2010. Valuing ecosystem services: theory, practice, and the need for a transdisciplinary synthesis. Ecological Economics Reviews **1185**:54-78.

Liu, W. D., H. L. You, and J. X. Dou. 2009. Urban-rural humidity and temperature differences in the Beijing area. Theoretical and Applied Climatology **96**:201-207.

Liu, Y., G. Wu, and X. Zhao. 2013. Recent declines in China's largest freshwater lake: trend or regime shift? Environmental Research Letters **8**:1-9.

Logsdon, R. A., and I. Chaubey. 2013. A quantitative approach to evaluating ecosystem services. Ecological Modelling **257**:57-65.

Lovett, G., C. Jones, M. Turner and K. Weathers. 2005. Ecosystem function in heterogeneous landscapes. Pages 1-4 *in* G. Lovett, M. Turner, C. Jones and K. Weathers, editors. Ecosystem function in heterogeneous landscapes. Springer, New York, NY, USA.

Lü, H., X. Gong, B. Gu, J. Li and X. Zhu. 2012. Discussing water quality measures on the Yongding River. Beijing Water Authority **S273.5**: 41-43 (in Chinese).

Lu, H. and Y. P. Shao. 2001. Toward quantitative prediction of dust storms: an integrated wind erosion modelling system and its applications. Environmental Modelling & Software **16**:233-249.

Lu, S., P. Zhang, X. Jin, C. Xiang, M. Gui, J. Zhang, and F. Li. 2009. Nitrogen removal from agricultural runoff by full-scale constructed wetland in China. Hydrobiologia **621:**115–126.

Luck, G. W., R. Harrington, P. A. Harrison, C. Kremen, P. M. Berry, R. Bugter, T. P. Dawson, F. de Bello, S. Diaz, C. K. Feld, J. R. Haslett, D. Hering, A. Kontogianni, S. Lavorel, M. Rounsevell, M. J. Samways, L. Sandin, J. Settele, M. T. Sykes, S. van den Hove, M. Vandewalle, and M. Zobel. 2009. Quantifying the contribution of organisms to the provision of ecosystem services. Bioscience **59**:223-235.

Maas, J., R. A.Verheij, P. P. Groenewegen, S. D. Vries, and P. Spreeuwenberg. 2006. Green space, urbanity, and health: how strong is the relation? Journal of Epidemical Community Health, **60:** 587-592.

Maes, J., B. Egoh, L. Willemen, C. Liquete, P. Vihervaara, J. P. Schägner, B. Grizzetti, E. G. Drakou, A. L. Notte, G. Zulian, F. Bouraoui, M. Luisa Paracchini, L. Braat, and G. Bidoglio. 2012. Mapping ecosystem services for policy support and decision making in the European Union. Ecosystem Services **1**:31-39.

Marcotullio, P. J., E. Williams, and J. D. Marshall. 2005. Faster, sooner, and more simultaneously: how recent road and air transportation CO_2 emission trends in developing countries differ from historic trends in the United States. Journal of Environment and Development **14**:125-148.

Marcotullio, P.J. 2007. Variations of urban environmental transitions: the experiences of rapidly developing Asia-Pacific cities. Pages 45-68 *in* P.J. Marcotullio and G. McGranahan, editors. Scaling urban environmental challenges: from local to global and back. Earthscan, London, UK.

Martínez-Harms, M. J. and P. Balvanera. 2012. Methods for mapping ecosystem service supply: a review. International Journal of Biodiversity Science, Ecosystem Services & Management **8**:17-25.

Maskell, L. C., A. Crowe, M. J. Dunbar, B. Emmett, P. Henrys, A. M. Keith, L. R. Norton, P. Scholefield, D. B. Clark, I. C. Simpson, and S. M. Smart. 2013. Exploring the ecological constraints to multiple ecosystem service delivery and biodiversity. Journal of Applied Ecology **50**:561-571.

Matsuoka, R. H., and R. Kaplan. 2008. People needs in the urban landscape: analysis of landscape and urban planning contributions. Landscape and Urban Planning **84:** 7-19.

Miao, S. G., J. X. Dou, F. Chen, J. Li, and A. G. Li. 2012. Analysis of observations on the urban surface energy balance in Beijing. Science China-Earth Sciences **55**:1881-1890.

(MA) Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: synthesis. Island Press Washington, DC, USA.

(MEP) Ministry of Environmental Protection. 2012. Report on the State of the Environment in China 2011. http://english.mep.gov.cn/standards_reports/soe.

Mishra, V., K. A. Cherkauer and L. C. Bowling. 2010. Parameterization of lakes and wetlands for energy and water Balance studies in the Great Lakes Region. Journal of Hydrometeorology **11**:1057-1082.

Mitsch, W.J., and J.G. Gosselink. 2007. Wetlands. John Wiley & Sons, Inc. Hoboken, New Jersey, USA.

Naidoo, R., A. Balmford, R. Costanza, B. Fisher, R. E. Green, B. Lehner, T. R. Malcolm, and T. H. Ricketts. 2008. Global mapping of ecosystem services and conservation priorities. Proceedings of the National Academy of Sciences of the United States of America **105**:9495-9500.

Nassauer, J. I., S. E. Kosek, and R. C. Corry. 2001. Meeting public expectations with ecological innovation in riparian landscapes. Journal of the American Water Resources Association **37**:1439-1443.

Naumann, S., M. D. Sandra, T. Kaphengst, M. Pieterse, and M. Rayment. 2011. Design, implementation and cost elements of green infrastructure projects. Final report to the European Commission, DG Environment, Contract 070307/2010/577182/ETU/F.1. Ecologic institute and GHK Consulting, Brussels, Belgium.

Nelson, E., G. Mendoza, J. Regetz, S. Polasky, H. Tallis, D. R. Cameron, K. M. A. Chan, G. C. Daily, J. Goldstein, P. M. Kareiva, E. Lonsdorf, R. Naidoo, T. H. Ricketts, and M. R. Shaw. 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. Frontiers in Ecology and the Environment **7**:4-11.

Nickling, W. G., and J. A. Gillies. 1993. Dust emission and transport in Mali, West Africa. Sedimentology **40**:859-868.

Nijssen, B., G. M. O'Donnell, A. F. Hamlet, and D. P. Lettenmaier. 2001. Hydrologic sensitivity of global rivers to climate change. Climatic Change **50**:143-175.

Oke, T. R. 1988. Street design and urban canopy layer climate. Energy and Buildings **11**:103-113.

Onaindia, M., B. F. de Manuel, I. Madariaga, and G. Rodriguez-Loinaz. 2013. Co-benefits and trade-offs between biodiversity, carbon storage and water flow regulation. Forest Ecology and Management **289**:1-9.

Ouyang, Z., T. Zhao, X. Wang, and H. Miao. 2004. Ecosystem services analyses and valuation of China terrestrial surfacewater system. Acta Ecologica Sinica **24**:2091-2099 (in Chinese).

Patz, J. A., D. Campbell-Lendrum, T. Holloway, and J. A. Foley. 2005. Impact of regional climate change on human health. Nature **438**:310-317.

Paul, M. J., and J. L. Meyer. 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics **32**:333-365.

Plummer, M. L. 2009. Assessing benefit transfer for the valuation of ecosystem services. Frontiers in Ecology and the Environment **7:**38-45.

Polasky, S., E. Nelson, J. Camm, B. Csuti, P. Fackler, E. Lonsdorf, C. Montgomery, D. White, J. Arthur, B. Garber-Yonts, R. Haight, J. Kagan, A. Starfield, and C. Tobalske. 2008. Where to put things? Spatial land management to sustain biodiversity and economic returns. Biological Conservation **141**:1505-1524.

Polasky, S., and K. Segerson. 2009. Integrating ecology and economics in the study of ecosystem services: some lessons learned. Annual Review of Resource Economics **1**:409-434.

Pope, C. A., and D. W. Dockery. 2006. Health effects of fine particulate air pollution: Lines that connect. Journal of the Air & Waste Management Association **56**:709-742.

Postel, S. L., and B. H. Thompson. 2005. Watershed protection: Capturing the benefits of nature's water supply services. Natural Resources Forum **29**:98-108.

Portman, M. E. 2013. Ecosystem services in practice: challenges to real world implementation of ecosystem services across multiple landscapes - a critical review. Applied Geography **45**:185-192.

Probe (Probe International Beijing Group). 2010. Beijing's water crisis 1949-2008 Olympics. Probe International, Toronto, Canada.

Qiu, J. X., and M. G. Turner. 2013. Spatial interactions among ecosystem services in an urbanizing agricultural watershed. Proceedings of the National Academy of Sciences of the United States of America **110**:12149-12154.

Raudsepp-Hearne, C., G. D. Peterson, and E. M. Bennett. 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proceedings of the National Academy of Sciences of the United States of America **107**:5242-5247.

Reddy, K. R., R. H. Kadlec, E. Flaig, and P. M. Gale. 1999. Phosphorus retention in streams and wetlands: A review. Critical Reviews in Environmental Science and Technology **29**:83-146.

Ren, Y. F., Z. W. Xu, X. Y. Zhang, X. K. Wang, X. M. Sun, D. J. Ballantine, and S. Z. Wang. 2014. Nitrogen pollution and source identification of urban ecosystem surface water in Beijing. Frontiers of Environmental Science & Engineering **8**:106-116.

Reyers, B., R. Biggs, G. S. Cumming, T. Elmqvist, A. P. Hejnowicz, and S. Polasky. 2013. Getting the measure of ecosystem services: a social-ecological approach. Frontiers in Ecology and the Environment **11**:268-273.

Richardson, L., J. Loomis, T. Kroeger, and F. Casey. 2014. The role of benefit transfer in ecosystem service valuation. Ecological Economics http://dx.doi.org/10.1016/j.ecolecon.2014.02.018.

Ricketts, T. H., G. C. Daily, P. R. Ehrlich, and C. D. Michener. 2004. Economic value of tropical forest to coffee production. Proceedings of the National Academy of Sciences of the United States of America **101**:12579-12582.

Ringold, P. L., J. Boyd, D. Landers, and M. Weber. 2013. What data should we collect? A framework for identifying indicators of ecosystem contributions to human well-being. Frontiers in Ecology and the Environment **11**:98-105.

Rogers, H. H., and D. E. Davis. 1972. Nutrient removal by water hyacinth. Weed Science **20**:423-428.

Rosenberger, R. S., and T. D. Stanley. 2006. Measurement, generalization, and publication: Sources of error in benefit transfers and their management. Ecological Economics **60**:372-378.

Ruckelshaus, M., E. McKenzie, H. Tallis, A. Guerry, G. Daily, P. Kareiva, S. Polasky, T. Ricketts, N. Bhagabati, S. A. Wood, and J. Bernhardt. 2013. Notes from the field: lessons learned from using ecosystem service approaches to inform real-world decisions. Ecological Economics http://dx.doi.org/10.1016/j.ecolecon.2013.07.009.

Russi, D., P, ten Brink, A. Farmer, T. Badura, D. Coates, J. Förster , R. Kumar, and N. Davidson. 2013. The Economics of Ecosystems and Biodiversity for Water and Wetlands. IEEP, London and Brussels, Ramsar Secretariat, Gland.

Scarlett, L., and J. Boyd. 2013. Ecosystem services and resource management: Institutional issues, challenges, and opportunities in the public sector. Ecological Economics. http://dx.doi.org/10.1016/j.ecolecon.2013.09.013.

Searns, R. M. 1995. The evolution of greenways as an adaptive urban landscape form. Landscape and Urban Planning **33:** 65-80.

Seppelt, R., C. F. Dormann, F. V. Eppink, S. Lautenbach, and S. Schmidt. 2011. A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. Journal of Applied Ecology **48**:630-636.

Shao, M., X. Y. Tang, Y. H. Zhang, and W. J. Li. 2006. City clusters in China: air and surface water pollution. Frontiers in Ecology and the Environment **4**:353-361.

Shi, B. 2013. Land rehab. Beijing Review **24**:12-18.

Shi, M. 1998. From imperial gardens to public parks: the transformation of urban space in early twentieth-century Beijing. Modern China **24:**219-254.

Steele, M. K., J. B. Heffernan, N. Bettez, J. Cavender-Bares, P. M. Groffman, J. M. Grove, S. Hall, S. E. Hobbie, K. Larson, J. L. Morse, C. Neill, K. C. Nelson, J. O'Neil-Dunne, L. Ogden, D. E. Pataki, C. Polsky, and R. R. Chowdhury. 2014. Convergent surface water distributions in US Cities. Ecosystems **17**:685-697.

Steinwender, A., C. Gundacker, and K. J. Wittmann. 2008. Objective versus subjective assessments of environmental quality of standing and running waters in a large city. Landscape and Urban Planning **84**:116-126.

Stevens, Q. 2009. Artificial waterfronts. Urban Design International **14:** 3-21.

Stewart, G. 2010. Meta-analysis in applied ecology. Biology Letters **6**:78-81.

Stone, R., and H. Jia. 2006. Hydroengineering - going against the flow. Science **313**:1034-1037.

Sun, C. 2011. Keeping a cool head about the management and development boom of Yongding River in Beijing. Social Science of Beijing **2**:38-41(in Chinese).

Suter, G. W. 1990. Endpoints for regional ecological risk assessments. Environmental Management **14**:9-23.

Suter, G. W. 2000. Generic assessment endpoints are needed for ecological risk assessment. Risk Analysis **20**:173-178.

Suter, G. W. 2008. Ecological risk assessment in the United States Environmental Protection Agency: a historical overview. Integrated Environmental Assessment and Management **4**:285-289.

Tallis, H., and S. Polasky. 2011. Assessing multiple ecosystem services: an integrated tool for the real world. Pages 34-50 *in* P. Kareiva, H. Tallis, T.H. Ricketts, G.C. Daily, and S. Polasky, editors. Natural Capital: Theory and practice of mapping ecosystem services. Oxford University Press, New York, NY, USA.

Tallis, H., H. Mooney, S. Andelman, P. Balvanera, W. Cramer, D. Karp, S. Polasky, B. Reyers, T. Ricketts, S. Running, K. Thonicke, B. Tietjen, and A. Walz. 2012. A global system for monitoring ecosystem service change. Bioscience **62**:977-986.

TEEB (The Economics of Ecosystems and Biodiversity). 2010. Mainstreaming the economics of nature: a synthesis of the approach, conclusions and recommendations of TEEB. Earthscan, London, UK.

Thornton, P. E., and S. W. Running. 1999. An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity, and precipitation. Agricultural and Forest Meteorology **93**:211-228.

Troy, A., and M. A. Wilson. 2006. Mapping ecosystem services: practical challenges and opportunities in linking GIS and value transfer. Ecological Economics **60**:435-449.

Tyrvainen, L. 1997. The amenity value of the urban forest: an application of the hedonic pricing method. Landscape and Urban Planning **37**:211-222.

UN-Habitat (United Nations Human Settlements Programme). 2008. State of the World's Cities 2008/2009 Harmonious Cities. Earthscan, London, UK.

UN-Habitat. Planning sustainable cities: global report on human settlements. 2009. Earthscan, London, UK.

Unger, J. 2004. Intra-urban relationship between surface geometry and urban heat island: review and new approach. Climate Research **27**:253-264.

US EPA (United States Environmental Protection Agency). 1995. National air quality and emissions trends report. US EPA, Washington, DC, USA.

US EPA. 1998. Guidelines for ecological risk assessment. US EPA, Washington, DC, USA.

US EPA. 2008. Reducing urban heat islands: compendium of strategies. US EPA, Washington, DC, USA.

US EPA. 2009. Valuing the protection of ecological systems and services. US EPA, Washington, DC, USA.

US NRC (United States National Research Council). 1999. Our Common Journey: a transition toward sustainability. National Academies Press, Washington, DC, USA.

US NRC. 2005.Valuing ecosystem services: toward better environmental decision-making. National Academies Press, Washington, DC, USA.

US NRC. 2012. Water reuse: potential for expanding the nation's water supply through reuse of municipal wastewater. National Academies Press, Washington, DC, USA.

Van Oudenhoven, A. P. E., K. Petz, R. Alkemade, L. Hein, and R. S. de Groot. 2012. Framework for systematic indicator selection to assess effects of land management on ecosystem services. Ecological Indicators **21**:110-122.

Von Stackelberg, K. E. 2013. Decision analytic strategies for integrating ecosystem services and risk assessment. Integrated Environmental Assessment and Management **9**:260-268.

Vymazal, J. 2007. Removal of nutrients in various types of constructed wetlands. Science of the Total Environment **380**:48-65.

Wainger, L., and M. Mazzotta. 2011. Realizing the potential of ecosystem services: a framework for relating ecological changes to economic benefits. Environmental Management **48**:710-733.

Wang, H., X. Li, H. Long, Y. Gai, and D. Wei. 2009. Monitoring the effects of land use and cover changes on net primary production: a case study in China's Yongding River basin. Forest Ecology and Management **258**:2654-2665.

Wang, S. G., J. Y. Wang, Z. J. Zhou, and K. Z. Shang. 2005. Regional characteristics of three kinds of dust storm events in China. Atmospheric Environment **39**:509-520.

Wang, S. G., W. Yuan, and K. Z. Shang. 2006. The impacts of different kinds of dust events on PM10 pollution in northern China. Atmospheric Environment **40**:7975-7982.

Wang, X. Q., and Y. B. Gong. 2010. The impact of an urban dry island on the summer heat wave and sultry weather in Beijing City. Chinese Science Bulletin **55**:1657-1661.

Wei, D. 2005. Beijing water resources and the south to north water diversion project. Canadian Journal of Civil Engineering **32**:159-163.

Wendel, H. E. W., R. K. Zarger, and J. R. Mihelcic. 2012. Accessibility and usability: green space preferences, perceptions, and barriers in a rapidly urbanizing city in Latin America. Landscape and Urban Planning **107**:272-282.

Wickham, J. D., K. H. Riitters, T. G. Wade, and P. Vogt. 2010. A national assessment of green infrastructure and change for the conterminous United States using morphological image processing. Landscape and Urban Planning **94**:186-195.

World Bank. 2007. Cost of pollution in China: economic estimates of physical damages. The World Bank, Washington, DC, USA.

WCED (World Commission on Environment and Development). 1987. Our Common Future. Oxford University Press, New York, NY, USA.

WWAP (World Water Assessment Programme). 2012. The United Nations World Water Development Report 4: managing water under uncertainty and risk. UNESCO, Paris, France.

Wu, F. L. 2012. China's eco-cities. Geoforum **43**:169-171.

Xie, S., Y. Zhang, L. Qi and X. Tang. 2005. Characteristics of air pollution in Beijing during sand-dust storm periods. Water, Air, and Soil Pollution **5:**217-229.

Xie, X. L., F. He, D. Xu, J. K. Dong, S. P. Cheng, and Z. B. Wu. 2012. Application of large-scale integrated vertical-flow constructed wetland in Beijing Olympic forest park: design, operation and performance. Water and Environment Journal **26**:100-107.

Yin, H., Y. Song, F. Kong, and Y. Qi. 2007. Measuring spatial accessibility of urban parks: a case study of Qingdao City, China. Geoinformatics **6753:** doi:10.1117/12.761871.

Yip, S. C. T. 2008. Eco-city: from concept to implementation case studies in Shanghai Dongtan and Beijing Changxindian. China City Planning Review **17**:45-53.

Yu, K. 1995. Cultural variations in landscape preference: comparisons among Chinese sub-groups and Western design experts. Landscape and Urban Planning **32:**107-126.

Yu, K., S. Wang, and D. Li. 2011. The negative approach to urban growth planning of Beijing, China. Journal of Environmental Planning and Management **54**:1209-1236.

Yue, D. 2004. Study on soil wind erosion and efficiency of wind prevention and sand resistance of artificial vegetation at sand-land in Yongding River in Beijing (Doctoral Dissertation). Beijing Forestry University, Beijing, China (in Chinese).

Yue, D., Y. Liu, R. Zang, and X. Wang. 2006a. Regularities of wind-erosion of different land-use types in Yongding River sandy land, Beijing. Frontiers of Forestry in China **1**:208-213.

Yue, D., Y. Liu, J. Wang, H. Li, and W. Cui. 2006b. Physical principle of wind erosion on sandy land surface in southern Beijing. Journal of Geographical Sciences 16:487-494.

Zedler, J. B., and S. Kercher. 2005. Wetland resources: status, trends, ecosystem services, and restorability. Annual Review of Environment and Resources **30:** 39-74.

Zhang, B., W. Li, and G. Xie. 2010. Ecosystem services research in China: Progress and perspective. Ecological Economics **69**:1389-1395.

Zhang, D. 2006. New courtyard houses of Beijing: direction of future housing development. Urban Design International **11:**133-150.

Zhang, D. Q., R. M. Gersberg, and T. S. Keat. 2009. Constructed wetlands in China. Ecological Engineering **35**:1367-1378.

Zhang, S., C. Wang, X. Meng, H. Dong, B. Men, and Z. Li. 2013. Evaporation study in Beijing section of the Yongding River. Progress in Geography **32:** 580-586 (in Chinese).

Zhang, W. J., and J. Yang. 2014. Development of outdoor recreation in Beijing, China between 1990 and 2010. Cities **37**:57-65.

Zhang, X., and Y. Wang. 2003. Analysis and case study of dust storms in the Beijing Area. Water, Air, and Soil Pollution 3:103-115.

Zheng, S., C. X. Cao, and R. P. Singh. 2014. Comparison of ground based indices (API and AQI) with satellite based aerosol products. Science of the Total Environment **488**:400-414.

Zhou, L., and G. S. Zhou. 2009. Measurement and modelling of evapotranspiration over a reed (Phragmites australis) marsh in Northeast China. Journal of Hydrology **372**:41-47.

Zhou, X. J., X. D. Xu, P. Yan, Y. H. Weng, and J. L. Wang. 2002. Dynamic characteristics of spring sandstorms in 2000. Science in China Series D-Earth Sciences **45**:921-930.

Zhu, L., X. Huang, H. Shi, X. Cai, and Y. Song. 2011. Transport pathways and potential sources of PM_{10} in Beijing. Atmospheric Environment **45**:594-604.

APPENDIX A

REMOTE SENSING METHODS

1. Landsat images were downloaded from the USGS Glovis website then imported into ERDAS Imagine 9.3. Two images were downloaded for each date, totaling four images. Every band file was separately imported (.tifs) and converted to IMAGINE files (.img) then combined to form a single stacked image. For the Landsat 5 TM images (9/22/2009), only bands 1-5 and 7 (visible and infrared bands) became part of the final stacked image. For the Landsat 8 images (9/1/2013), bands 1-7 were stacked.

2. All images were georectified. For each year two images were combined using the mosaic tool, and clipped to create one complete image across the study area for each year.

3. To help identify different vegetation types the normalized difference vegetation index (NDVI) was calculated:

$$NDVI = \frac{R_{NIR} - R_{red}}{R_{NIR} + R_{red}} \quad (1)$$

where R_{NIR} and R_{red} are the spectral reflectances of the TM red and near-infrared bands. The NDVI equation produces values ranging from -1 to 1, where positive values indicate vegetated areas and negative values signify non-vegetated surface features, such as water, barren, and urban.

4. For each year, I classified the images at two separate scales: (1) lakes (i.e., local) and (2) full Corridor + 5km buffer (i.e., regional). These were classified into seven broad classes: (1) deciduous trees, (2) water, (3) grass, (4) wetlands, (5) cropland, (6) bare soil, and (7) urban.

5. I used a hybrid technique of *unsupervised classification* (ISODATA algorithm) and *supervised classification* to classify the Landsat images at both scales. First an *unsupervised classification* was conducted using the clustering option of 15 classes and 30 iterations with convergence threshold of 0.95. I evaluated the classes and labeled them into the seven general LULC classes in step 4.

6. I refined the *unsupervised classification* by conducting a *supervised classification* (maximum likelihood) via the AOI tool to designate signatures of objects to known classes using ground control points, my knowledge of the study area, and Google Earth and Baidu high-resolution images. I consolidated all the spectral classes into the seven broad LULC classes using the Recode function.

7. After the classification there is a tendency to get a salt and pepper effect with some of the classes, thus classification smoothing was conducted using the 7 x 7 majority filter.

8. Accuracy assessments were conducted on the four maps (2 lakes for 2009 and 2013; 2 full Corridor for 2009 and 2013) to compare pixels in thematic raster layers to reference pixels. First, random points were generated for all four maps. For the lakes 100 points and full Corridor 175 points the search count was set to 1024. The points were identified using GPS ground control points and Google Earth and Baidu high-resolution images for the respective time periods. Accuracy reports were generated for each map consisting of error matrices, accuracy totals, and kappa statistics (Tables 1-4).

9. Four LULC maps were created representing the lakes and full Corridor for the pre-Corridor and post-Corridor time periods (Figs. 1-4).

10. The area (km^2) for each land cover class was calculated to estimate the difference in total area and percent change per land cover class between the pre- and post-Corridor.

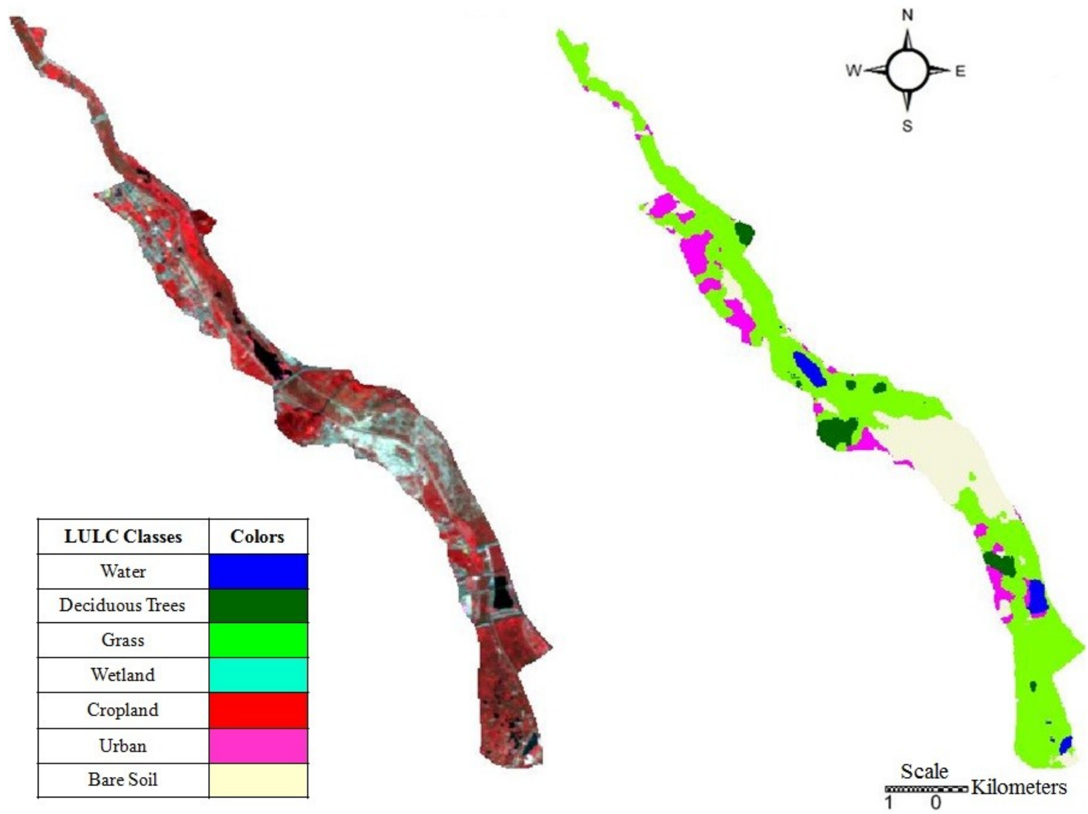


FIG.1. Landsat 5 satellite image (left) and classified map of the lakes for the pre-Corridor condition (right).

TABLE 1. Accuracy assessment for the lakes map for the pre-Corridor condition (September 22, 2009).

ERROR MATRIX

Reference Data

Class	Water	Deciduous trees	Grass	Wetland	Cropland	Urban	Bare Soil	Row Total
Water	6	0	0	0	0	0	0	6
Deciduous trees	0	5	0	0	0	0	0	5
Grass	0	0	58	0	0	2	0	60
Wetland	0	0	0	0	0	0	0	0
Cropland	0	0	0	0	0	0	0	0
Urban	0	0	0	0	0	8	0	8
Bare soil	0	0	4	0	0	4	13	21
Column Total	6	5	62	0	0	14	13	100

Accuracy Totals

Class	Reference Totals	Classified Totals	Number Correct	Producer's Accuracy	User's Accuracy
Water	6	6	6	100.00%	100.00%
Deciduous trees	5	5	5	100.00%	100.00%
Grass	62	60	58	93.55%	96.67%
Wetland	0	0	0	---	---
Cropland	0	0	0	---	---
Urban	14	8	8	57.14%	100.00%
Bare soil	13	21	13	100.00%	61.90%
Totals	100	100	90		

Overall Classification Accuracy = 90.00%

Kappa (ǩ) Statistics

Overall Kappa Statistics = 0.83

Class	Kappa	Class	Kappa
Water	1.00	Cropland	0.00
Deciduous trees	1.00	Urban	1.00
Grass	0.91	Bare soil	0.56
Wetland	0.00		

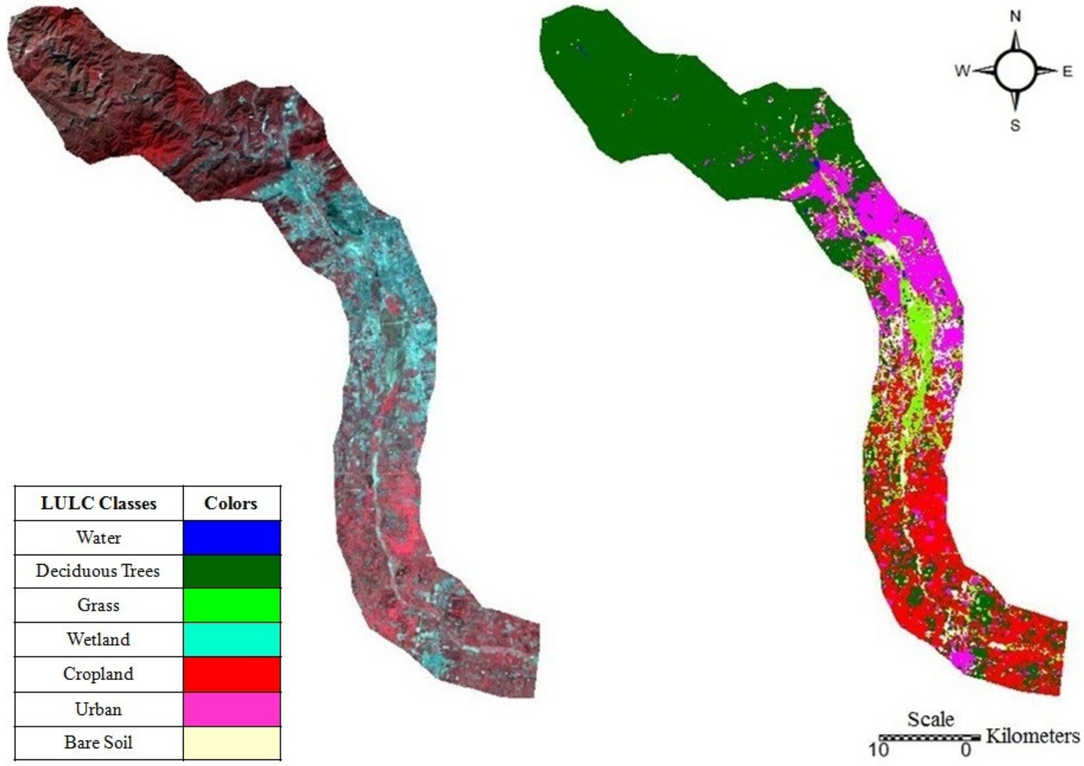


FIG.2. Landsat 5 satellite image (left) and classified map of the full Corridor for the pre-Corridor condition (right).

TABLE 2. Accuracy assessment for the full Corridor map for the pre-Corridor condition (September 22, 2009).

ERROR MATRIX

Reference Data

Class	Water	Deciduous trees	Grass	Wetland	Cropland	Urban	Bare Soil	Row Total
Water	0	0	0	0	0	0	0	0
Deciduous trees	0	86	0	0	3	1	0	90
Grass	0	0	13	0	0	3	0	16
Wetland	0	0	0	0	0	0	0	0
Cropland	0	0	1	0	36	0	0	37
Urban	0	0	0	0	0	26	0	26
Bare soil	0	0	0	0	0	2	4	6
Column Total	0	86	14	0	39	32	4	175

Accuracy Totals

Class	Reference Totals	Classified Totals	Number Correct	Producer's Accuracy	User's Accuracy
Water	0	0	0	---	---
Deciduous trees	86	90	86	100.00%	95.56%
Grass	14	16	13	92.86%	81.25%
Wetland	0	0	0	---	---
Cropland	39	37	36	92.31%	97.30%
Urban	32	26	26	81.25%	100.00%
Bare soil	4	6	4	100.00%	66.67%
Totals	175	175	165		

Overall Classification Accuracy = 94.29%

Kappa (ǩ) Statistics

Overall Kappa Statistics = 0.91

Class	Kappa	Class	Kappa
Water	0.00	Cropland	0.97
Deciduous trees	0.91	Urban	1.00
Grass	0.80	Bare soil	0.66
Wetland	0.00		

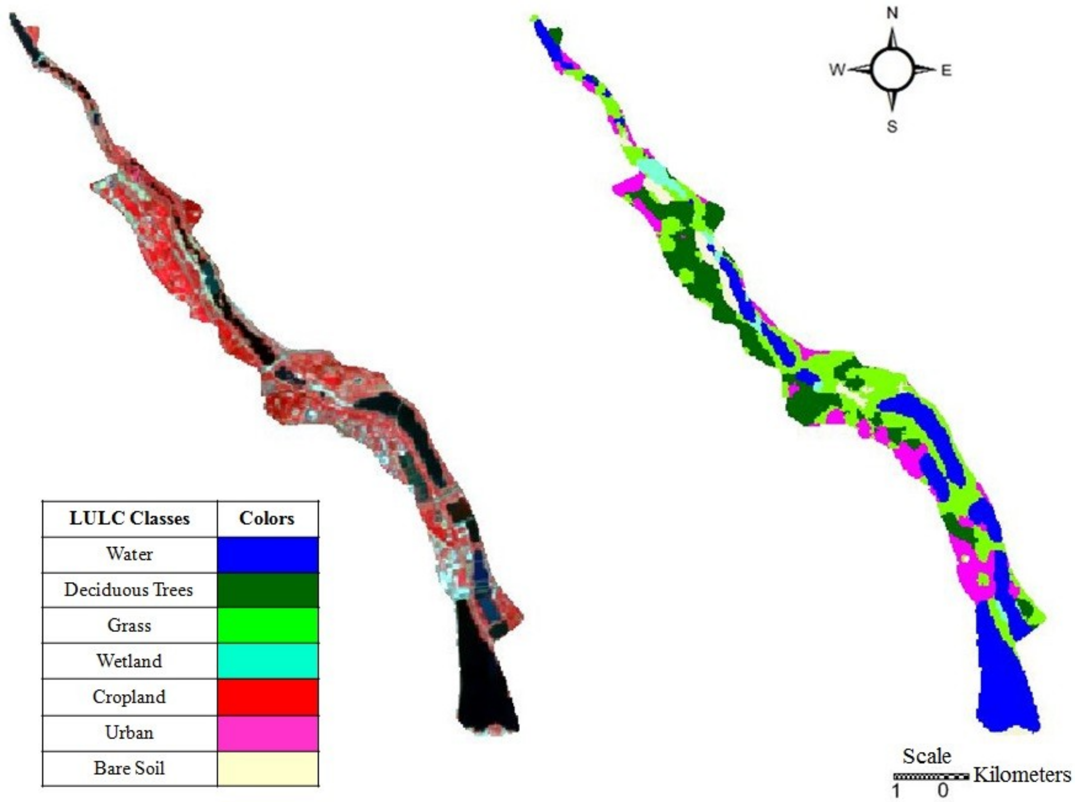


FIG.3. Landsat 8 satellite image (left) and classified map of the lakes for the post-Corridor condition (right).

TABLE 3. Accuracy assessment for the lakes map for the post-Corridor condition (September 1, 2013).

ERROR MATRIX

Reference Data								
Class	Water	Deciduous trees	Grass	Wetland	Cropland	Urban	Bare Soil	Row Total
Water	30	0	0	0	0	1	0	31
Deciduous trees	0	18	0	0	0	0	0	18
Grass	2	1	21	0	0	1	0	25
Wetland	0	0	0	6	0	0	0	6
Cropland	0	0	0	0	0	0	0	0
Urban	0	0	1	0	0	15	0	16
Bare soil	0	0	2	0	0	0	2	4
Column Total	32	19	24	6	0	17	2	100

Accuracy Totals

Class	Reference Totals	Classified Totals	Number Correct	Producer's Accuracy	User's Accuracy
Water	32	31	30	93.75%	96.77%
Deciduous trees	19	18	18	94.74%	100.00%
Grass	24	25	21	87.50%	84.00%
Wetland	6	6	6	100.00%	100.00%
Cropland	0	0	0	---	---
Urban	17	16	15	88.24%	93.75%
Bare soil	2	4	2	100.00%	50.00%
Totals	100	100	92		

Overall Classification Accuracy = 92.00%

Kappa (ǩ) Statistics

Overall Kappa Statistics = 0.90

Class	Kappa	Class	Kappa
Water	0.95	Cropland	0.00
Deciduous trees	1.00	Urban	0.92
Grass	0.79	Bare soil	0.49
Wetland	1.00		

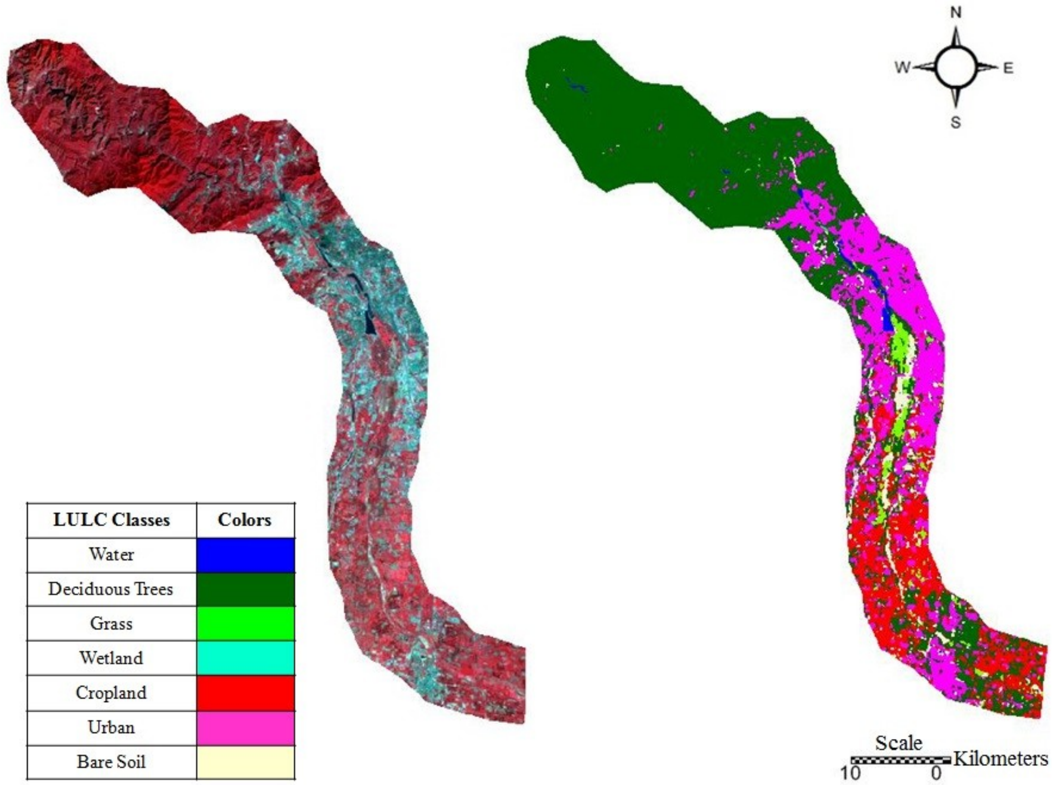


FIG.4. Landsat 8 satellite image (left) and classified map of the full Corridor for the post-Corridor condition (right).

TABLE 4. Accuracy assessment for the full Corridor map for the post-Corridor condition (September 1, 2013).

ERROR MATRIX

Reference Data

Class	Water	Deciduous trees	Grass	Wetland	Cropland	Urban	Bare Soil	Row Total
Water	0	0	0	0	0	0	0	0
Deciduous trees	1	92	1	0	3	1	0	98
Grass	0	0	3	0	0	0	0	3
Wetland	0	0	0	1	0	0	0	1
Cropland	0	0	0	0	26	0	0	26
Urban	0	0	0	0	0	43	0	43
Bare soil	0	0	1	0	0	0	3	4
Column Total	1	92	5	1	29	44	3	175

Accuracy Totals

Class	Reference Totals	Classified Totals	Number Correct	Producer's Accuracy	User's Accuracy
Water	1	0	0	---	---
Deciduous trees	92	98	92	100.00%	93.88%
Grass	5	3	3	60.00%	100.00%
Wetland	1	1	1	100.00%	100.00%
Cropland	29	26	26	89.66%	100.00%
Urban	44	43	43	97.73%	100.00%
Bare soil	3	4	3	100.00%	75.00%
Totals	175	175	168		

Overall Classification Accuracy = 96.00%

Kappa (ǩ) Statistics

Overall Kappa Statistics = 0.94

Class	Kappa	Class	Kappa
Water	0.00	Cropland	1.00
Deciduous trees	0.87	Urban	1.00
Grass	1.00	Bare soil	0.75
Wetland	1.00		

APPENDIX B

VARIABLE INFILTRATION CAPACITY MODEL

The Variable Infiltration Capacity (VIC) model version 4.1.2 is a process-based hydrological model (Liang et al. 1994, Bowling and Lettenmaier 2010). VIC allows the analyst to estimate the energy and water balances of the land surface including lakes and wetlands. The VIC model with its lake/wetland parameterization has been used to simulate evaporation and water storage on Arctic lakes (Bowling and Lettenmaier 2010), energy and water balance for the Great Lakes (Mishra et al. 2010), and lake level and water storage of Lake Chad (Gao et al. 2011). For VIC the lake and wetland exchange water as follows: all drainage from the wetland discharges directly to the lake then the lake expands in turn reducing the amount of wetland area . Simply when the lake is at its maximum extent there are no wetlands present, and as the lake shrinks the wetland area expands. In all other respects, the wetland is simulated in the same way as other land cover classes.

MODEL PARAMETERIZATION

Grid cells and land use and land cover

Water can only enter a grid cell via the atmosphere, thus there is no non-channel flow between grid cells. Grid cells are physically separate lakes (i.e., presence of dam, bridge, and/or waterfall) to prevent backflow from one lake to another. The only flow between lakes is the inflow, which I determined using engineering data. Grid cells were simulated independent of each other. The entire simulation was run at an hourly time-step for each grid cell separately. Meteorological input data for each grid cell were read from a file specific to that grid cell. Every grid cell was subdivided into land cover “tiles” each corresponding to the fraction of the cell covered by that particular land cover (e.g., deciduous broadleaf, grass, water, etc.). VIC averages the water storages and energy fluxes of the land cover classes together (weighted by area fraction) to generate average grid cell values for output variables.

Land use and land cover (LULC) data were calculated using Landsat remote sensing images for pre-Corridor (9/22/2009) and post-Corridor (9/1/2013). Yue et al. (2006a) characterized the land cover of the Yongding River into three main types: (1) forest, (2) cropland, and (3) grassland. The forest is mainly deciduous broad-leaf as *Populus tomentosa* (Chinese white poplar trees) plantations with a density of 4 m x 4 m and average height of 18m. The cropland is mainly corn (*Zea mays*) surrounded by coarse sand, and is the largest bare area in winter and spring. The grassland consists mainly of *Digitaria sanguinalis* (crabgrass) and *Chloris virgata* (feather fingergrass) with an average height of 5-10 cm. I selected six LULC classes to parameterize the vegetation parameter file: (1) deciduous broad-leaf, (2) grass, (3) lake/wetland (dominant vegetation type is *Phragmites*), (4) cropland, and (5) urban.

Vegetation parameters

Values for the vegetation library and parameter files were determined using LULC data, VIC global input dataset (Nijssen et al. 2001), and literature values for the wetland and urban classes (Tables 1-5). Literature values were used for *Phragmites* (i.e., common reed) the dominant wetland species, and urban albedo and displacement values for Beijing.

TABLE 1. Deciduous broad-leaf

Variable	Value	Description	Citation
overstory	1	Whether or not current veg class has overstory	Nijssen et al. 2001 (VIC global input parameter file at 0.5-degree resolution)
rarc	60	Architectural resistance of vegetation type (sm^{-1})	
rmin	150	Min. stomatal resistance of vegetation type (sm^{-1})	
LAI-1	1.680	Leaf area index per month	
LAI-2	1.520		
LAI-3	1.680		
LAI-4	2.900		
LAI-5	4.900		
LAI-6	5.000		
LAI-7	5.000		
LAI-8	4.600		
LAI-9	3.440		
LAI-10	3.040		
LAI-11	2.160		
LAI-12	2.000		
albedo-1	0.18	Shortwave albedo for vegetation type (fraction)	
albedo-2	0.18		
albedo-3	0.18		
albedo-4	0.18		
albedo-5	0.18		
albedo-6	0.18		
albedo-7	0.18		
albedo-8	0.18		
albedo-9	0.18		
albedo-10	0.18		
albedo-11	0.18		
albedo-12	0.18		
rough-1	1.23	Vegetation roughness length (m)	
rough-2	1.23		
rough-3	1.23		
rough-4	1.23		
rough-5	1.23		
rough-6	1.23		
rough-7	1.23		
rough-8	1.23		
rough-9	1.23		
rough-10	1.23		
rough-11	1.23		
rough-12	1.23		
displacement-1	6.70	Vegetation displacement height (m)	
displacement-2	6.70		
displacement-3	6.70		
displacement-4	6.70		
displacement-5	6.70		
displacement-6	6.70		
displacement-7	6.70		
displacement-8	6.70		
displacement-9	6.70		
displacement-10	6.70		
displacement-11	6.70		
displacement-12	6.70		
wind_h	50	Wind speed height (m)	
RGL	30	Min. incoming shortwave radiation for transpiration	
rad_atten	0.5	Radiation attenuation factor (fraction)	
wind_atten	0.5	Wind speed attenuation through the overstory (fraction)	
trunk_ratio	0.2	Ratio of total tree height that is trunk (fraction)	

TABLE 2. Grass

Variable	Value	Description	Citation
overstory	0	Whether or not current veg class has overstory	
rarc	25	Architectural resistance of vegetation type (sm^{-1})	
rmin	120	Min. stomatal resistance of vegetation type (sm^{-1})	
LAI-1	2.000	Leaf area index per month	
LAI-2	2.250		
LAI-3	2.950		
LAI-4	3.850		
LAI-5	3.750		
LAI-6	3.500		
LAI-7	3.550		
LAI-8	3.200		
LAI-9	3.300		
LAI-10	2.850		
LAI-11	2.600		
LAI-12	2.200		
albedo-1	0.2	Shortwave albedo for vegetation type (fraction)	
albedo-2	0.2		
albedo-3	0.2		
albedo-4	0.2		
albedo-5	0.2		
albedo-6	0.2		
albedo-7	0.2		
albedo-8	0.2		
albedo-9	0.2		
albedo-10	0.2		
albedo-11	0.2		
albedo-12	0.2		
rough-1	0.0738	Vegetation roughness length (m)	Nijssen et al. 2001
rough-2	0.0738		
rough-3	0.0738		
rough-4	0.0738		
rough-5	0.0738		
rough-6	0.0738		
rough-7	0.0738		
rough-8	0.0738		
rough-9	0.0738		
rough-10	0.0738		
rough-11	0.0738		
rough-12	0.0738		
displacement-1	0.402	Vegetation displacement height (m)	
displacement-2	0.402		
displacement-3	0.402		
displacement-4	0.402		
displacement-5	0.402		
displacement-6	0.402		
displacement-7	0.402		
displacement-8	0.402		
displacement-9	0.402		
displacement-10	0.402		
displacement-11	0.402		
displacement-12	0.402		
wind_h	3	Wind speed height (m)	
RGL	100	Min. incoming shortwave radiation for transpiration	
rad_atten	0.5	Radiation attenuation factor (fraction)	
wind_atten	0.5	Wind speed attenuation through the overstory (fraction)	
trunk_ratio	0.2	Ratio of total tree height that is trunk (fraction)	

TABLE 3. Lake/Wetlands

Variable	Value	Description	Citation
overstory	0	Whether or not current veg class has overstory	
rarc	25	Architectural resistance of vegetation type (sm^{-1})	Nijssen et al. 2001
rmin	120	Min. stomatal resistance of vegetation type (sm^{-1})	
LAI-1	2.000		
LAI-2	2.000		
LAI-3	2.250		
LAI-4	2.250		
LAI-5	2.250		
LAI-6	5.000	Leaf area index per month	
LAI-7	5.000		Liang et al. 2011, Irmack et al. 2013
LAI-8	5.000		
LAI-9	5.000		
LAI-10	2.250		
LAI-11	2.250		
LAI-12	2.000		
albedo-1	0.2		
albedo-2	0.2		
albedo-3	0.2		
albedo-4	0.2		
albedo-5	0.2		
albedo-6	0.2		
albedo-7	0.2	Shortwave albedo for vegetation type (fraction)	
albedo-8	0.2		Nijssen et al. 2001
albedo-9	0.2		
albedo-10	0.2		
albedo-11	0.2		
albedo-12	0.2		
rough-1	0.3075		
rough-2	0.3075		
rough-3	0.3075		
rough-4	0.3075		
rough-5	0.3075		
rough-6	0.3075	Vegetation roughness length (m)	
rough-7	0.3075		
rough-8	0.3075		
rough-9	0.3075		
rough-10	0.3075		
rough-11	0.3075		
rough-12	0.3075		
displacement-1	1.675		Zhou and Zhou 2009, Irmack et al. 2013
displacement-2	1.675		
displacement-3	1.675		
displacement-4	1.675		
displacement-5	1.675		
displacement-6	1.675	Vegetation displacement height (m)	
displacement-7	1.675		
displacement-8	1.675		
displacement-9	1.675		
displacement-10	1.675		
displacement-11	1.675		
displacement-12	1.675		
wind_h	20	Wind speed height (m)	
RGL	100	Min. incoming shortwave radiation for transpiration	
rad_atten	0.5	Radiation attenuation factor (fraction)	
wind_atten	0.5	Wind speed attenuation through the overstory (fraction)	Nijssen et al. 2001
trunk_ratio	0.2	Ratio of total tree height that is trunk (fraction)	

TABLE 4. Cropland (corn)

Variable	Value	Description	Citation
overstory	0	Whether or not current veg class has overstory	
rarc	25	Architectural resistance of vegetation type (sm^{-1})	
rmin	120	Min. stomatal resistance of vegetation type (sm^{-1})	
LAI-1	0.050		
LAI-2	0.020		
LAI-3	0.050		
LAI-4	0.250		
LAI-5	1.500		
LAI-6	3.000	Leaf area index per month	
LAI-7	4.500		
LAI-8	5.000		
LAI-9	2.500		
LAI-10	0.500		
LAI-11	0.050		
LAI-12	0.020		
albedo-1	0.1		
albedo-2	0.1		
albedo-3	0.1		
albedo-4	0.1		
albedo-5	0.2		
albedo-6	0.2		
albedo-7	0.2	Shortwave albedo for vegetation type (fraction)	
albedo-8	0.2		
albedo-9	0.2		
albedo-10	0.1		
albedo-11	0.1		
albedo-12	0.1		
rough-1	0.006		Nijssen et al. 2001
rough-2	0.006		
rough-3	0.006		
rough-4	0.006		
rough-5	0.012		
rough-6	0.062		
rough-7	0.123	Vegetation roughness length (m)	
rough-8	0.185		
rough-9	0.215		
rough-10	0.215		
rough-11	0.006		
rough-12	0.006		
displacement-1	0.03		
displacement-2	0.03		
displacement-3	0.03		
displacement-4	0.03		
displacement-5	0.07		
displacement-6	0.34		
displacement-7	0.67	Vegetation displacement height (m)	
displacement-8	1.01		
displacement-9	1.17		
displacement-10	1.17		
displacement-11	0.03		
displacement-12	0.03		
wind_h	2	Wind speed height (m)	
RGL	100	Min. incoming shortwave radiation for transpiration	
rad_atten	0.5	Radiation attenuation factor (fraction)	
wind_atten	0.5	Wind speed attenuation through the overstory (fraction)	
trunk_ratio	0.2	Ratio of total tree height that is trunk (fraction)	

TABLE 5. Urban

Variable	Value	Description	Citation
overstory	0	Whether or not current veg class has overstory	
rarc	60	Architectural resistance of vegetation type (sm^{-1})	
rmin	1200	Min. stomatal resistance of vegetation type (sm^{-1})	
LAI-1	0		
LAI-2	0		
LAI-3	0		
LAI-4	0		
LAI-5	0		
LAI-6	0	Leaf area index per month	
LAI-7	0		
LAI-8	0		
LAI-9	0		
LAI-10	0		
LAI-11	0		
LAI-12	0		
albedo-1	0.14		
albedo-2	0.14		
albedo-3	0.12		
albedo-4	0.12		
albedo-5	0.12		
albedo-6	0.10	Shortwave albedo for urban surfaces in Beijing (fraction)	Miao et al. 2012
albedo-7	0.10		
albedo-8	0.10		
albedo-9	0.12		
albedo-10	0.12		
albedo-11	0.12		
albedo-12	0.14		
rough-1	0.626		
rough-2	0.626		
rough-3	0.626		
rough-4	0.626		
rough-5	0.626		
rough-6	0.626	Vegetation roughness length (m)	
rough-7	0.626		
rough-8	0.626		
rough-9	0.626		
rough-10	0.626		
rough-11	0.626		
rough-12	0.626		Oke 1988, Miao et al. 2012
displacement-1	5.819		
displacement-2	5.819		
displacement-3	5.819		
displacement-4	5.819		
displacement-5	5.819		
displacement-6	5.819	Vegetation displacement height (m)	
displacement-7	5.819		
displacement-8	5.819		
displacement-9	5.819		
displacement-10	5.819		
displacement-11	5.819		
displacement-12	5.819		
wind_h	50	Wind speed height (m)	
RGL	0	Min. incoming shortwave radiation for transpiration	
rad_atten	0.5	Radiation attenuation factor (fraction)	
wind_atten	0.5	Wind speed attenuation through the overstory (fraction)	
trunk_ratio	1	Ratio of total tree height that is trunk (fraction)	

Lake/wetland parameters

Lake area can vary with time as a function of storage and bathymetry. In this context, wetland refers to the exposed vegetated portion of the land cover tile, which allows for seasonal inundation as the lake grows and shrinks. The physical description of the lake and wetland consists of the extent of permanent open water (minimum lake storage) and seasonally flooded area (max lake storage). Bathymetric profiles of basin area to basin depth were calculated using LULC and engineering data where the assumed bathymetry is a trapezoid channel since these are lakes in concrete channels (Fig.1).

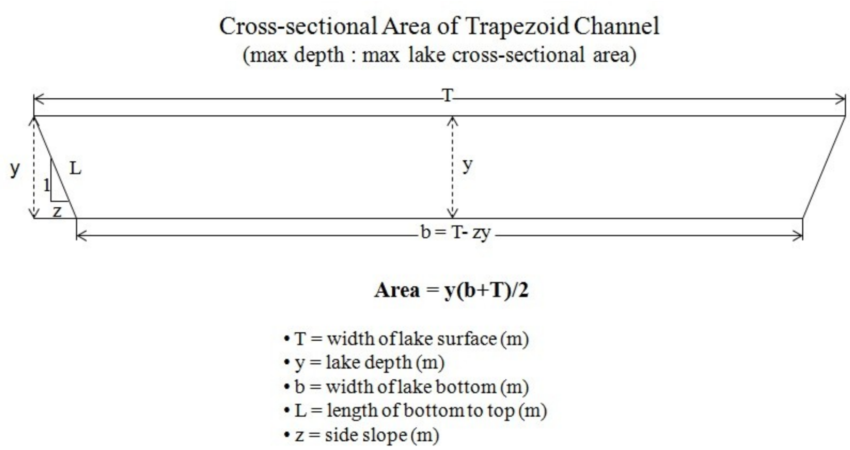


FIG.1. Trapezoid channel cross-sectional area used to calculate lake bathymetric profiles.

The lake model parameters include: n_L (number of lake layers), d_{min} (lake depth below which channel outflow is 0), w_{frac} (width of lake outlet as a fraction of the lake perimeter), d_0 (initial lake depth), r_{pct} (fraction of runoff from the grid cell's non-wetland vegetation tiles that enters the lake), and the bathymetric profile (lake depth: lake area at each layer). I ran the model at two scales: (1) *regional* - the full Corridor as one grid cell, and (2) *local* - the seven lakes and wetlands as individual grid cells. For all lakes d_{min} was 0, and w_{frac} was 0 because every lake is separated by a physical structure. The r_{pct} was 0 at full Corridor because the system at this scale is designed for no surface runoff to enter the lakes, however at the local scale it was 1.0 because the system is designed for shoreline surface runoff to enter the lakes and wetlands (Table 6).

TABLE 6. Lake and wetland parameters for engineered and calibrated conditions.

Engineered									
Grid Cell	n_L	d_{min}	w_{frac}	d_0 (m)	r_{pct} (fraction)	depth (m)	area (fraction)	Inflow ($m^3 d^{-1}$)	D_{smax} (mm d^{-1})
Full Corridor	10	0	0	2.0	0.0	6-0.5	0.021-0.002	361,644	42.53
Mencheng Lake	10	0	0	2.0	1.0	3.0-0.1	0.677-0.023	40,000	98.75
Wetlands	10	0	0	1.0	1.0	2.75-0.1	0.390-0.014	40,000	75.03
Lianshi Lake	10	0	0	1.8	1.0	3.0-0.1	0.498-0.017	190,000	221.31
Garden Expo Lake	10	0	0	2.0	1.0	3-0.1	0.412-0.014	80,000	39.35
Xiaoyue Lake	10	0	0	2.0	1.0	2.75-0.1	0.416-0.015	150,000	395.05
Wanping Lake	10	0	0	2.0	1.0	2.75-0.1	0.677-0.025	150,000	260.38
Daning Reservoir	10	0	0	4.0	1.0	4.0-0.1	1.0-0.025	150,000	56.95
Calibrated									
Grid Cell	n_L	d_{min}	w_{frac}	d_0 (m)	r_{pct} (fraction)	depth (m)	area (fraction)	Inflow ($m^3 d^{-1}$)	D_{smax} (mm d^{-1})
Full Corridor	10	0	0	1.5	0.0	6.0-0.5	0.021-0.002	200,000-361,644	42.53
Mencheng Lake	10	0	0	1.5	1.0	3.0-0.1	0.677-0.023	27,350-35,000	98.75
Wetlands	10	0	0	0.9	1.0	2.75-0.1	0.390-0.014	1,300-40,000	39.09
Lianshi Lake	10	0	0	1.8	1.0	3.0-0.1	0.498-0.017	32,254-104,247	150.75
Garden Expo Lake	10	0	0	2.0	1.0	3-0.1	0.412-0.014	17,081-58,598	20.15
Xiaoyue Lake	10	0	0	2.0	1.0	2.75-0.1	0.416-0.015	32,596-78,024	270.05
Wanping Lake	10	0	0	2.0	1.0	2.75-0.1	0.677-0.025	40,196-99,979	180.38
Daning Reservoir	10	0	0	4.0	1.0	4.0-0.1	1.0-0.025	79,871-134,063	47.05

Soil

Soil parameters fall into two categories: those that are fixed and those subject to calibration. Fixed soil parameters were taken from the global VIC input parameter dataset (Nijssen et al. 2001), which include all physical properties that can be derived from soil texture (e.g., porosity and hydraulic conductivity). The parameters subject to calibration include thicknesses of the model's three hydrologic soil layers, the shape of the moisture infiltration capacity distribution (b_{infilt}), and the shape of the relationship between bottom layer moisture storage and baseflow (D_s, W_s, and D_{smax}) (Liang et al. 1994). For pre-Corridor I used the global input dataset values, but for post-Corridor I calibrated the D_{smax} to represent outflow in the engineered system (Table 6).

Forcing: meteorological and inflow

I obtained climate data from the Mentougou Meteorological Bureau, which are daily: (1) maximum air temperature, (2) minimum air temperature, (3) precipitation, and (4) wind speed. The VIC model uses MTCLIM algorithms (Kimball et al. 1997, Thornton and Running 1999) to convert daily maximum and minimum air temperatures to humidity and incoming shortwave radiation. VIC then uses the Tennessee Valley Authority algorithm (Bras 1990) to deduce incoming longwave radiation from humidity and temperature. VIC also computes atmospheric pressure and density from grid cell elevation and global mean pressure lapse rate. VIC converts these daily meteorological values into hourly values. Lastly, I used engineered inflow rates then calibrated the inflow rates to simulate the seasonal changes in lake volumes (Table 6).

MODEL RESULTS

The VIC model was used to dynamically estimate key ecosystem characteristics as inputs to empirically-based models and ecological production functions, which were: (1) ET (mm), (2) latent heat flux (W m^{-2}), (3) sensible heat flux (W m^{-2}), (4) lake volume (m^3), (5) water loss (i.e. lake evaporation) (m^3), (6) lake surface area (m^2), (7) wetland surface area (m^2), (8) water temperature (°C), and (9) water depth (m). In this appendix, I report the ET and lake volume results, which were used to determine water and climate regulation services. Also these output variables were used to evaluate model accuracy and sensitivity.

I calculated the mean hourly, monthly, and annual ET and lake volume at the local and regional scales for pre- and post-Corridor conditions (Fig. 2, Table 7-8). The mean hourly ET doubled from pre-Corridor to post-Corridor from 0.06 mm in the pre-Corridor to 0.11-0.13 mm in the post-Corridor (Table 7). This relationship is explained by the overall higher latent heat flux for the post-Corridor. In particular the higher latent heat flux and lower sensible heat flux in the summer, which is when ET rates are the highest (Fig. 3). In the pre-Corridor the estimated total annual ET was 402 mm at the local scale, and 541 mm at the regional scale. In the post-Corridor, the mean annual ET was greatest at the Wetlands (1,121 mm) and lowest at Daning Reservoir (873 mm). The Wetlands on the Yongding Corridor is wide and shallow making it more susceptible to more water losses compared to other sections (Fig. 4). Lastly the estimated total annual ET was 1,088 mm and mean total water volume was 6.95 million m^3 (Table 8).

TABLE 7. Local scale estimated mean hourly and monthly ET, and total annual ET for each lake and wetland compared to pre-Corridor with no lakes and wetlands.

Hour								
	Pre-Corridor	Mencheng	Wetlands	Lianshi	Garden Expo	Xiaoyue	Wanping	Daning Reservoir
ET (mm)	0.06	0.12	0.13	0.12	0.11	0.10	0.13	0.11
Std.	0.09	0.12	0.15	0.13	0.11	0.15	0.13	0.11
Volume (m^3)	---	310,931	144,944	475,090	2,681,177	192,217	302,286	4,433,797
Std.	---	87,788	143,114	94,322	619,966	65,963	105,637	401,324
Month								
	Pre-Corridor	Mencheng	Wetlands	Lianshi	Garden Expo	Xiaoyue	Wanping	Daning Reservoir
ET (mm)	42.45	83.37	93.46	86.18	78.78	71.26	89.15	72.75
Std.	33.66	56.39	61.47	57.03	51.25	55.75	59.48	47.18
Volume (m^3)	---	316,438	137,253	476,846	2,759,554	191,361	295,869	4,477,069
Std.	---	25,016	36,281	31,966	98,725	19,888	30,176	121,960
Annual								
	Pre-Corridor	Mencheng	Wetlands	Lianshi	Garden Expo	Xiaoyue	Wanping	Daning Reservoir
ET (mm)	402	1,000	1,121	1,034	945	855	1,070	873
Volume (m^3)	---	310,931	192,217	475,090	2,681,177	192,217	302,286	4,433,797
Surface area (m^2)	---	342,205	286,502	598,387	2,263,772	220,396	342,205	2,273,442
Surface area: Volume	---	1.10	1.49	1.26	0.84	1.15	1.13	0.51

TABLE 8. Regional scale estimated mean hourly and monthly ET, and total annual ET for pre-Corridor and post-Corridor.

Hour		
	Pre-Corridor	Post-Corridor
ET (mm)	0.07	0.13
Std.	0.09	0.12
Volume (m^3)	---	6,955,370
Std.	---	2,833,901
Month		
	Pre-Corridor	Post-Corridor
ET (mm)	45.07	90.67
Std.	39.75	71.06
Volume (m^3)	---	7,233,865
Std.	---	581,069
Annual		
	Pre-Corridor	Post-Corridor
ET (mm)	541	1,088
Volume (m^3)	---	6,955,370
Surface area (m^2)	---	7,121,795
Surface area: Volume	---	1.0239

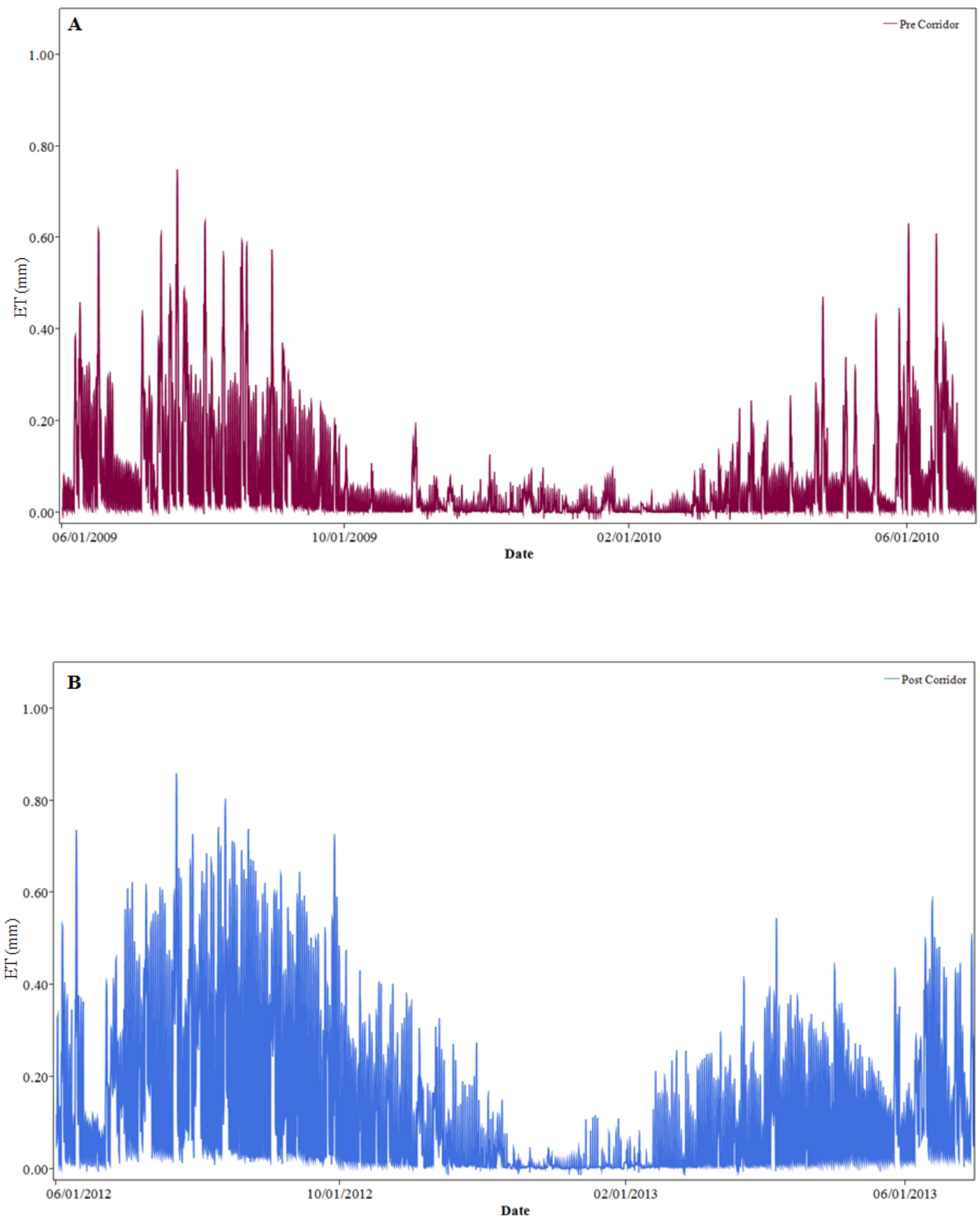


FIGURE 2. Regional estimated hourly ET rates for pre-Corridor (6/1/2009 to 6/30/2010) and post-Corridor (6/1/2012 to 6/30/2013).

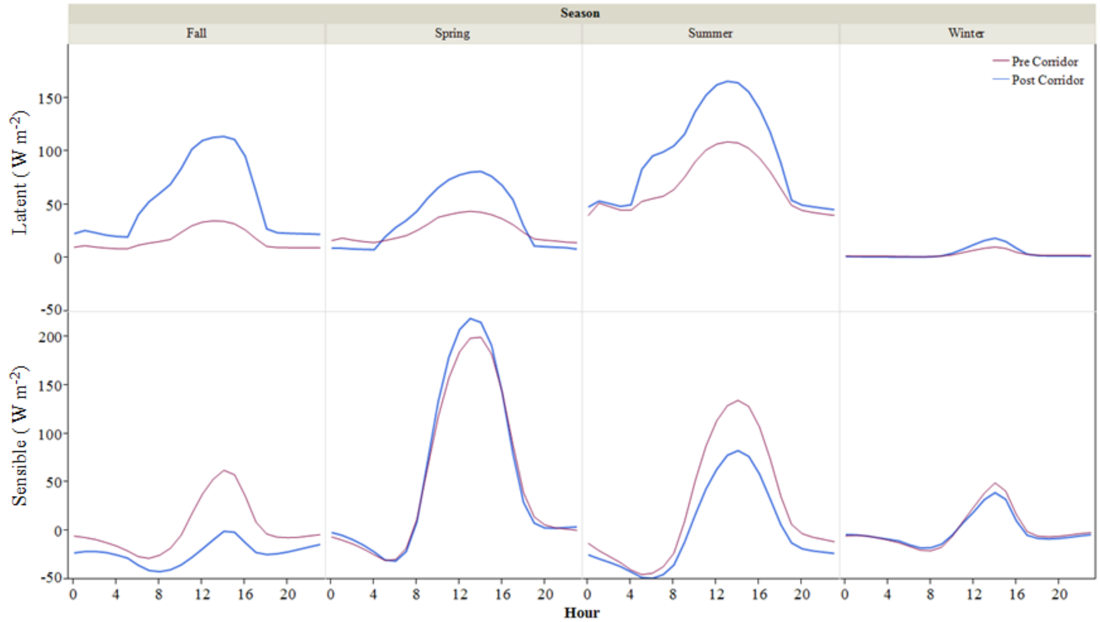
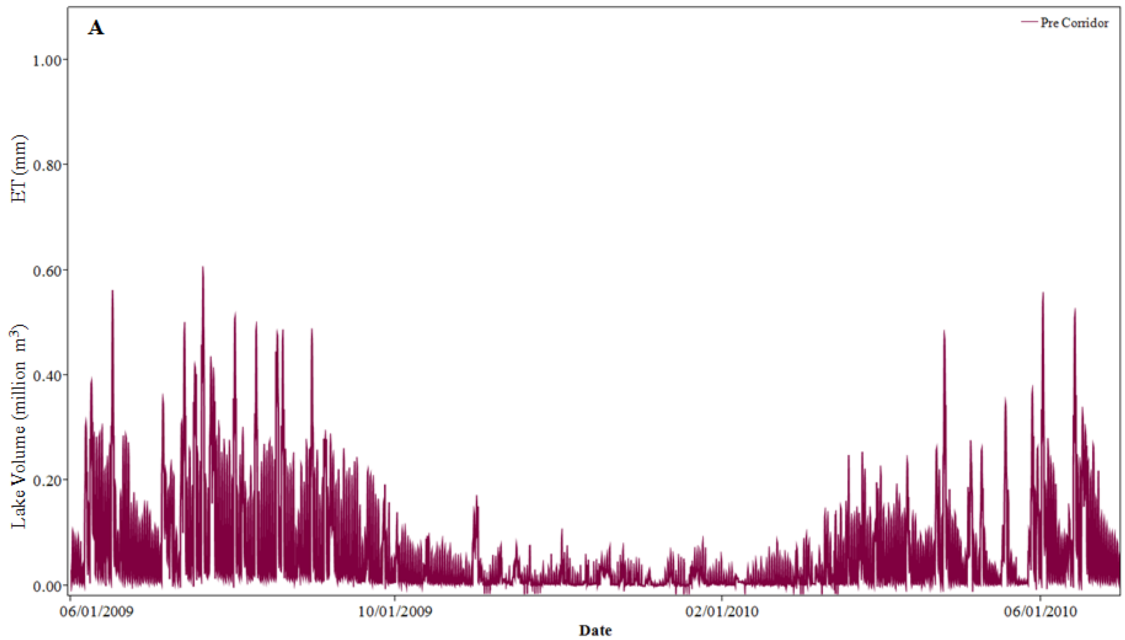
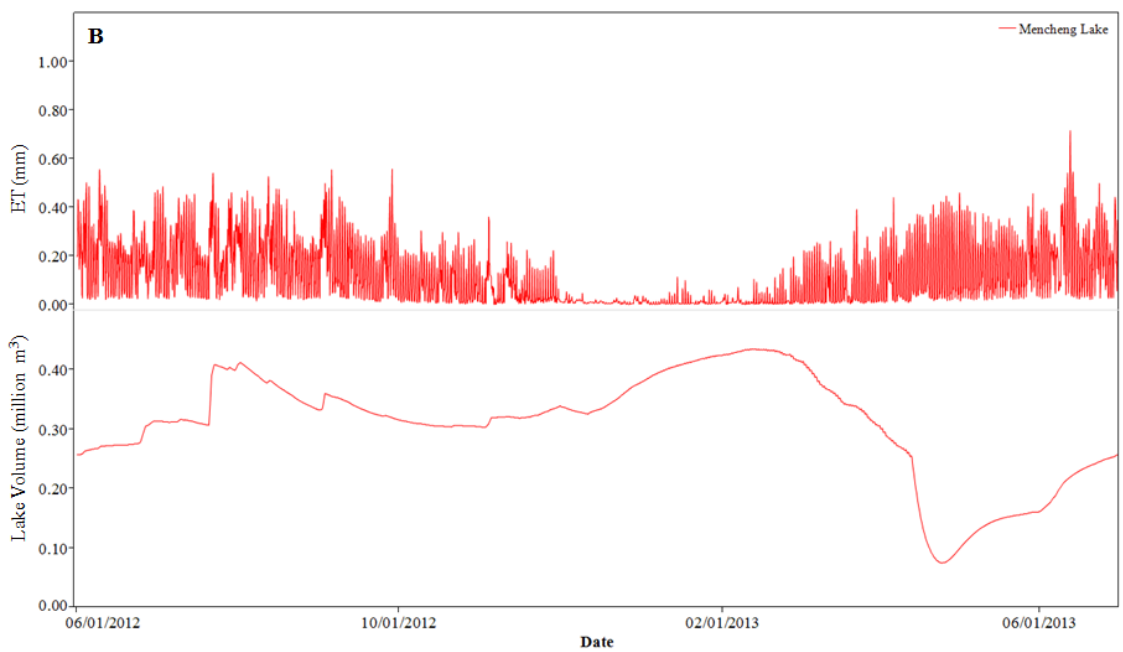
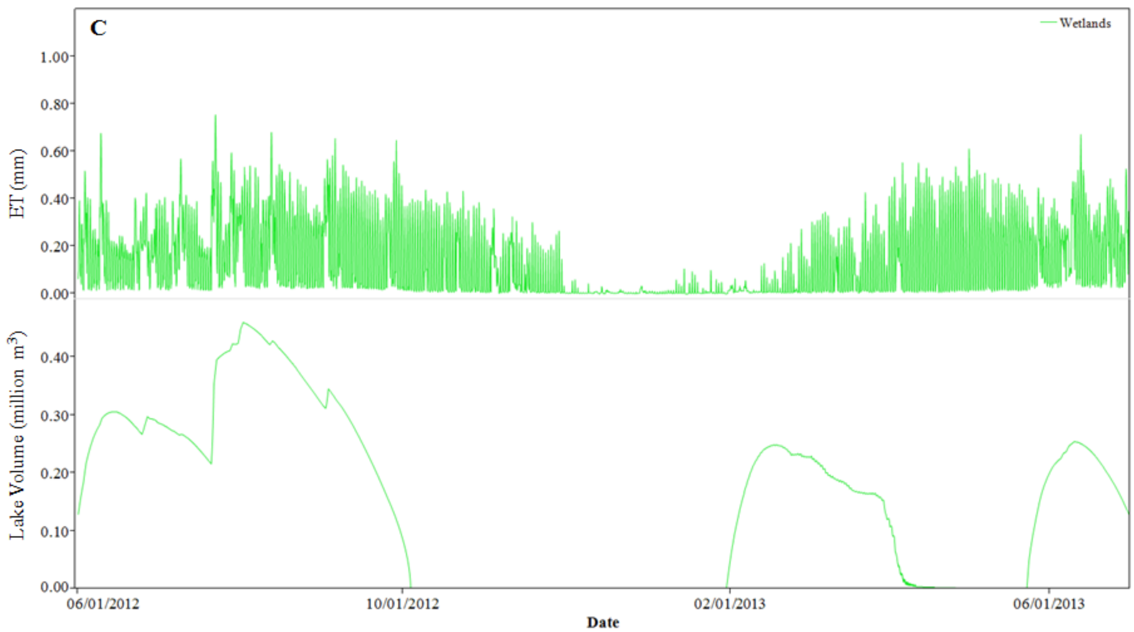
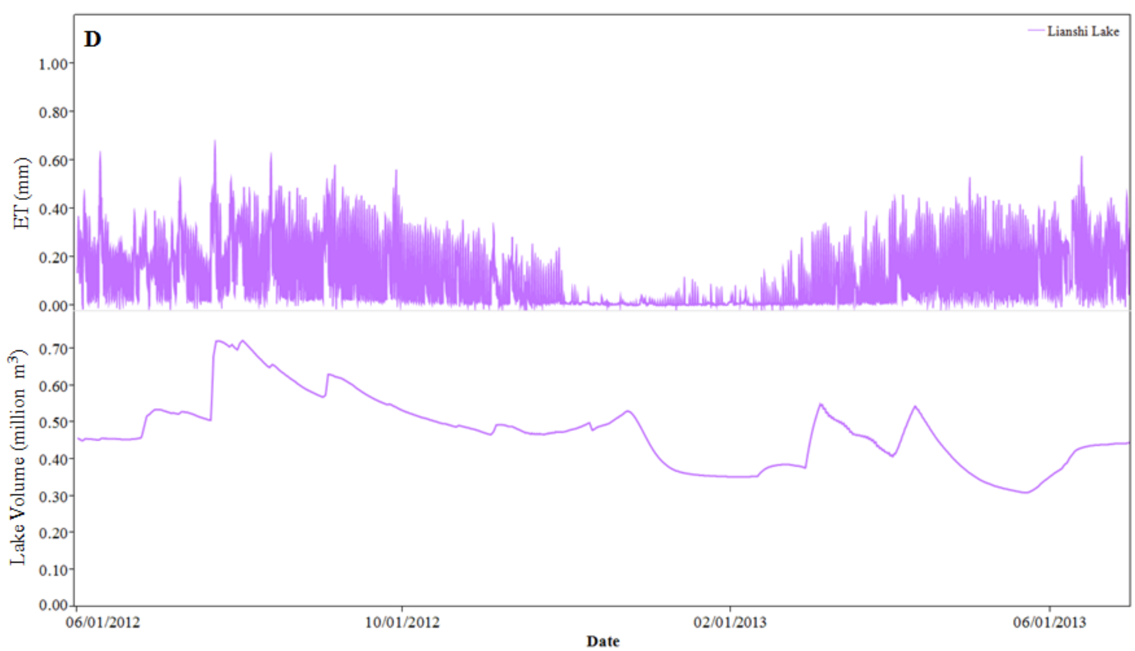


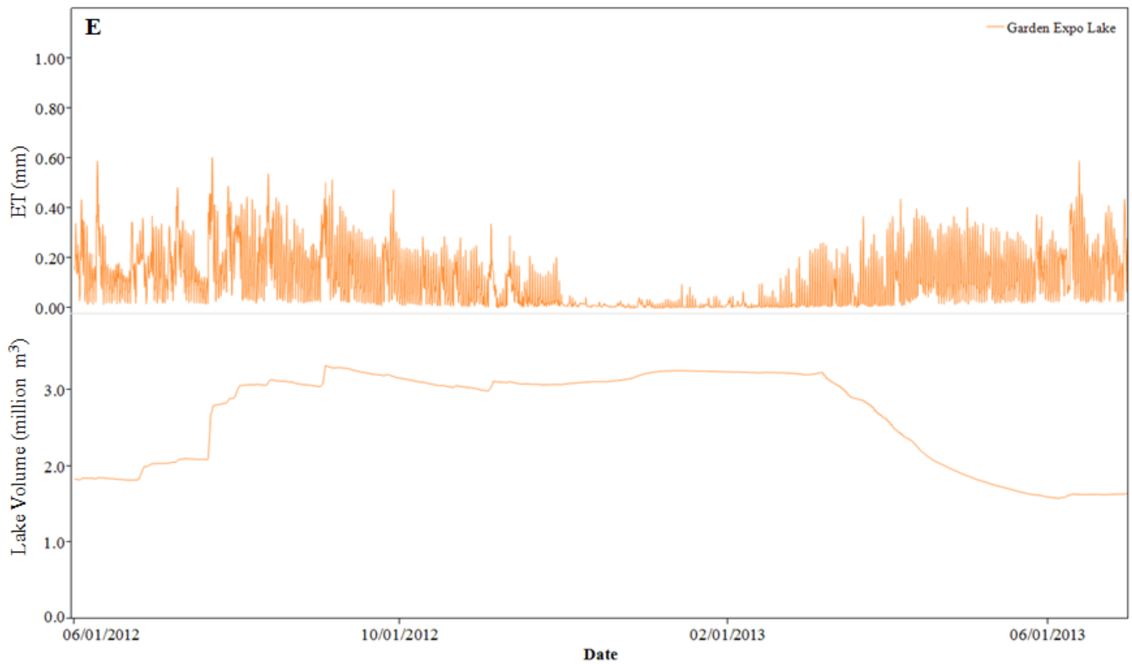
FIGURE 3. Diurnal cycle of regional mean hourly latent and sensible heat fluxes separated by season.

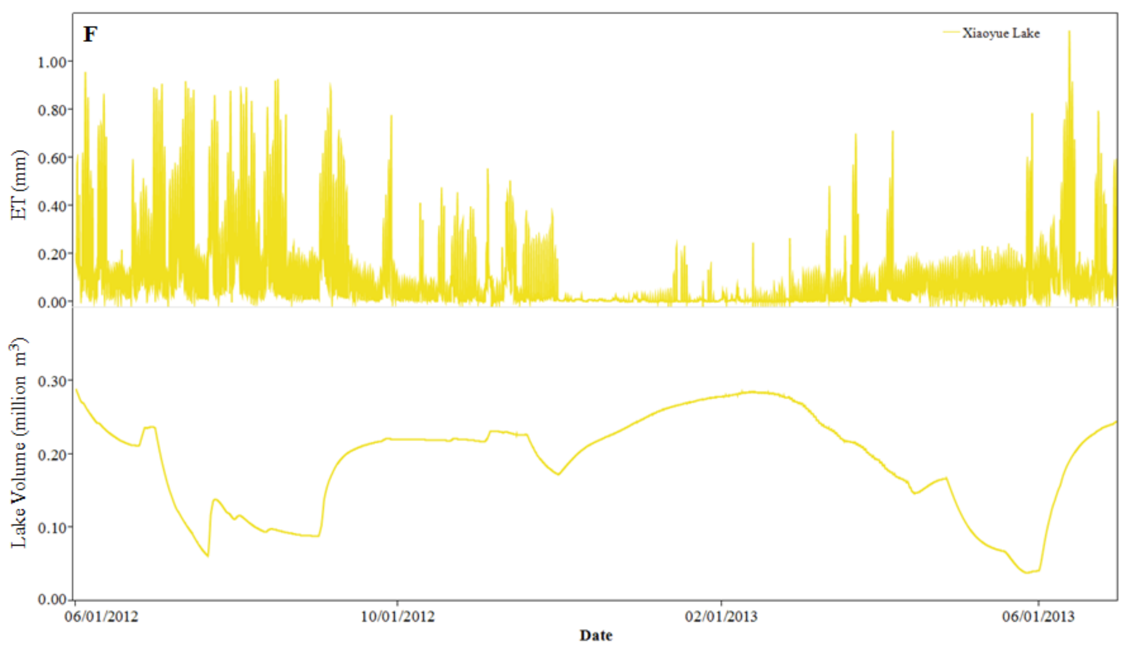

A
Pre Corridor
1.00
0.80
0.60
0.40
0.20
0.00
ET (mm)
Lake Volume (million m3)
06/01/2009
10/01/2009
02/01/2010
06/01/2010
Date

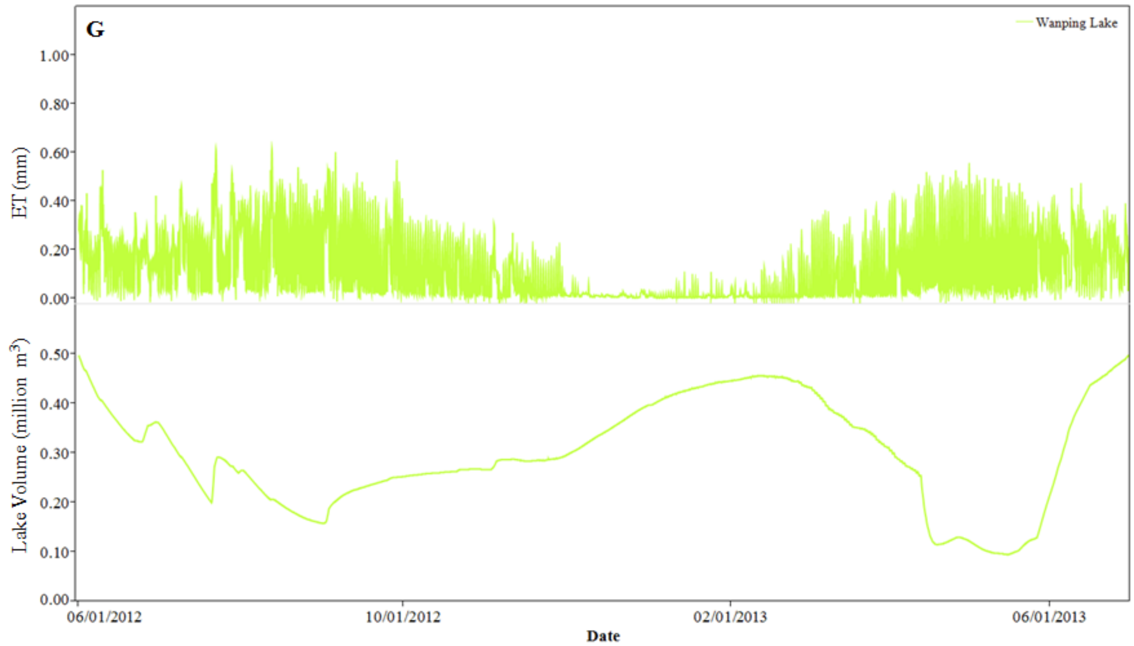

B
Mencheng Lake
1.00
0.80
0.60
0.40
0.20
0.00
ET (mm)
0.40
0.30
0.20
0.10
0.00
Lake Volume (million m3)
06/01/2012
10/01/2012
02/01/2013
06/01/2013
Date


C
Wetlands
ET (mm)
1.00
0.80
0.60
0.40
0.20
0.00
Lake Volume (million m³)
0.40
0.30
0.20
0.10
0.00
06/01/2012
10/01/2012
02/01/2013
06/01/2013
Date


D
Lianshi Lake
ET (mm)
1.00
0.80
0.60
0.40
0.20
0.00
Lake Volume (million m³)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
06/01/2012
10/01/2012
02/01/2013
06/01/2013
Date


E
Garden Expo Lake
ET (mm)
1.00
0.80
0.60
0.40
0.20
0.00
Lake Volume (million m³)
3.0
2.0
1.0
0.0
06/01/2012
10/01/2012
02/01/2013
06/01/2013
Date


F
Xiaoyue Lake
ET (mm)
1.00
0.80
0.60
0.40
0.20
0.00
Lake Volume (million m³)
0.30
0.20
0.10
0.00
06/01/2012
10/01/2012
02/01/2013
06/01/2013
Date



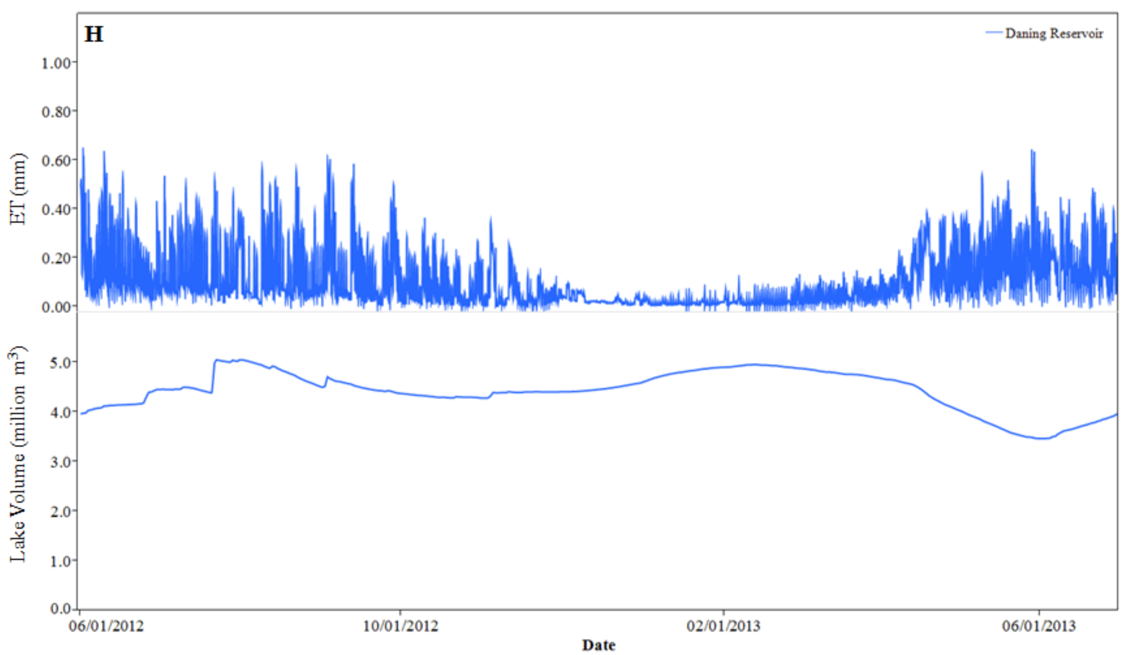


FIGURE 4. ET rates and lake volume at the local scale: (A) pre-Corridor, (B) Mencheng Lake, (C) wetlands, (D) Lianshi Lake, (E) Garden Expo Lake, (F) Xiaoyue Lake, (G) Wanping Lake, (H) Daning Reservoir.

MODEL EVALUATION

Model results were evaluated: (1) comparing VIC potential evapotranspiration rates (PET) to Penman-Monteith estimates and literature ET values for the Yongding River, and (2) comparing VIC net radiation to measured net radiation in Beijing.

The Penman-Monteith (P-M) equation:

$$\lambda ET_p = \frac{\frac{\Delta}{\gamma}(R_n - G) + \frac{\rho_a \lambda}{r_a}(q^*(T_a) - q_a)}{1 + \frac{\Delta}{\gamma} + \frac{r_s}{r_a}} \qquad (1)$$

where λ the latent heat of vaporization, R_n is the net radiation, G is the ground heat flux, Δ represents the Clausius-Clayperon relation, γ is the psychrometric constant, ρ_a is the air density, r_a is the aerodynamic resistance, q_a is the specific humidity in the air, $q^*(T_a)$ is the saturated specific humidity evaluated at the air temperature, T_a, and r_s is the stomatal resistance.

The VIC ET results were similar to P-M calculations and literature values. The mean VIC vegetation PET (PET_{veg}) was 717-841 mm and the P-M PET_{veg} was 776-859 mm, however the VIC water PET (PET_{water}) was lower than the P-M PET_{water} likely due to differences in albedo, surface roughness, and displacement values (Table 9). Next I compared the full Corridor VIC PET and ET results for the pre-Corridor period to Zhang et al. (2013) values. Zhang et al. (2013) calculated different PET values using the P-M and Priestly-Taylor equations, and concluded the 969 mm was representative of the

Yongding River in Beijing. Zhang et al. (2013) also estimated estimate a mean ET value from 1999-2009 for the Yongding Corridor, which was 494 mm similar to the VIC model estimate of 542 mm (Table 9).

TABLE 9. VIC potential evapotranspiration (PET) rates compared to Penman-Monteith (P-M) PET. Zhang et al. (2013) PET values using P-M and Priestly-Taylor, and measured ET for the Yongding River in Beijing for pre-Corridor conditions.

	VIC PET_{veg} (mm)	P-M PET_{veg} (mm)	VIC PET_{water} (mm)	P-M PET_{water} (mm)	VIC ET (mm)
Pre-Corridor	841	776	1467	1717	542
Post-Corridor	717	859	1416	2518	1088

Zhang et al. 2013				
	P-M PET_{veg} (mm)	P-M PET_{water}	Priestly-Taylor PET_{veg}	ET (mm) 1999-2009
Full Corridor	1100	1289	969	494

The VIC model was able to estimate the energy balance in Beijing evident in the similar diurnal and seasonal cycle between modeled and observed net radiation (Fig. 5). The pre-Corridor VIC hourly net radiation (R_n) values were compared to measured hourly R_n at the Chinese Academy of Sciences, Research Center for Eco-Environmental Sciences (RCEES). Mean modeled R_n was 53.18 W m^{-2} with standard deviation of 177.67; RCEES mean observed R_n was 53.53 W m^{-2} with standard deviation of 152.71. VIC model R_n was lower than the RCEES. The RCEES climate station is over 15km away, closer to the city center than the Yongding Corridor, thus it was expected that the RCEES R_n would be higher than the VIC R_n. Despite these differences the VIC model showed it was able to estimate the energy balance of the Beijing region.

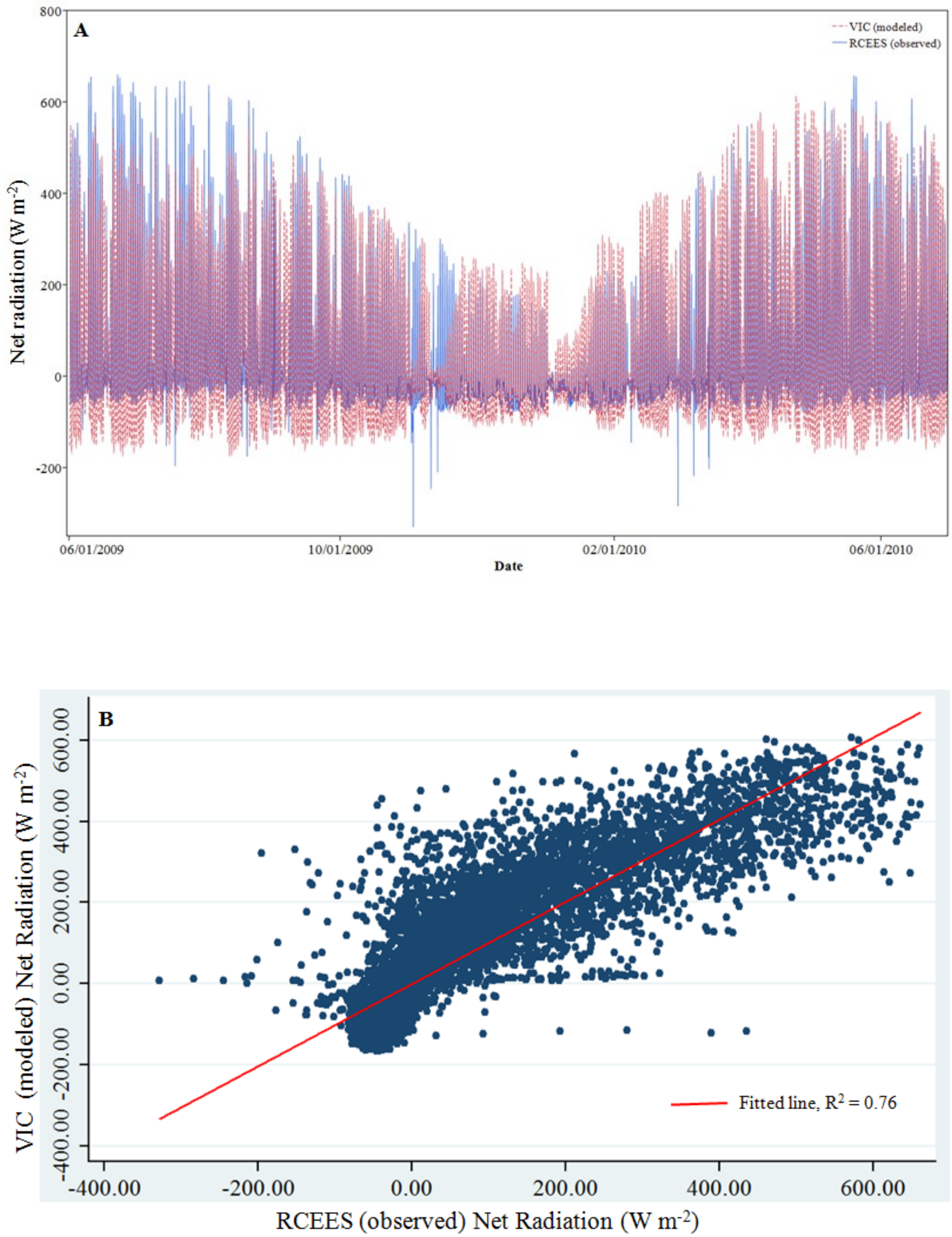


FIGURE 5. VIC modeled and RCEES observed net hourly radiation fluxes from 6/1/2009 to 6/30/2010 (A) time series and (B) fitted line.

SENSITIVITY ANALYSIS

A common approach to sensitivity analysis is to systematically vary model parameters one-by-one while keeping other parameters constant, thus allowing the modeler to identify parameters that have the most influence on model output responses (Larocque et al. 2008). It provides the analyst a means to assess the possible consequences of changing a given input parameter on model results (Hamby 1994). I decided to take a strategic approach to sensitivity analysis selecting parameters representing key ecosystem characteristics and management options known to influence ET and lake volume. The objective was to create a sensitivity ranking to assess the relative influence of these key input parameters on model output. A sensitivity ranking can be obtained quickly by increasing each parameter by a given percentage while leaving all others constant, and quantifying the change in model output. I ran eight simulations comparing the baseline to these scenarios: (1) 20% increase in albedo, (2) 20% decrease in albedo, (3) 20% increase in leaf area index (LAI), (4) 20% decrease in LAI, (5) 20% increase in precipitation, (6) 20% decrease in precipitation, (7) 20% increase in air temperature, and (8) 20% decrease in air temperature.

The sensitivity analysis suggests that evapotranspiration rates are more sensitive to climate variables than vegetation and soil variables (Tables 10-11). Overall the pre- and post-Corridor scenario results for ET matched baseline results evident in the high coefficients of determination, reflecting the goodness of fit between simulated results and baseline results. For the pre-Corridor the sensitivity ranking was: precipitation> temperature> LAI> albedo, for instance at the lakes scale the ± 20% change in precipitation led to an 231.4-308.9% change in mean hourly ET. However for the post-

Corridor it was: temperature>precipitation>LAI>albedo. The influence of temperature on ET was greatest for the wetlands (± 20% change in temperature led to 16.3-21.2% change in mean hourly ET), Xiaoyue Lake (± 20% change in temperature led to 17.0-22.9% change in mean hourly ET), and Daning Reservoir (± 20% change in temperature led to 20.4-27.5% change in mean hourly ET).

The sensitivity analysis suggests that lake volumes are on average more sensitive to climate variables than vegetation and soil variables (Table 12). However unlike ET, the scenario results for lake volume were not consistent across all grid cells. Overall the scenario results for lake volume did not deviate greatly from baseline results evident in the high coefficients of determination. Wetlands lake volume was highly sensitive under all the scenarios because it is the shallowest portion of the Yongding Corridor calibrated to reflect seasonal drying. The sensitivity analysis suggests when the lake volume of the wetlands is not consistently maintained they become increasingly sensitive to climatic, vegetation, and soil changes. The sensitivity ranking for Mencheng Lake, Lianshi Lake, Xiaoyue Lake, and Wanping Lake was: temperature> precipitation> LAI>albedo. The sensitivity ranking for the Garden Expo Lake, Daning Reservoir, and the Full Corridor was: precipitation>temperature>LAI> albedo. The sensitivity ranking for the wetlands was: albedo>precipitation> temperature>LAI.

TABLE 10. ET sensitivity statistics for eight scenarios under pre-Corridor conditions. From calibrated baseline conditions a: (1) 20% increase in albedo, (2) 20% decrease in albedo, (3) 20% increase in leaf area index (LAI), (4) 20% decrease in LAI, (5) 20% increase in precipitation, (6) 20% decrease in precipitation, (7) 20% increase in air temperature, and (8) 20% decrease in air temperature.

Pre-Conditions: Lakes									
	Baseline	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean	0.065	0.065	0.066	0.067	0.064	0.078	0.058	0.066	0.065
Std. dev.	0.100	0.099	0.102	0.101	0.098	0.106	0.094	0.105	0.096
R^2	---	0.997	0.996	0.999	0.996	0.948	0.965	0.971	0.963
RMSE	---	0.005	0.006	0.004	0.006	0.023	0.019	0.017	0.019
Average percent change (%)	---	2.1	1.9	77.3	3.5	552.8	16.7	231.4	308.9
Pre-Conditions: Full Corridor									
	Baseline	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean	0.061	0.061	0.062	0.062	0.060	0.072	0.055	0.061	0.116
Std. dev.	0.087	0.086	0.088	0.088	0.085	0.094	0.082	0.091	0.172
R^2	---	0.998	0.998	0.998	0.997	0.957	0.973	0.967	0.981
RMSE	---	0.004	0.004	0.003	0.005	0.018	0.143	0.016	0.012
Average percent change (%)	---	3.6	2.5	4.8	7.1	76.2	16.6	19.2	22.4

$Baseline_{ENG}$ = Engineering conditions

$Baseline_{Cal}$ = Calibrated conditions

Std. dev. = standard deviation; R^2 = coefficient of determination; RMSE = root mean square error

TABLE 11. ET sensitivity statistics for eight scenarios under post-Corridor conditions.

Post-Conditions: Mencheng Lake										
	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (mm hr^{-1})	0.115	0.121	0.119	0.123	0.128	0.113	0.125	0.116	0.120	0.124
Std. dev.	0.103	0.121	0.119	0.124	0.129	0.113	0.125	0.117	0.118	0.131
R^2	---	---	0.998	0.998	0.997	0.996	0.990	0.986	0.932	0.919
RMSE	---	---	0.006	0.005	0.006	0.008	0.012	0.014	0.032	0.035
Average percent change (%)	---	---	1.4	1.3	4.5	4.8	4.6	5.2	16.8	18.1

Post Conditions: Wetlands										
	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (mm hr^{-1})	0.127	0.133	0.131	0.146	0.141	0.125	0.146	0.122	0.132	0.140
Std. dev.	0.137	0.148	0.145	0.168	0.157	0.140	0.164	0.136	0.144	0.165
R^2	---	---	0.999	0.981	0.996	0.992	0.980	0.988	0.936	0.912
RMSE	---	---	0.005	0.021	0.009	0.014	0.021	0.016	0.037	0.044
Average percent change (%)	---	---	3.2	16.1	7.0	9.0	13.0	8.1	16.3	21.2

Post Conditions: Lianshi Lake										
	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (mm hr^{-1})	0.116	0.124	0.122	0.125	0.130	0.116	0.133	0.112	0.123	0.127
Std. dev.	0.105	0.126	0.123	0.128	0.133	0.117	0.136	0.114	0.123	0.135
R^2	---	---	0.999	0.999	0.996	0.996	0.992	0.988	0.937	0.926
RMSE	---	---	0.003	0.003	0.008	0.008	0.011	0.014	0.032	0.034
Average percent change (%)	---	---	1.1	1.1	4.7	4.6	6.5	7.0	15.3	16.9

Post Conditions: Garden Expo Lake										
	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (mm hr^{-1})	0.112	0.113	0.111	0.114	0.117	0.107	0.122	0.102	0.112	0.115
Std. dev.	0.106	0.110	0.108	0.112	0.115	0.105	0.119	0.100	0.109	0.116
R^2	---	---	0.998	0.998	0.997	0.995	0.986	0.975	0.932	0.924
RMSE	---	---	0.005	0.005	0.006	0.008	0.013	0.017	0.029	0.031
Average percent change (%)	---	---	2.4	2.2	4.2	5.2	9.5	9.9	17.4	18.2

Post Conditions: Xiaoyue Lake										
	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (mm hr^{-1})	0.093	0.104	0.102	0.105	0.108	0.099	0.107	0.099	0.102	0.106
Std. dev.	0.135	0.153	0.150	0.156	0.156	0.150	0.158	0.150	0.146	0.161
R^2	---	---	0.988	0.989	0.990	0.999	0.952	0.934	0.913	0.958
RMSE	---	---	0.017	0.016	0.005	0.006	0.034	0.039	0.045	0.031
Average percent change (%)	---	---	3.1	2.0	4.1	4.4	8.2	7.9	22.9	17.0

Post Conditions: Wanping Lake										
	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (mm hr^{-1})	0.111	0.127	0.125	0.129	0.134	0.118	0.132	0.120	0.126	0.130
Std. dev.	0.092	0.127	0.124	0.130	0.135	0.117	0.133	0.119	0.124	0.136
R^2	---	---	0.999	1.000	0.997	0.995	0.996	0.995	0.927	0.915
RMSE	---	---	0.003	0.003	0.007	0.009	0.008	0.009	0.034	0.037
Average percent change (%)	---	---	1.1	1.1	4.6	4.8	4.0	5.0	15.8	17.3

Post Conditions: Daning Reservoir										
	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (mm hr^{-1})	0.101	0.106	0.105	0.106	0.107	0.104	0.116	0.107	0.106	0.104
Std. dev.	0.117	0.111	0.111	0.111	0.111	0.110	0.106	0.110	0.117	0.102
R^2	---	---	0.999	0.999	0.999	0.999	0.906	0.999	0.872	0.840
RMSE	---	---	0.001	0.001	0.003	0.003	0.034	0.004	0.040	0.044
Average percent change (%)	---	---	0.6	1.7	2.1	3.3	30.7	6.9	20.4	27.5

Post-Conditions: Full Corridor										
	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (mm hr^{-1})	0.127	0.127	0.125	0.128	0.131	0.121	0.134	0.113	0.124	0.131
Std. dev.	0.153	0.153	0.150	0.157	0.160	0.145	0.159	0.146	0.146	0.168
R^2	---	---	0.997	0.997	0.996	0.996	0.983	0.973	0.948	0.944
RMSE	---	---	0.009	0.009	0.010	0.009	0.020	0.025	0.035	0.036
Average percent change (%)	---	---	2.1	2.1	4.9	4.7	11.7	13.5	18.6	16.4

$Baseline_{ENG}$ = Engineering conditions

$Baseline_{Cal}$ = Calibrated conditions

Std. dev. = standard deviation; R^2 = coefficient of determination; RMSE = root mean square error

TABLE 12. Lake volume (m^3) statistics for eight scenarios under post-Corridor conditions.

Post-Conditions: Mencheng Lake

	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (m^3)	4.70E+05	3.11E+05	3.11E+05	3.11E+05	3.10E+05	3.13E+05	3.17E+05	3.06E+05	3.04E+05	3.23E+05
Std. dev.	7.69E+04	8.77E+04	8.76E+04	8.77E+04	8.78E+04	8.85E+04	8.81E+04	8.53E+04	8.12E+04	9.47E+04
R^2	---	---	1.00	1.00	1.00	1.00	0.99	0.99	0.95	0.87
RMSE	---	---	1.10E+02	1.18E+02	4.18E+02	3.15E+03	8.58E+03	7.84E+03	1.97E+04	3.15E+04
Average percent change (%)	---	---	0.11	0.11	0.39	0.99	2.55	2.12	5.13	11.29

Post Conditions: Wetlands

	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (m^3)	3.51E+05	1.45E+05	1.46E+05	8.51E+04	1.40E+05	1.47E+05	1.55E+05	1.26E+05	1.44E+05	1.40E+05
Std. dev.	1.09E+05	1.43E+05	1.44E+05	1.03E+05	1.41E+05	1.48E+05	1.72E+05	1.23E+05	1.44E+05	1.47E+05
R^2	---	---	1.00	0.12	0.98	0.89	0.79	0.96	0.97	0.75
RMSE	---	---	7.06E+03	1.30E+05	2.04E+04	4.83E+04	6.55E+04	2.82E+04	2.60E+04	7.10E+04
Average percent change (%)	---	---	9.1E+07	2.9E+10	5.8E+02	2.1E+09	4.2E+09	3.8E+01	2.0E+03	3.1E+09

Post Conditions: Lianshi Lake

	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (m^3)	1.02E+06	4.75E+05	4.75E+05	4.75E+05	4.74E+05	4.77E+05	4.84E+05	4.67E+05	4.64E+05	4.86E+05
Std. dev.	1.63E+05	9.42E+04	9.43E+04	9.41E+04	9.39E+04	9.46E+04	1.04E+05	8.52E+04	9.91E+04	9.07E+04
R^2	---	---	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.97
RMSE	---	---	2.40E+02	2.50E+02	8.91E+02	1.02E+03	5.98E+03	6.88E+03	1.31E+04	1.63E+04
Average percent change (%)	---	---	0.08	0.09	0.30	0.35	1.65	1.34	2.55	2.80

Post Conditions: Garden Expo Lake

	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (m^3)	2.92E+06	2.68E+06	2.68E+06	2.68E+06	2.66E+06	2.73E+06	2.89E+06	2.49E+06	2.64E+06	2.74E+06
Std. dev.	4.58E+05	6.19E+05	6.22E+05	6.22E+05	6.21E+05	6.15E+05	6.77E+05	5.66E+05	6.21E+05	6.13E+05
R^2	---	---	1.00	1.00	1.00	0.99	0.98	0.98	0.99	0.97
RMSE	---	---	1.68E+04	1.47E+04	1.22E+04	6.03E+04	9.74E+04	7.94E+04	5.60E+04	1.00E+05
Average percent change (%)	---	---	0.42	0.50	0.74	1.84	7.58	7.14	1.84	2.77

Post Conditions: Xiaoyue Lake										
	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (m^3)	4.15E+05	1.92E+05	1.92E+05	1.92E+05	1.92E+05	1.92E+05	1.94E+05	1.91E+05	1.88E+05	1.97E+05
Std. dev.	6.14E+04	6.59E+04	6.58E+04	6.59E+04	6.60E+04	6.57E+04	6.57E+04	6.60E+04	6.35E+04	6.83E+04
R^2	---	---	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99
RMSE	---	---	4.55E+01	4.48E+01	1.60E+02	1.87E+02	2.37E+03	2.30E+03	6.92E+03	6.18E+03
Average percent change (%)	---	---	0.05	0.05	0.19	0.22	1.24	1.13	2.10	2.26

Post Conditions: Wanping Lake										
	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (m^3)	6.28E+05	3.02E+05	3.02E+05	3.02E+05	3.02E+05	3.03E+05	3.06E+05	2.99E+05	2.96E+05	3.09E+05
Std. dev.	9.20E+04	1.06E+05	1.05E+05	1.06E+05	1.06E+05	1.05E+05	1.06E+05	1.05E+05	1.01E+05	1.10E+05
R^2	---	---	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.96
RMSE	---	---	8.42E+01	8.40E+01	2.99E+02	3.49E+02	4.60E+03	4.58E+03	1.70E+04	2.04E+04
Average percent change (%)	---	---	0.1	0.1	0.3	0.3	1.4	1.4	3.2	4.9

Post Conditions: Daning Reservoir										
	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (m^3)	4.84E+06	4.43E+06	4.43E+06	4.43E+06	4.43E+06	4.44E+06	3.41E+06	4.36E+06	4.40E+06	4.43E+06
Std. dev.	2.59E+05	4.01E+05	4.01E+05	4.01E+05	4.02E+05	4.00E+05	5.15E+05	3.72E+05	3.99E+05	4.30E+05
R^2	---	---	1.00	1.00	1.00	1.00	0.62	0.99	0.99	0.98
RMSE	---	---	2.65E+02	2.43E+02	8.47E+02	9.83E+02	2.50E+05	4.41E+04	4.28E+04	5.31E+04
Average percent change (%)	---	---	0.0	0.0	0.0	0.0	23.3	1.6	0.9	1.0

Post-Conditions: Full Corridor										
	$Baseline_{ENG}$	$Baseline_{Cal}$	+20% Albedo	-20% Albedo	+20% LAI	-20% LAI	+20% Prec.	-20% Prec.	+20% Temp.	-20% Temp.
Mean (m^3)	1.02E+07	6.96E+06	6.97E+06	6.93E+06	6.83E+06	7.09E+06	7.52E+06	6.42E+06	6.78E+06	7.09E+06
Std. dev.	1.66E+06	2.83E+06	2.84E+06	2.82E+06	2.79E+06	2.87E+06	3.27E+06	2.42E+06	2.87E+06	2.70E+06
R^2	---	---	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99
RMSE	---	---	2.47E+04	1.59E+04	6.95E+04	8.10E+04	2.30E+05	3.20E+05	2.10E+05	2.50E+05
Average percent change (%)	---	---	0.5	0.6	2.4	2.4	7.1	6.7	3.8	5.0

APPENDIX C

ECOLOGICAL PRODUCTION FUNCTIONS

I created ordinary least squares (OLS) regressions using Stata 12.1 software. I conducted the five steps below to select the ecological production functions listed in Chapters 5-7. For Chapter 8 the steps were modified for an ordinal logistic regression model (described in the aesthetic subsection below). The following steps for the OLS regressions were:

1. Evaluated the correlation matrices for all variables to minimize multicollinearity between input variables, which can bias interpretation of marginal changes.

2. Created OLS regressions using different combinations of the variables known to have a causal relationship with the final service indicator. For each ecosystem service, I was looking to balance efficiency using few ecosystem characteristic metrics while not minimizing precision, and reducing multicollinearity.

3. After selecting possible regression models, I used the Ramsey RESET test, which is a general specification test for the linear regression model. It specifically tests whether non-linear combinations of the fitted values help explain the response variable and/or if there are important explanatory variables missing. The Ramsey RESET test was used to determine if the model demonstrates significant variables that likely have strong explanatory power.

4. Next a link test was applied, which looks for a specific type of error called a link error where a dependent variable needs to be transformed (linked) to accurately relate to the independent variable. The link test adds the squared independent variable to the model and tests for significance versus the non-squared model. A model without a link error will have a non-significant t-test versus the un-squared version.

5. I evaluated for homoskedasticity, meaning the error term has the same variance, by checking residuals. The Breusch-Pagan test was used to test for heteroscedasticity in the linear regression models. It tests whether the estimated variance of the residuals from a regression are dependent on the values of the independent variables. If the test showed the presence of heteroskedastic errors than robust standard errors were used.

6. I evaluated the severity of multicollinearity in each model using the variance inflation factor (VIF), which provides an index that measures how much the variance of an estimated regression coefficient is increased because of collinearity. A low VIC of less than 10 suggests that multicollinearity is not a problem.

WATER STORAGE

To evaluate water efficiency of the lakes/wetlands I created an ecological production function relating the surface water area: volume ratio to water loss:

$$logWaterLoss = \beta_0 + \beta_1 logSA\_V + \varepsilon \tag{1}$$

where β_0 is the constant (y intercept), β_1 is the marginal effect (regression coefficient) of surface water area (hectares): lake volume (million m^3) noted as *SA_V* on the final service indicator – annual water loss (evapotranspiration (m^3): lake volume (m^3)) noted as *WaterLoss*, and ε is the error term. The y and x variables were logarithmically transformed, thus a semi-log relationship was used to create an OLS regression. Using the logarithm of one or more variables instead of the un-logged form makes the effective relationship non-linear, while still preserving the linear model. Economists commonly use the log-log transformation to interpret marginal effects of non-linear relationships. Also note I used *natural* logarithms (the base is *e* approx. 2.71828).

First I determined the relationship between the variables shown in Fig. 1. I then conducted a log transformation on *SA_V* and *WaterLoss* resulting in a linear relationship, which is shown in Fig. 2. I ran the regression, and present the statistics of the ecological production function in Table 1.

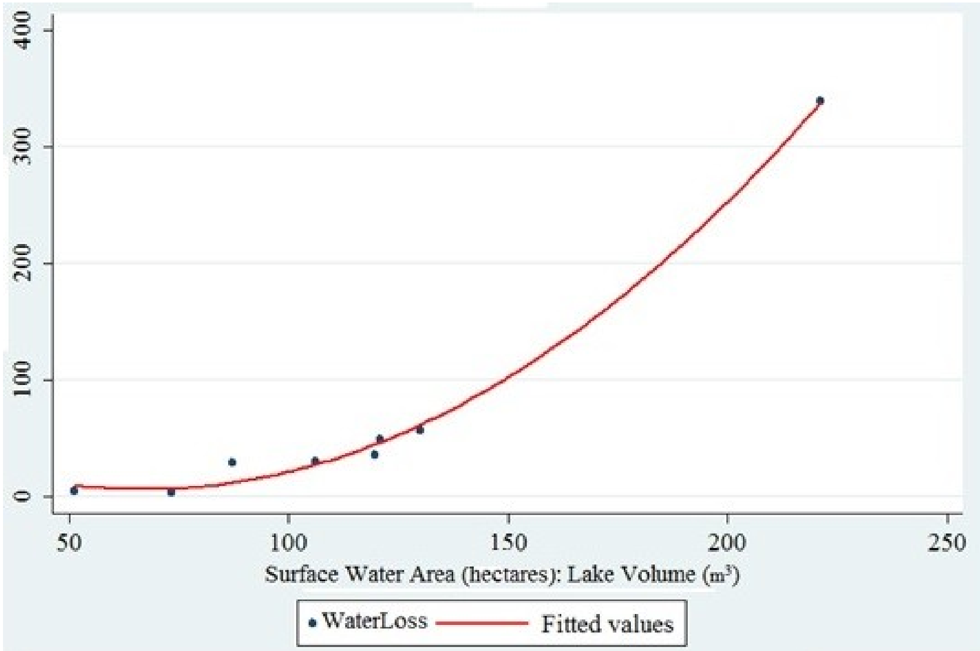


FIG. 1. Power-law relationship between water efficiency and surface area: volume ratio.

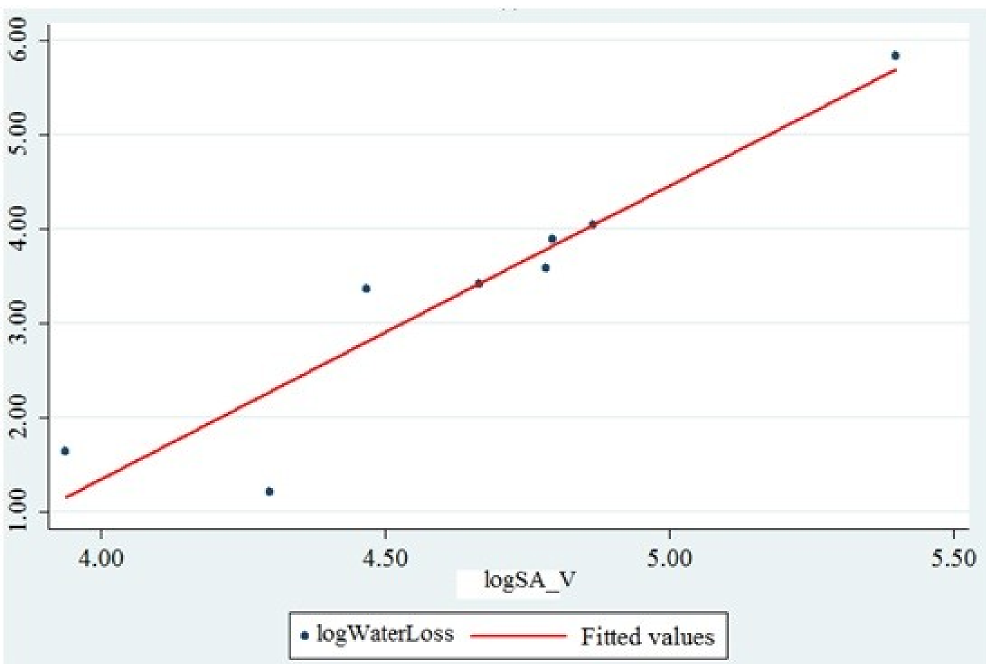


FIG. 2. Linear relationship between log transformed water efficiency and log transformed surface area: volume ratio.

TABLE 1. Regression statistics of the ecological production function for water loss.

	R^2	RMSE	Coefficients (Marginal Changes)			
			logSA_V	95% CI	constant (β_0)	95% CI
logWaterLoss	0.88	0.54	3.11* (0.47)	1.96 - 4.57	-11.09* (2.35)	-16.84 - -5.35

*P<0.05 in parenthesis below coefficient is the standard error
R^2 is coefficient of determination, RMSE is root mean squared error, CI is the 95% confidence interval

LOCAL CLIMATE REGULATION

To evaluate the influence of the ecosystems on summer human comfort, I created ecological production functions for each lake and wetland relating three modeled ecosystem characteristics (ET (mm), sensible heat flux (W m^{-2}), and pressure (kPa)) to measured final service indicators (air temperature (°C) and heat index):

$$Temperature = \beta_0 + \beta_1 ET + \beta_2 Sensible + \beta_3 Pressure + \varepsilon \quad (2)$$

$$Comfort = \beta_0 + \beta_1 ET + \beta_2 Sensible + \beta_3 Pressure + \varepsilon \quad (3)$$

where β_0 is the constant (y intercept), β_1 is the marginal effect (regression coefficient) of *ET* on the final service indicator (*T* (air temperature) or *Comfort* (heat index)), β_2 is the marginal effect *Sensible* on the final service indicator, β_3 is the marginal effect of *Pressure* on the final service indicator, and ε is the error term.

TABLE 2. Correlation matrix

	T	Comfort	RH	ET	Sensible	Pressure
T	1.00					
Comfort	0.98	1.00				
RH	-0.17	-0.25	1.00			
ET	0.63	0.63	-0.05	1.00		
Sensible	0.39	0.36	-0.27	0.49	1.00	
Pressure	0.98	0.97	-0.13	0.64	0.39	1.00

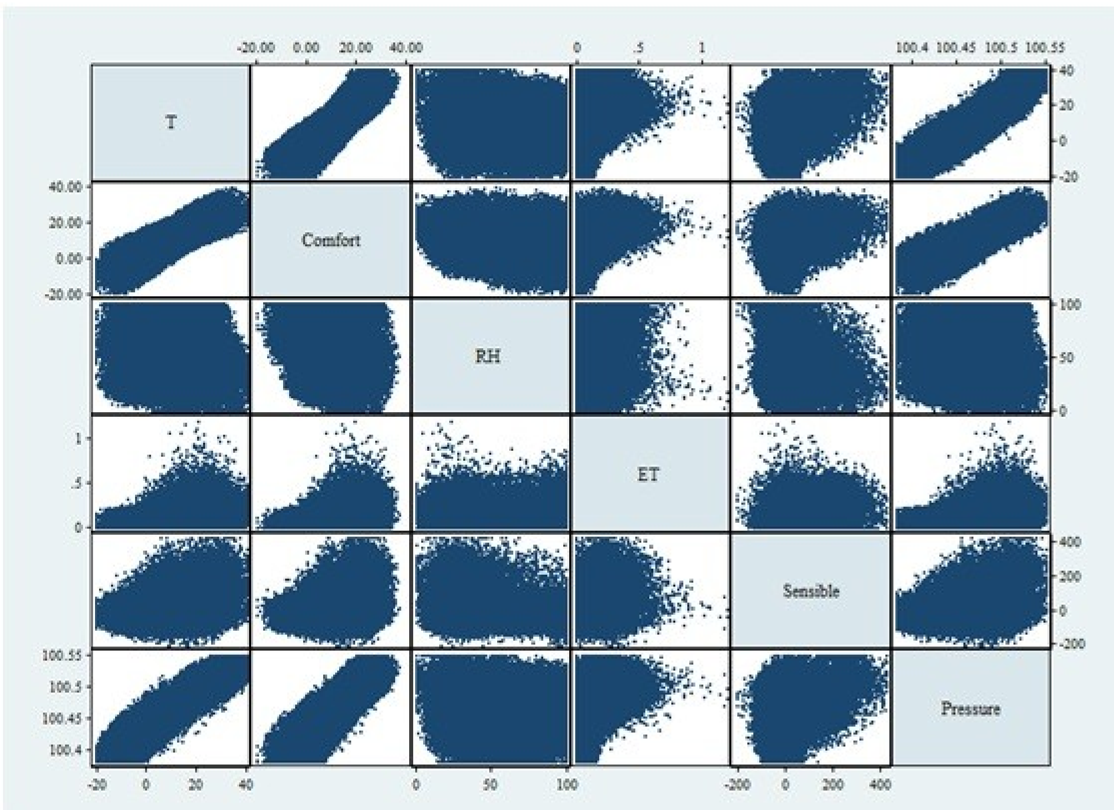


FIG.3. Scatter plots between the output and input variables.

I used the diagnostic tools (described above) to select the input variables known to influence air temperature and relative humidity, but lower correlation to ET (Table 2, Fig.3). Next I evaluated the relationship between ET and air temperature and human comfort for the time series of 11/9/2012 to 6/30/2013. However ET on average was positively associated with air temperature and human comfort because the majority of the days in the dataset are in the winter and spring, thus the cooling effect was not detected. Hence I decided to analyze summer daytime and nighttime air temperatures, and associated impacts on human comfort via the heat index. Presented are the summer nighttime graphs, however daytime showed the same relationships. First I graphed the general relationships between air temperature and ET (Figs. 4-8) then ran the respective regressions. The regression statistics from the OLS regressions are presented for summer daytime in Table 3 and summer nighttime in Table 4.

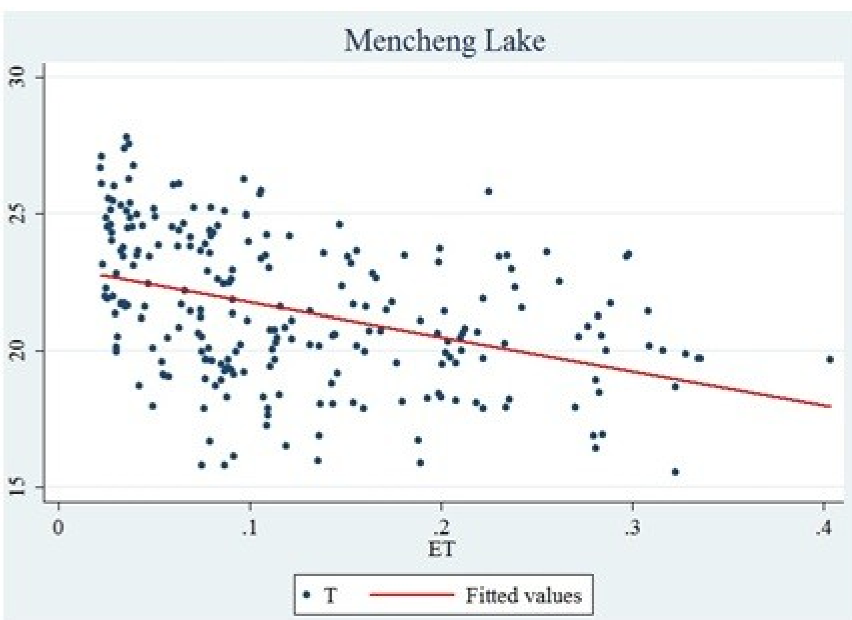


FIG. 4. Fitted line relating hourly measured summer nighttime air temperature (°C) to modeled hourly ET at Mencheng Lake.

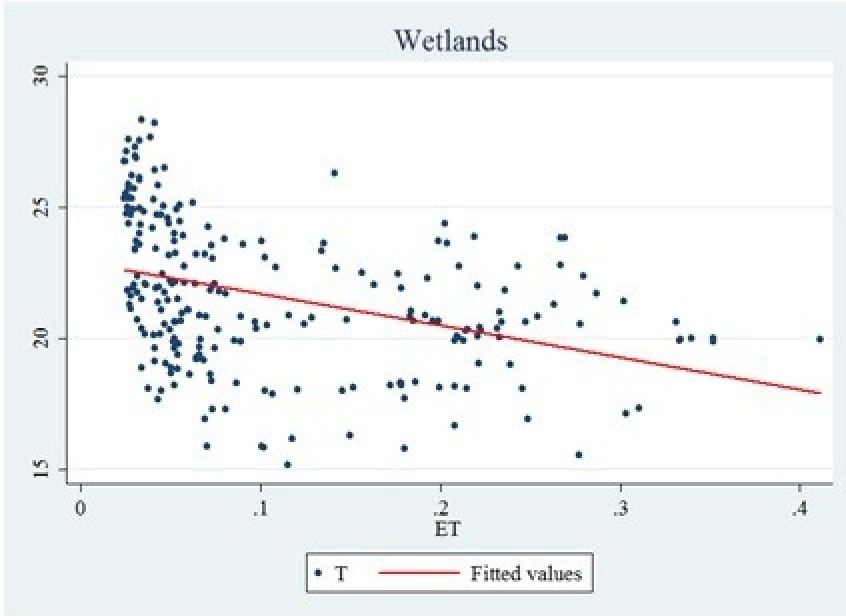


FIG. 5. Fitted line relating hourly measured summer nighttime air temperature (°C) to modeled hourly ET at Wetlands.

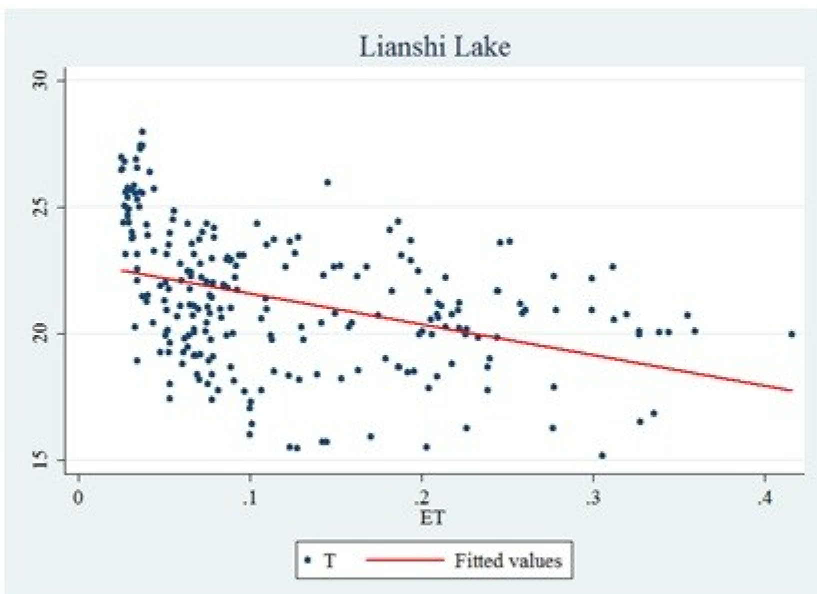


FIG. 6. Fitted line relating hourly measured summer nighttime air temperature (°C) to modeled hourly ET at Lianshi Lake.

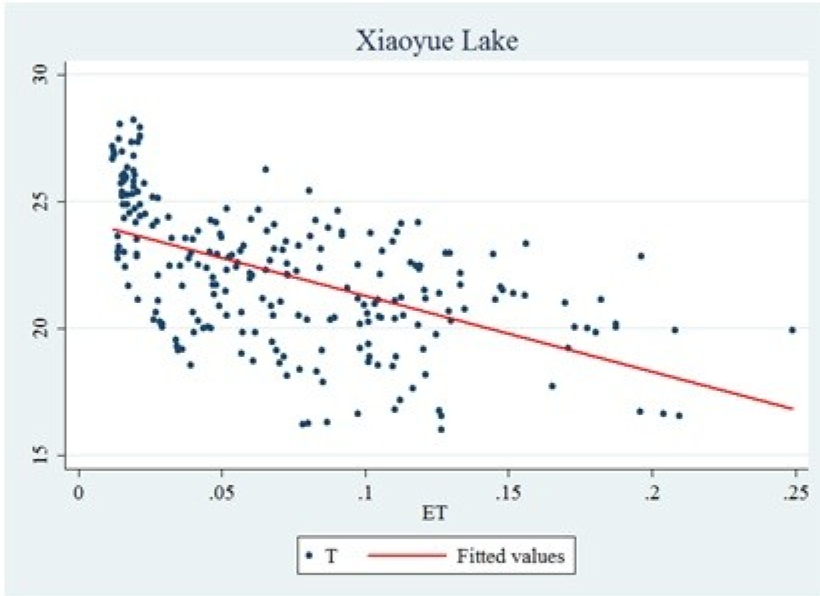


FIG. 7. Fitted line relating hourly measured summer nighttime air temperature (°C) to modeled hourly ET at Xiaoyue Lake.

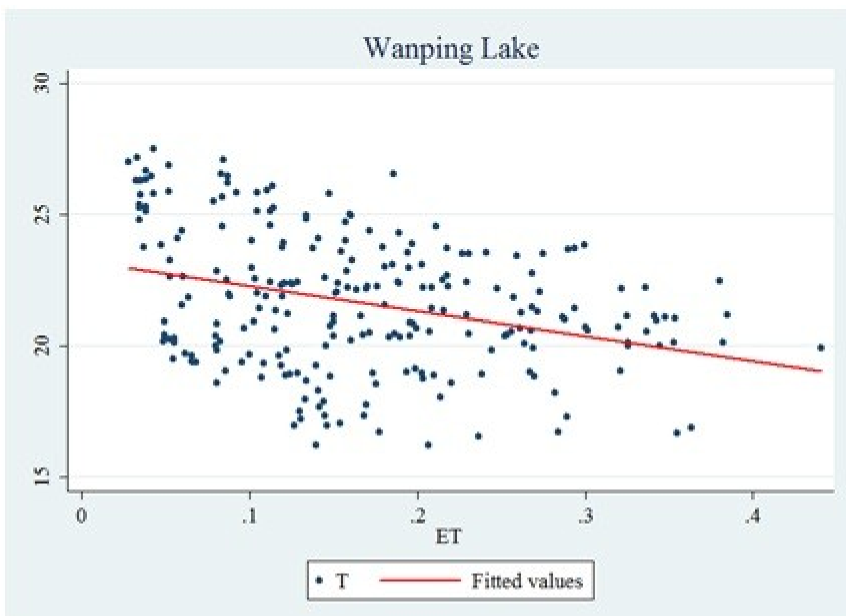


FIG. 8. Fitted line relating hourly measured summer nighttime air temperature (°C) to modeled hourly ET at Wanping Lake.

TABLE 3. Regression statistics of each ecological production function for June 2013 daytime air temperature.

Lake	R^2	RMSE	Coefficients (Marginal Changes)							
			ET	95% CI	Sensible	95% CI	Pressure	95% CI	constant (β_0)	95% CI
Mencheng Lake	0.88	1.73	0.01 (0.59)	-1.17- 1.14	-0.004* (0.001)	-0.007- -0.001	452* (9)	433- 470	-45386* (935)	-47223- -43549
Wetlands	0.89	1.63	-3.78* (0.55)	-4.87- -2.69	-0.00004 (0.0009)	-0.002- 0.002	420* (9)	403- 437	-42192* (870)	-43900- -40483
Lianshi Lake	0.87	1.70	-4.70* (0.70)	-6.07- -3.32	-0.004* (0.001)	0.002- 0.006	388* (9)	371- 406	-39018* (911)	-40807- -37229
Xiaoyue Lake	0.83	1.99	-1.20* (0.34)	-1.87- -0.53	-0.004* (0.0009)	-0.005- -0.002	422* (8)	406- 438	-42403* (805)	-43985- -40820
Wanping Lake	0.87	1.78	-8.39* (0.86)	-10.07- -6.70	0.009* (0.002)	0.005- 0.013	390* (10)	371- 409	-39166* (986)	-41104 - -37229

*P<0.05 in parenthesis below coefficient is the standard error

R^2 is coefficient of determination, RMSE is root mean squared error, CI is the 95% confidence interval

TABLE 4. Regression statistics of each ecological production function for June 2013 nighttime air temperature.

Lake	R^2	RMSE	Coefficients (Marginal Changes) ET	95% CI	Sensible	95% CI	Pressure	95% CI	constant (β_0)	95% CI
Mencheng Lake	0.84	1.07	-5.42* (0.88)	-7.16- -3.68	-0.02* (0.01)	-0.03- -.003	324* (9)	306- 342	-32595* (916)	-34399- -30790
Wetlands	0.87	1.00	-7.54* (0.93)	-9.37- -5.71	-.0.02* (0.004)	-0.03- -0.01	340* (8)	325- 357	-34233* (825)	-35860- -32606
Lianshi Lake	0.89	0.90	-6.52* (0.83)	-8.15- -4.89	-0.02* (0.004)	-0.03- -0.01	332* (8)	315- 348	-33345* (824)	-34969- -31721
Xiaoyue Lake	0.85	1.05	-15.95* (1.66)	-19.22- -12.69	-0.06* (0.01)	-0.09- -0.03	308* (10)	288- 328	-30945* (1033)	-32980- -28910
Wanping Lake	0.87	0.93	-7.53* (0.79)	-9.09- -5.97	-0.03* (0.008)	-0.04- -0.01	323* (8)	308- 339	-32459* (792)	-34019- -30899

*$P<0.05$ in parenthesis below coefficient is the standard error

R^2 is coefficient of determination, RMSE is root mean squared error, CI is the 95% confidence interval

Next I graphed heat index values and ET to visually inspect the potential cooling effect on summer nighttime human comfort presented in Figs. 9-13. Next I ran the regressions, and present the statistics of the ecological production functions summer daytime in Table 5 and nighttime in Table 6.

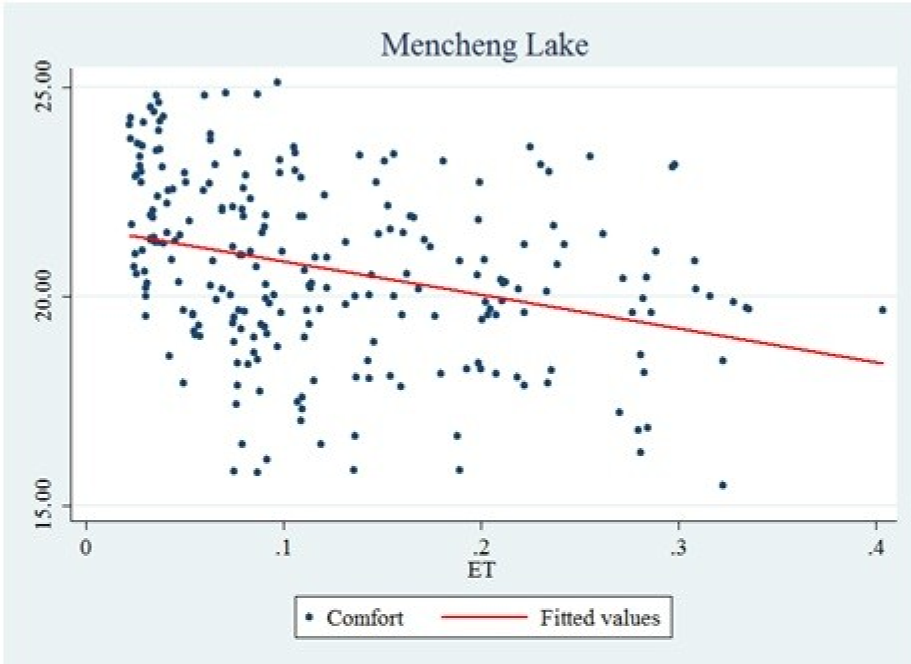


FIG. 9. Fitted line relating summer nighttime hourly calculated heat index to modeled hourly ET at Mencheng Lake.

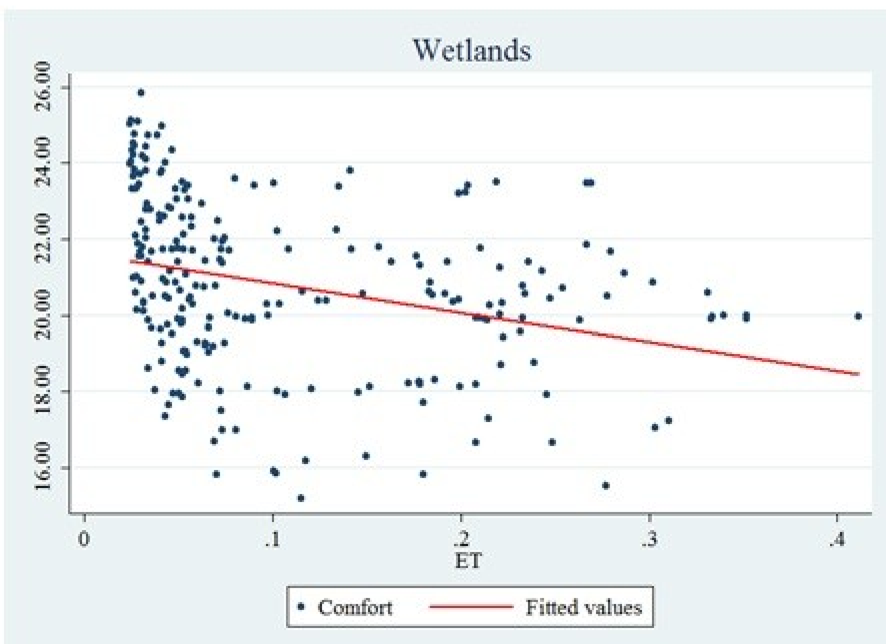


FIG. 10. Fitted line relating summer nighttime hourly calculated heat index to modeled hourly ET at Wetlands.

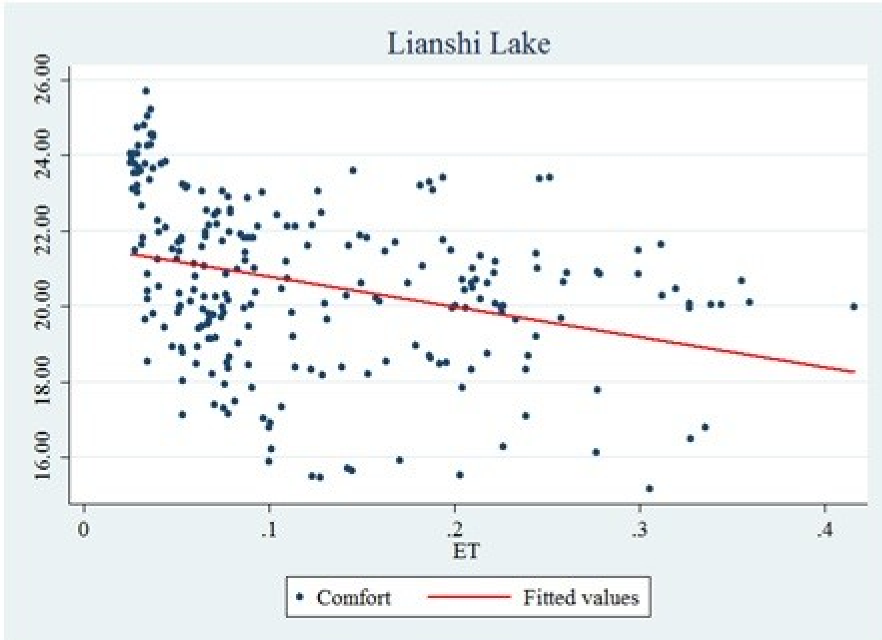


FIG. 11. Fitted line relating summer nighttime hourly calculated heat index to modeled hourly ET at Lianshi Lake.

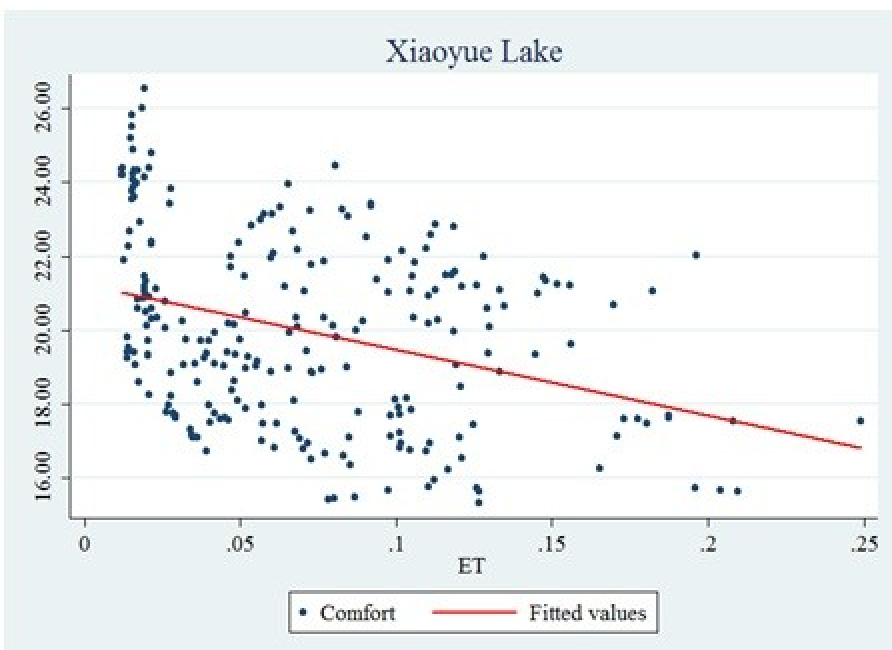


FIG. 12. Fitted line relating summer nighttime hourly calculated heat index to modeled hourly ET at Xiaoyue Lake.

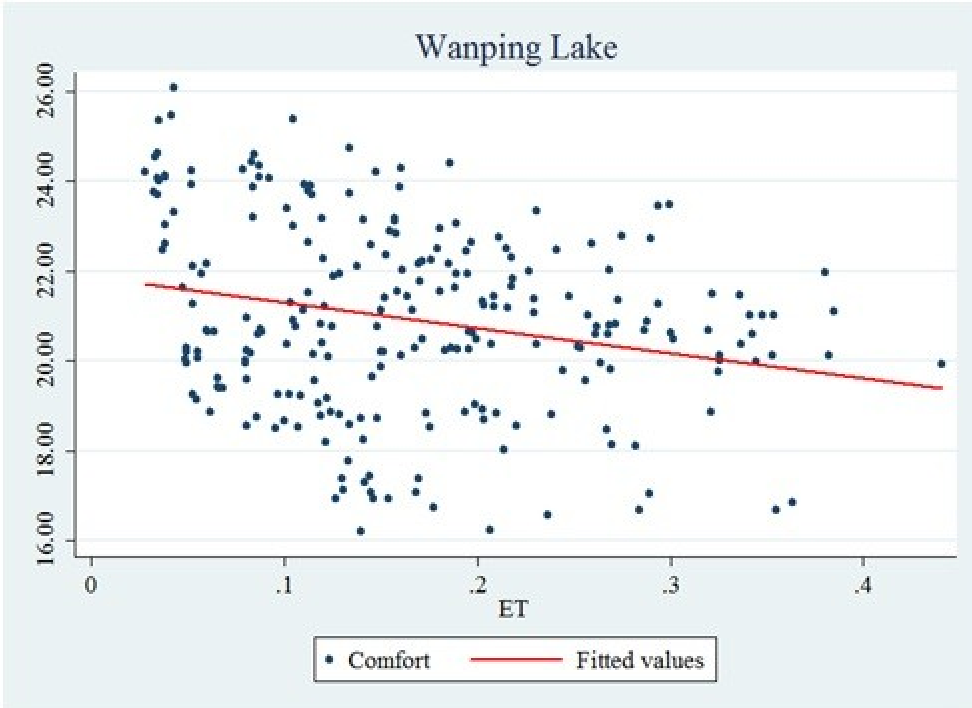


FIG. 13. Fitted line relating summer nighttime hourly calculated heat index to modeled hourly ET at Wanping Lake.

TABLE 5. Regression statistics of each ecological production function for June 2013 daytime human comfort using the heat stress index values.

Lake	R^2	RMSE	Coefficients (Marginal Changes)							
			ET	95% CI	Sensible	95% CI	Pressure	95% CI	constant (β_0)	95% CI
Mencheng Lake	0.84	1.25	-0.67 (0.46)	-1.57-0.24	-0.003* (0.001)	-0.005--0.0004	279* (7)	265-294	-28076* (729)	-29509--26644
Wetlands	0.84	1.17	-2.37* (0.48)	-3.31--1.43	-0.0009 (0.0008)	-0.002-0.0006	252* (7)	238-266	-25309* (694)	-26673--23945
Lianshi Lake	0.82	1.24	-3.36* (0.58)	-4.49--2.22	0.0015 (0.0009)	-0.0002-0.003	229* (7)	215-243	-22993* (715)	-24398--21587
Xiaoyue Lake	0.75	1.80	-1.00 (0.29)	-1.58--0.43	-0.004* (0.0009)	-0.006--0.002	308* (8)	292-324	-30907* (826)	-32530--29285
Wanping Lake	0.84	1.25	-6.44* (0.65)	-7.72--5.17	0.004* (0.001)	0.001 - 0.007	235* (7)	221-250	-23618* (741)	-25075--22162

*P<0.05 in parenthesis below coefficient is the standard error

R^2 is coefficient of determination, RMSE is root mean squared error, CI is the 95% confidence interval

TABLE 6. Regression statistics of each ecological production function for June 2013 nighttime human comfort using the heat stress index values.

	R^2	RMSE	Coefficients (Marginal Changes)							
			ET	95% CI	Sensible	95% CI	Pressure	95% CI	constant (β_0)	95% CI
Mencheng Lake	0.85	0.83	-2.24* (0.75)	-3.71--0.77	-0.02* (0.01)	-0.03--0.002	268* (8)	252-284	-26930* (835)	-28575--25284
Wetlands	0.88	0.76	-4.60* (0.62)	-5.82--3.38	-0.02* (0.003)	-0.03--0.01	279* (8)	264-294	-28000* (765)	-29507--26494
Lianshi Lake	0.87	0.80	-4.41* (0.71)	-5.81--3.00	-0.02* (0.004)	-0.03--0.01	275* (8)	259-291	-27672* (818)	-29283--26061
Xiaoyue Lake	0.79	1.17	-1.22 (1.80)	-4.77--2.32	-0.03* (0.01)	-0.05--0.004	315* (11)	293-337	-31641* (1132)	-33871--29411
Wanping Lake	0.87	0.76	-4.50* (0.66)	-5.80--3.20	-0.03* (0.007)	-0.04--0.02	272* (7)	258-287	-27357* (742)	-28820--25893

*P<0.05 in parenthesis below coefficient is the standard error

R^2 is coefficient of determination, RMSE is root mean squared error, CI is the 95% confidence interval

WATER PURIFICATION

To evaluate water purification, I created ecological production functions relating wetland area and nutrient loading to TN and TP at Lianshi Lake:

$$LianshiLake = \beta_0 + \beta_1 Area + \beta_2 Loading + \varepsilon \quad (4)$$

where β_0 is the constant (y intercept), β_1 and β_2 are the marginal effect (regression coefficient) of wetland area (ha) noted as *Area* on Lianshi Lake final service indicators (i.e., total nitrogen and total phosphorus concentrations) noted as *LianshiLake*, and ε is the error term. The relationships between the TN and TP and wetland area were inspected using a scatter plot and fitted lines, which are shown in Fig. 14 for TN and Fig. 15 for TP. The relationships between nutrient loading and TN and TP were inspected using a scatter plot and fitted lines, which are shown in Fig. 16 for TN and Fig. 17 for TP. I ran the regressions, and present the statistics in Table 7.

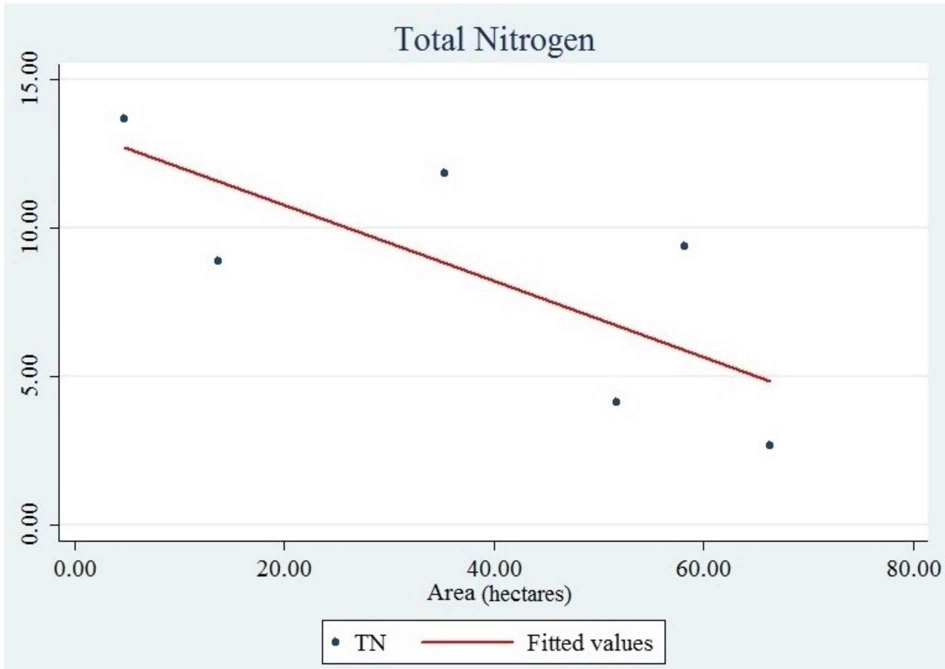


FIG. 14. Fitted line relating wetland area (hectares) and total nitrogen (mg/L) of Lianshi Lake.

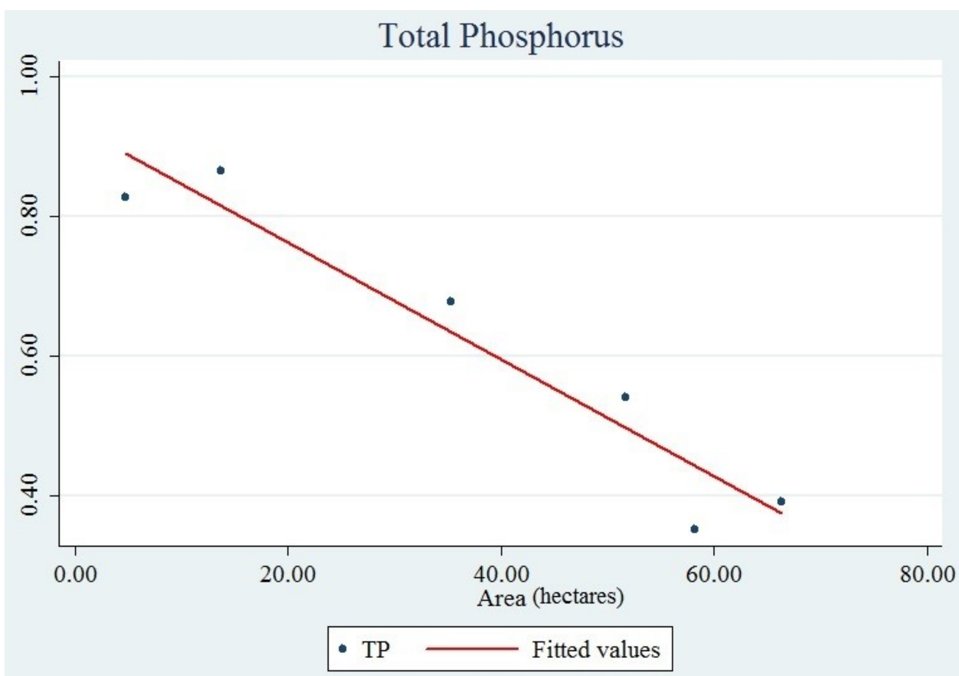


FIG. 15. Fitted line relating wetland area (hectares) and total phosphorus (mg/L) of Lianshi Lake.

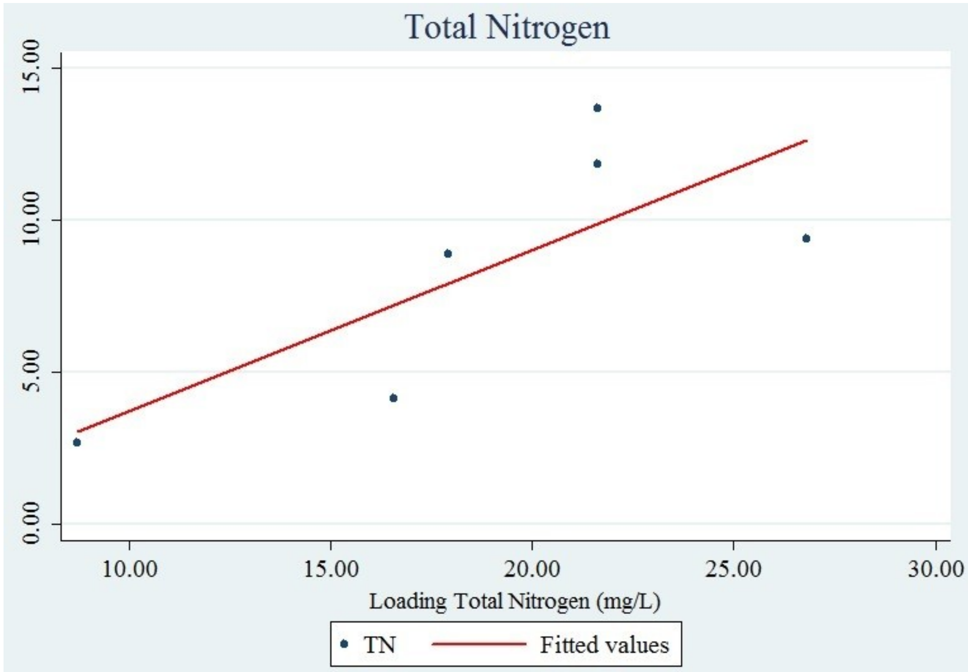


FIG.16. Fitted line relating loading of total nitrogen (mg/L) to total nitrogen (mg/L) of Lianshi Lake.

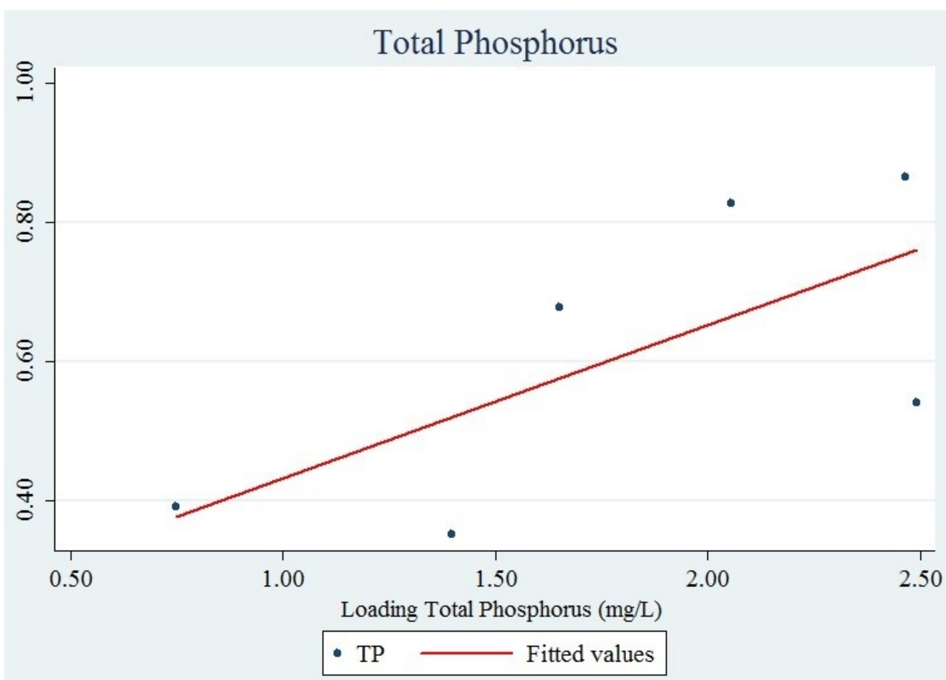


FIG.17. Fitted line relating loading of total phosphorus (mg/L) to total phosphorus (mg/L) of Lianshi Lake.

TABLE 7. Regression statistics TN and TP for wetland area and nutrient loading.

	R^2	RMSE	Coefficients (Marginal Changes)					
			Area	95% CI	Loading	95% CI	constant (β_0)	95% CI
TN	0.86	2.04	-0.10*	-0.19 - -0.01	0.41*	0.09 - 0.72	4.48	-3.50 - 12.46
TP	0.93	0.07	-0.01*	-0.01 - -0.003	0.04	-0.06 - 0.15	0.82	0.49 - 1.15

*P<0.05 in parenthesis below coefficient is the standard error
R^2 is coefficient of determination, RMSE is root mean squared error, CI is the 95% confidence interval

DUST CONTROL

To evaluate dust control, I created an ecological production function relating sand flux to local and regional PM_{10} for pre-Corridor and post-Corridor periods:

$$PM_{10} = \beta_0 + \beta_1 Sand + \varepsilon \quad (5)$$

where β_0 is the constant (y intercept), β_1 is the marginal effect (regression coefficient) of sand flux (g day^{-1}) noted as *Sand* on PM_{10} noted as PM_{10} and ε is the error term. The relationship between the variables was inspected using scatter plots and fitted lines, which are shown in Figs. 18-19 for pre-Corridor PM_{10} and Figs. 20-21 for post-Corridor PM_{10}. I ran the regressions, and present the statistics of sand flux to air quality for pre-Corridor in Table 8 and post-Corridor in Table 9.

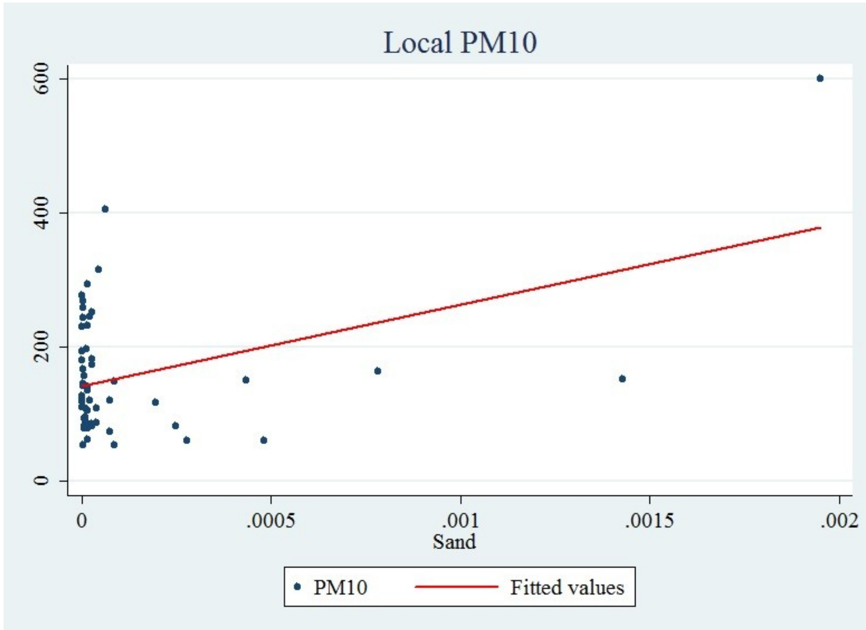


FIG. 18. Fitted line relating sand flux (g day^{-1}) to mean PM10 (µg m^{-3} day^{-1}) at local scale for pre-Corridor period.

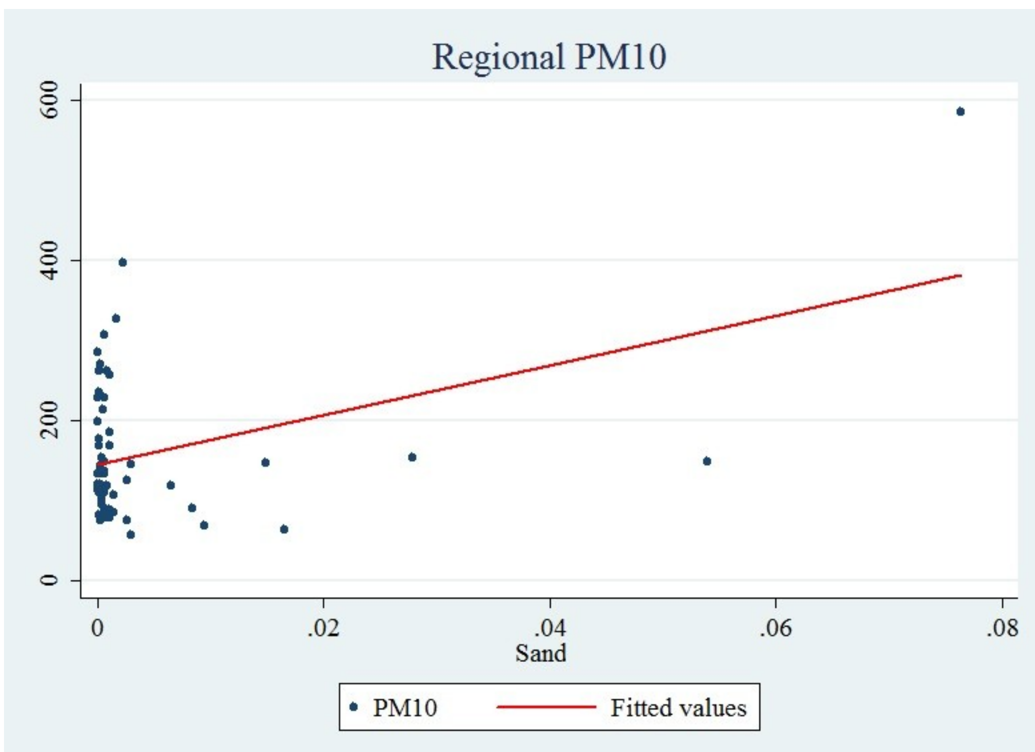


FIG. 19. Fitted line relating sand flux (g day^{-1}) to mean PM_{10} (µg m^{-3} day^{-1}) at regional scale for pre-Corridor period.

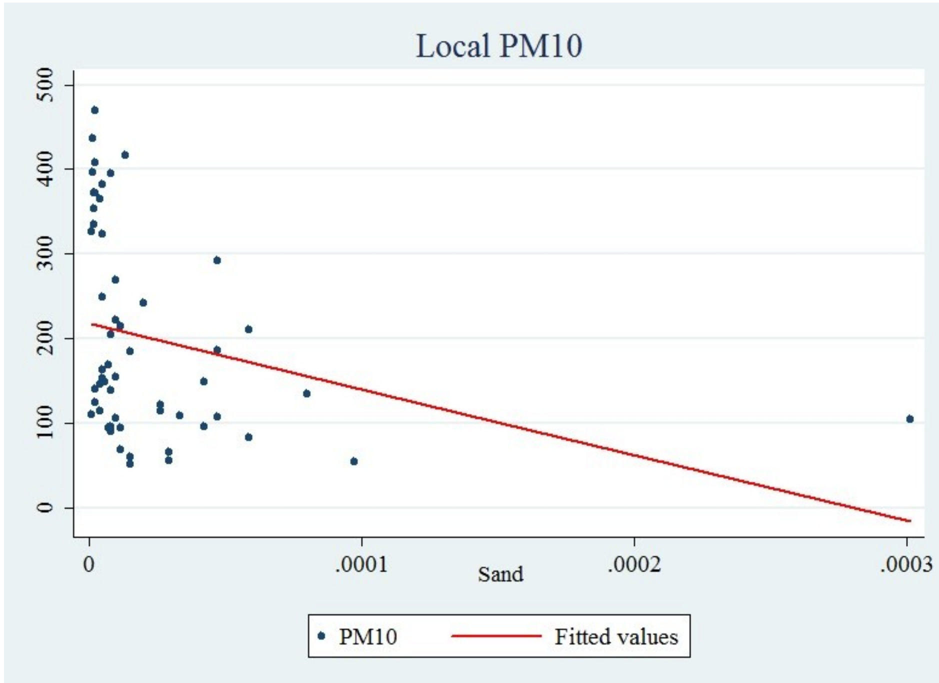


FIG. 20. Fitted line relating sand flux (g day^{-1}) to mean PM_{10} (µg m^{-3} day^{-1}) at local scale for post-Corridor period.

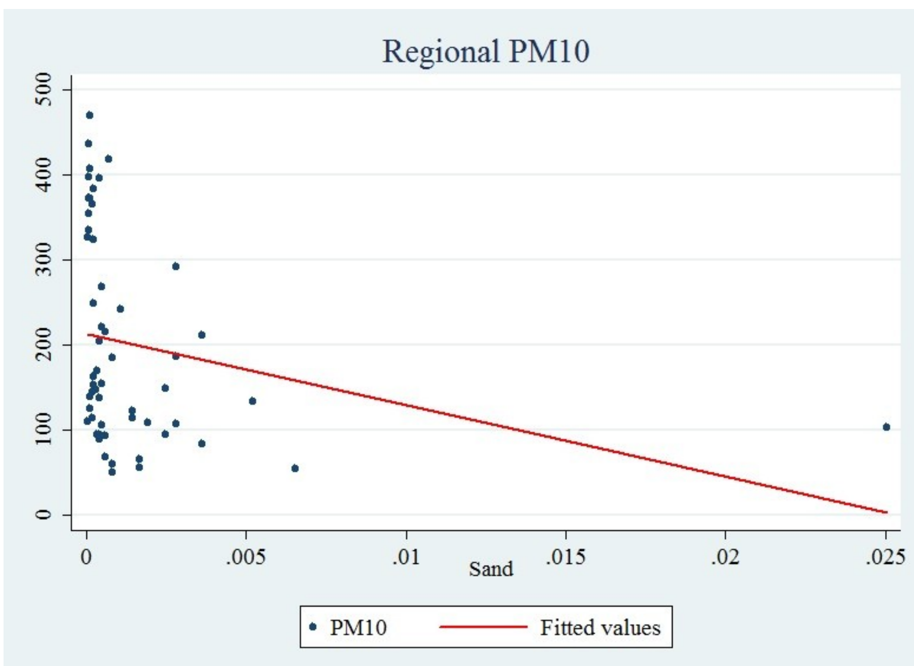


FIG. 21. Fitted line relating sand flux (kg day^{-1}) to mean PM_{10} (µg m^{-3} day^{-1}) at regional scale for post-Corridor period.

TABLE 8. Regression statistics for pre-Corridor PM_{10} (local and regional) ecological production functions.

	R^2	RMSE	Coefficients (Marginal Changes) Sand	95% CI	constant (β_0)	95% CI
PM_{10} (Local)	0.18	87.32	120780 (75681)	-30888 - 272449	141.8* (11.6)	118 - 165
PM_{10} (Regional)	0.18	86.01	3101 (1892)	-691 - 6892	144.3* (11.5)	121 - 167

*P<0.05 in parenthesis below coefficient is the standard error.
R^2 is coefficient of determination, RMSE is root mean squared error, and CI is the 95% confidence interval.

TABLE 9. Regression statistics for post-Corridor PM_{10} (local and regional) ecological production functions.

	R^2	RMSE	Coefficients (Marginal Changes) Sand	95% CI	constant (β_0)	95% CI
PM_{10} (Local)	0.07	118.12	-763251* (370057)	-1505492- -21009	214* (19)	175 - 252
PM_{10} (Regional)	0.06	118.69	-8355* (4011)	-16401 - -309	213* (18)	177 - 249

*P<0.05 in parenthesis below coefficient is the standard error.
R^2 is coefficient of determination, RMSE is root mean squared error, and CI is the 95% confidence interval.

AESTHETICS

I evaluated the potential contributions of the ecosystems to landscape aesthetics using an ecological production function by creating an ordinal logistic regression model to link visitor rankings of environmental quality to rankings of aesthetics. The general model is shown below:

$$ln\left(\frac{prob(Aesthetics)}{(1\text{-}prob(Aesthetics))}\right) = \beta_0 + \beta_1 Air + \beta_2 Water + \beta_3 Cooling + \beta_4 Enjoyment + \varepsilon \quad (6)$$

where *Aesthetics* is visitor rankings of scenic beauty where 1 = very unattractive; 2 = unattractive; 3 = okay; 4 = beautiful; 5 = very beautiful. The selected explanatory variables represent three regulating ecosystem services (e.g., dust control, water purification, and local climate regulation) and personal satisfaction of trip experience. The *Air* variable is visitor rankings on air quality: 1 = very unhealthy; 2 = unhealthy; 3 = moderate; 4 = healthy; 5 = very healthy. The *Water* variable is visitor rankings on water quality: 1 = very unhealthy; 2 = unhealthy; 3 = moderate; 4 = healthy; 5 = very healthy. The *Cooling* variable is visitor rankings on climate conditions: 1 = very hot; 2 = hot; 3 = warm; 4 = cool; 5 = cold. Lastly, the *Enjoyment* variable is visitor rankings on overall trip experience: 1 = very unpleasant; 2 = unpleasant; 3 = ok; 4 = enjoyable; 5 = very enjoyable unpleasant. β_0 is the constant (y intercept), β_1- β_4 are regression coefficients interpreted as proportional odds ratios, percent change in the odds, and predicted probabilities for final service indicators (Aesthetics = 5 (very beautiful) and 4 (beautiful)).

I tested the proportional odds assumption using a common statistical test in Stata, which is the omodel test. When you fit an ordinal regression the assumption is that the relationships between the independent variables and the response variable are same for all groups. I checked this assumption first using the omodel test to evaluate whether or not the null model (one that assumes proportional relationship) versus a general model (one that does not assume proportional relationship by allowing the coefficients to vary). For the omodel test one wants to see if the null hypothesis holds (i.e., no significant difference in the coefficients between models), thus one is looking for a non-significant result. For the above model, I ran the omodel test and got a chi-square (8) value of 4.57 with p-value of 0.803, which is non-significant thus the general model does not improve the fit. Next I evaluated the goodness of fit measures and the McFadden R^2 was 0.123. Below I present the regression coefficients: (1) logit coefficients, (2) proportional odds ratio, and (3) percent change in odds in Table 10. Predicted probabilities are a useful way to interpret the results of how marginal changes in the explanatory variables may impact high aesthetic rankings (i.e., final services are rankings of beautiful and very beautiful). The predicted probabilities are displayed in Figs. 22-29 and Table 11-12.

TABLE 10. Regression statistics of the aesthetics ecological production function.

	Logit coeff	95% CI	Odds ratio	Percent change (%)
Air	0.20 (0.27)	-0.32-0.72	1.22 (1.14)	22.2 (14.0)
Water	0.62 (0.23)*	0.16-1.08	1.86 (1.54)	86.5 (54.5)
Cooling	0.56 (0.22)*	0.12-0.99	1.75 (1.46)	75.0 (45.7)
Enjoyment	0.95 (0.28)*	0.41-1.50	2.60 (1.80)	159.7 (80.1)

*P<0.05 in parenthesis below coefficient is the standard error for logit coeff, and for odds ratio and percent change is the standard deviation.

Logit coeff are the ordinal logisitc regression model coefficients, odds ratio are the proportional odds ratios, and the percent change is the percent change in odds. CI is the 95% confidence interval.

TABLE 11. Predicted probabilities to see how each of the values of the specified explanatory variables changes for an aesthetic value of 4 (beautiful) holding other variables at their means.

Aesthetic value of 4 (Beautiful)								
Ranking	Air[a]	95% CI	Water[b]	95% CI	Cooling[c]	95% CI	Enjoyment[d]	95%CI
1	0.56 (0.04)*	0.47-0.64	0.50 (0.08)*	0.34-0.66	0.48 (0.10)*	0.29-0.67	0.20 (0.13)	-0.06-0.46
2	0.55 (0.05)*	0.46-0.64	0.55 (0.04)*	0.47-0.64	0.54 (0.05)*	0.45-0.64	0.36 (0.12)*	0.13-0.60
3	0.54 (0.04)*	0.45-0.63	0.54 (0.04)*	0.45-0.62	0.55 (0.04)*	0.47-0.64	0.52 (0.06)*	0.41-0.63
4	0.52 (0.04)*	0.44-0.61	0.45 (0.05)*	0.36-0.55	0.51 (0.04)*	0.43-0.59	0.55 (0.04)*	0.46-0.63
5	0.50 (0.06)*	0.39-0.61	0.34 (0.09)*	0.17-0.51	0.42 (0.06)*	0.29-0.54	0.42 (0.05)*	0.32-0.52

*P<0.05 in parenthesis below coefficient is the standard error; 95% CI is the 95% confidence interval.
[a] Air are rankings for air quality: 1 = very unhealthy; 2 = unhealthy; 3 = moderate; 4 = healthy; 5 = very healthy.
[b] Water are rankings for water quality: 1 = very unhealthy; 2 = unhealthy; 3 = moderate; 4 = healthy; 5 = very healthy.
[c] Cooling are rankings for climate: 1 = very hot; 2 = hot; 3 = warm; 4 = cool; 5 = cold.
[d] Enjoyment are rankings for trip satisfaction: 1 = very unpleasant; 2 = unpleasant; 3 = ok; 4 = enjoyable; 5 = very enjoyable.

TABLE 12. Predicted probabilities to see how each of the values of the specified explanatory variables changes for an aesthetic value of 5 (very beautiful) holding other variables at their means.

Aesthetic value of 5 (Very Beautiful)								
Ranking	Air[a]	95% CI	Water[b]	95% CI	Cooling[c]	95% CI	Enjoyment[d]	95%CI
1	0.22 (0.13)	-0.04-0.48	0.11 (0.05)*	0.01-0.22	0.10 (0.06)	-0.01-0.21	0.02 (0.02)	-0.02-0.06
2	0.25 (0.10)*	0.06-0.45	0.19 (0.05)*	0.09-0.29	0.16 (0.06)*	0.05-0.27	0.05 (0.03)	-0.01-0.12
3	0.29 (0.06)*	0.18-0.41	0.31 (0.04)*	0.24-0.38	0.25 (0.04)*	0.17-0.34	0.13 (0.04)*	0.04-0.22
4	0.34 (0.04)*	0.26-0.41	0.46 (0.06)*	0.33-0.58	0.37 (0.04)*	0.29-0.46	0.28 (0.04)*	0.21-0.36
5	0.38 (0.08)*	0.22-0.55	0.61 (0.11)*	0.40-0.82	0.51 (0.08)*	0.35-0.67	0.51 (0.06)*	0.38-0.63

*P<0.05 in parenthesis below coefficient is the standard error; 95% CI is the 95% confidence interval.
[a] Air are rankings for air quality: 1 = very unhealthy; 2 = unhealthy; 3 = moderate; 4 = healthy; 5 = very healthy.
[b] Water are rankings for water quality: 1 = very unhealthy; 2 = unhealthy; 3 = moderate; 4 = healthy; 5 = very healthy.
[c] Cooling are rankings for climate: 1 = very hot; 2 = hot; 3 = warm; 4 = cool; 5 = cold.
[d] Enjoyment are rankings for trip satisfaction: 1 = very unpleasant; 2 = unpleasant; 3 = ok; 4 = enjoyable; 5 = very enjoyable.

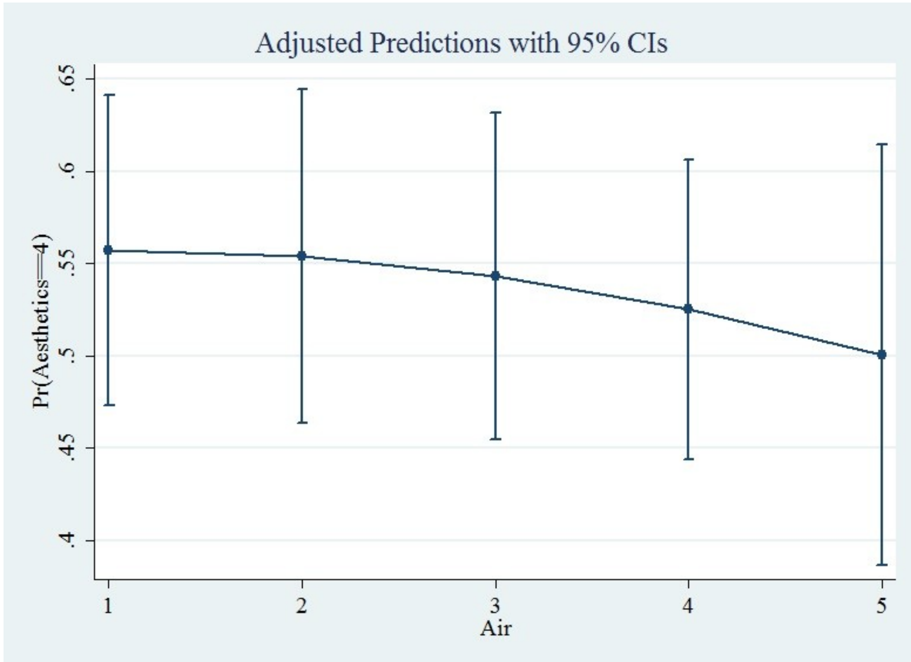


FIG.22. Predicted margins for aesthetic value 4 (beautiful) under varying air quality rankings with 95% confidence intervals.

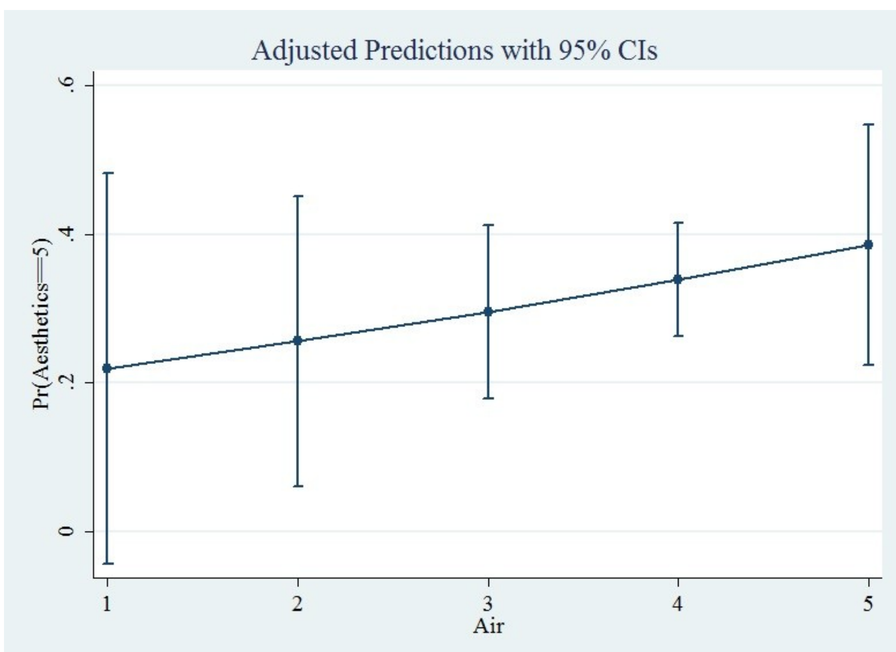


FIG.23. Predicted margins for aesthetic value 5 (very beautiful) under varying air quality rankings with 95% confidence intervals.

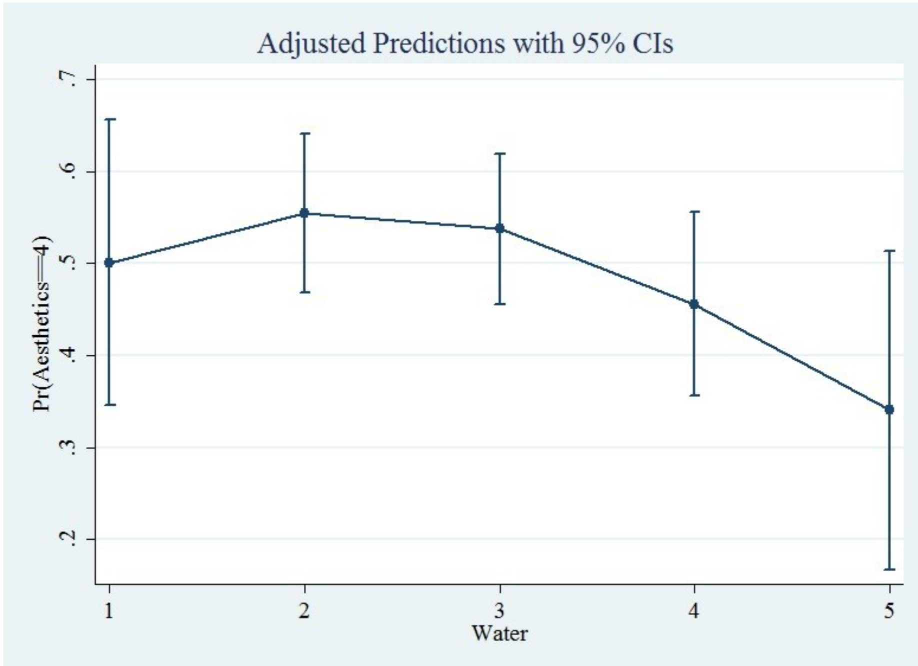


FIG.24. Predicted margins for aesthetic value 4 (beautiful) under varying water quality rankings with 95% confidence intervals.

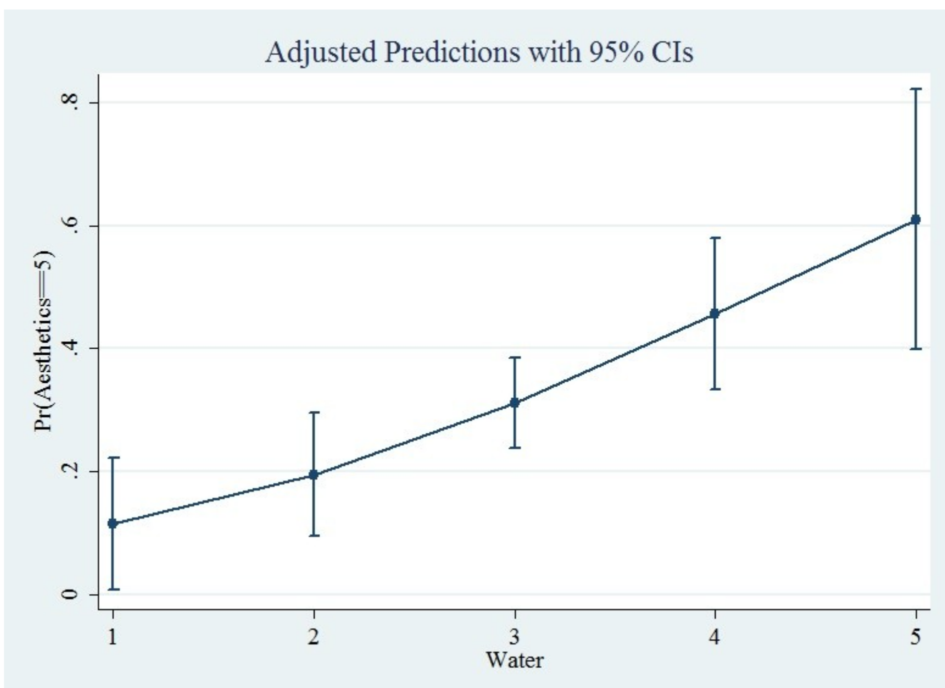


FIG.25. Predicted margins for aesthetic value 5 (very beautiful) under varying water quality rankings with 95% confidence intervals.

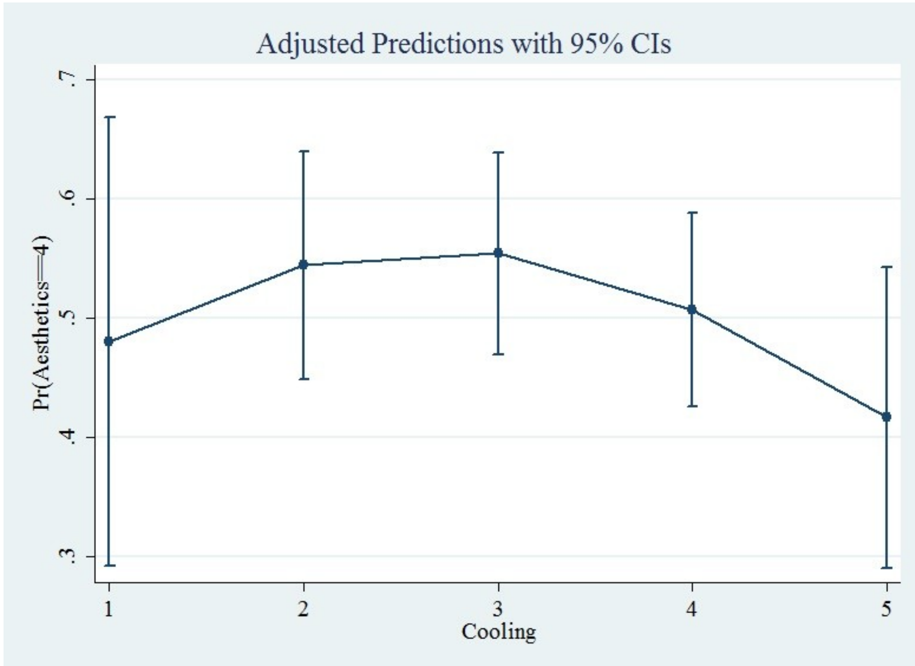


FIG.26. Predicted margins for aesthetic value 4 (beautiful) under varying climate rankings with 95% confidence intervals.

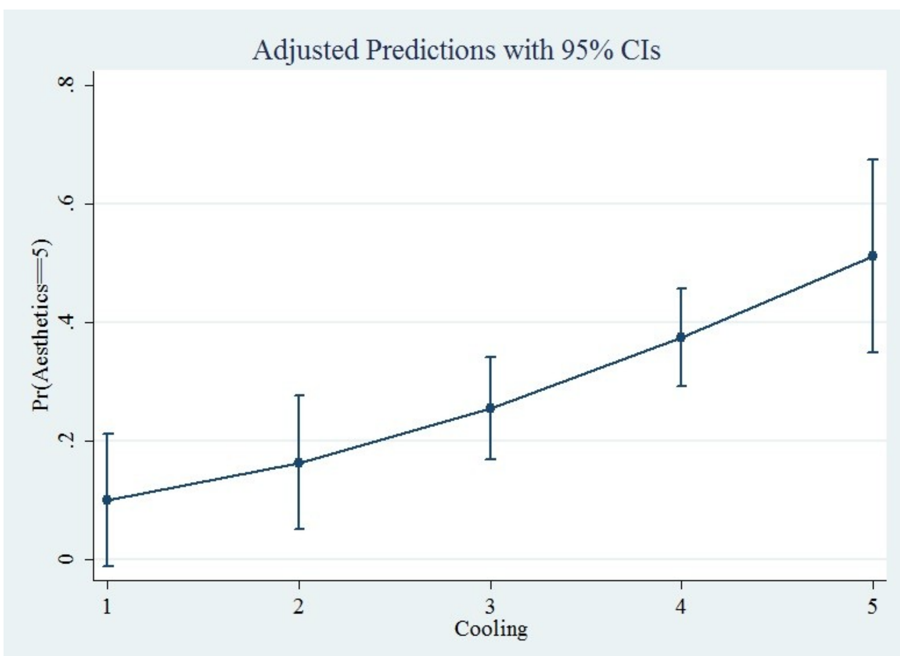


FIG.27. Predicted margins for aesthetic value 5 (very beautiful) under varying climate rankings with 95% confidence intervals.

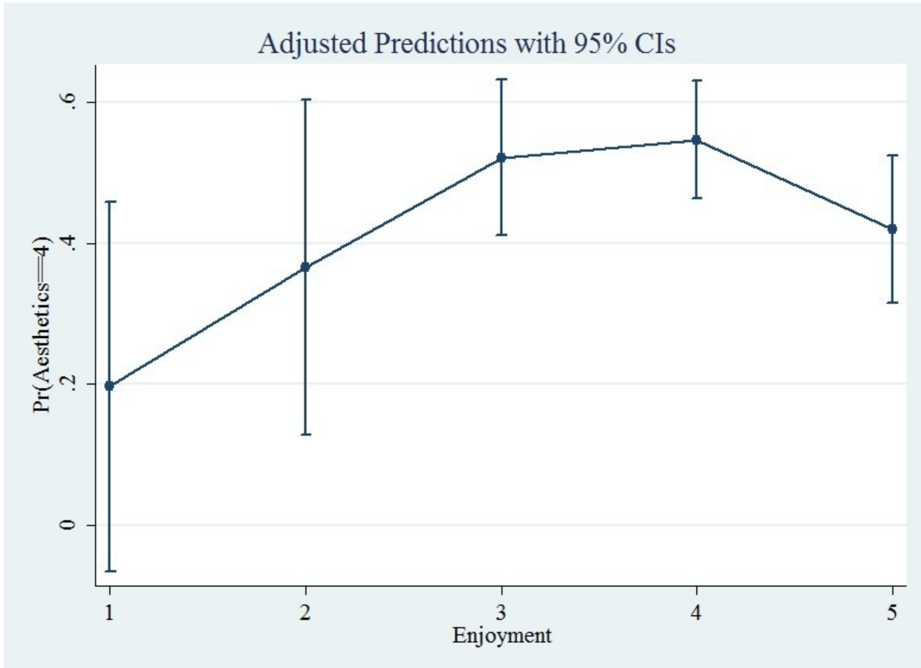


FIG.28. Predicted margins for aesthetic value 4 (beautiful) under varying trip satisfaction rankings with 95% confidence intervals.

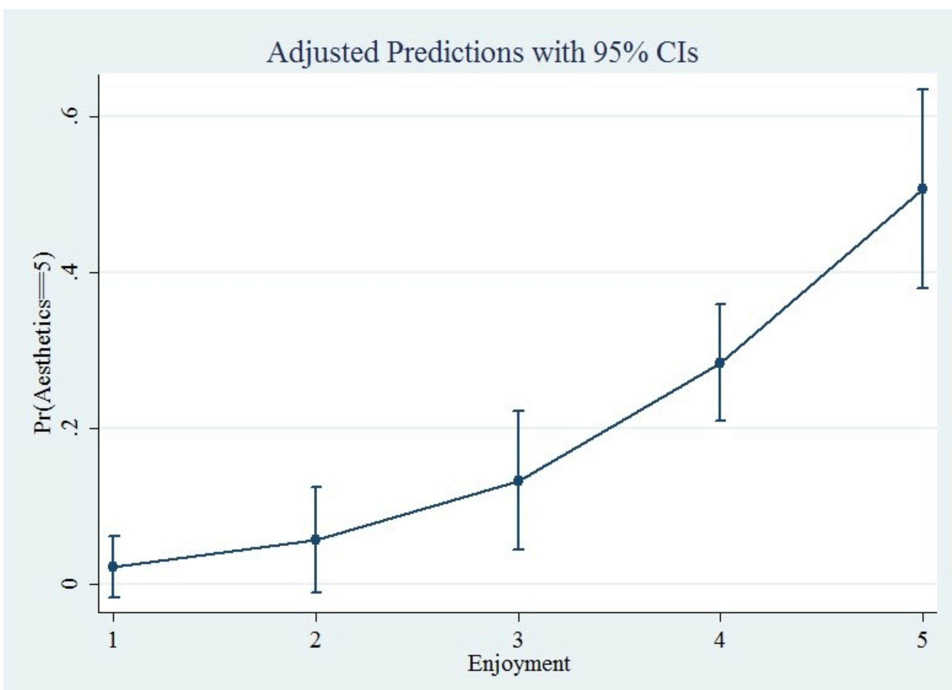


FIG.29. Predicted margins for aesthetic value 5 (very beautiful) under varying trip satisfaction rankings with 95% confidence intervals.

APPENDIX D

SOCIAL SURVEYS

ASU Knowledge Enterprise Development

Office of Research Integrity and Assurance

To:	Ann Kinzig LSA 124
From:	Mark Roosa, Chair Soc Beh IRB
Date:	05/29/2012
Committee Action:	**Exemption Granted**
IRB Action Date:	05/29/2012
IRB Protocol #:	1205007851
Study Title:	Yongding River Visitor Survey of Recreation Preferences and Leisure Values

The above-referenced protocol is considered exempt after review by the Institutional Review Board pursuant to Federal regulations, 45 CFR Part 46.101(b)(2) .

This part of the federal regulations requires that the information be recorded by investigators in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects. It is necessary that the information obtained not be such that if disclosed outside the research, it could reasonably place the subjects at risk of criminal or civil liability, or be damaging to the subjects' financial standing, employability, or reputation.

You should retain a copy of this letter for your records.

Questionnaire Number	

Questionnaire Review	*Surveyors*	*Reviewers*	*Recorders*
Date			
Signature			

Yongding River Visitor Survey of Recreation Preferences and Leisure Values

Dear Visitor,

We are students from Arizona State University and the Chinese Academy of Sciences Research Center for Eco-Environmental Sciences. The questionnaire is designed to collect information on recreation preferences and leisure values of the Yongding River. The purpose of our study is to provide management suggestions for the Yongding River. All information provided will be anonymous, and will be kept confidential and is for research use only. You may withdraw from the survey at any time. We appreciate your participation in our research.

P1. Gender: ☐Male ☐Female

P2. Your age is (if you are under 12, please withdraw from the survey):

☐12-20 ☐21 - 30 ☐31 - 40 ☐41 - 50 ☐51 - 60 ☐above 60

P3. Education: ☐Middle school and or less ☐High school

☐College or equivalent ☐Master's or more

P4. Occupation: ☐Student ☐Teacher ☐Researcher ☐Military ☐Government

☐Commercial, service personnel ☐Professional, technical personnel

☐Farming, Forestry, Animal Husbandry, and Fishery

☐Self-employed ☐Retired ☐Unemployed ☐Other (please specify_____)

P5. What is your personal monthly income (after-taxes including benefits, allowances, bonuses, etc.) is?

☐No income ☐2000 yuan and below ☐2,001–3,000 yuan

☐3,001 - 4,000 yuan ☐4,001 - 5,000 yuan ☐5,001 - 6,000 yuan

☐6,001 - 7,000 yuan ☐7,001 - 8,000 yuan ☐8,001 - 9,000 yuan

☐9,001 - 10,000 yuan ☐10,001 - 12,000 yuan ☐12,001 - 15,000 yuan

☐ above 15,000 yuan

P6. Your address is:

☐Beijing__________(District) ☐Other Provinces/Municipalities____________

P7. Before the development of the Yongding River Ecological Corridor in 2010, how many times had you been to the Yongding River?

☐0 ☐1 ☐2 ☐3 ☐4 ☐5 ☐6-10 ☐more than 10 times

P8. After the completion of the Yongding River Ecological Corridor in 2010, how many times have you been to the Yongding River?

☐0 ☐1 ☐2 ☐3 ☐4 ☐5 ☐6-10 ☐more than 10 times

P9. Today from your starting point to the Yongding River, your one way transportation cost was__________ RMB/person, and the time you spent on your one way trip was __________minutes.

P10. Today how much time did you spend on the Yongding River (do not include travel time):

☐less than 30 minutes ☐31 - 60 minutes ☐1 - 2 hours ☐2 - 4 hours

☐1 day

P11. The purpose of your visit today to the Yongding River was:

☐Exercise (jogging, walking, dancing) ☐Relaxation

☐Tourism ☐Other:_________

P12. If you chose not to travel to the Yongding River today, what would you have likely done otherwise?

☐Work ☐Watch TV ☐Housework ☐Shopping ☐Other

P13. If you were to work today, your time spent on the Yongding River would be equivalent to an earnings value of _______yuan.

P14. What are the most important values to you from the Yongding River Ecological Corridor:

☐Air quality improvements ☐Cooling effects ☐Increase water supply

☐Water quality improvements ☐Place for leisure and travel

☐Recreation opportunities ☐Heritage value for future generations

☐Landscape preservation ☐Other_________

P15. You think the Yongding River Ecological Corridor is:

☐Very Unattractive ☐Unattractive ☐Okay ☐Beautiful ☐Very Beautiful

P16. During your trip today, the air quality on the Yongding River Ecological Corridor was:

☐Very Unhealthy ☐Unhealthy ☐Moderate ☐Healthy ☐Very healthy

P17. During your trip today, the water quality on the Yongding River Ecological Corridor was:

☐Very Unhealthy ☐Unhealthy ☐Moderate ☐Healthy ☐Very healthy

P18. During your trip today, the weather on the Yongding River Ecological Corridor was:

☐Very hot ☐Hot ☐Warm ☐Cool ☐Cold

P19. Overall, did you enjoy your trip today:

☐Very unpleasant ☐Unpleasant ☐Ok ☐Enjoyable ☐Very enjoyable

P20. There are many parks near the Yongding River, such as Mencheng Lake, Xiaoyue Lake and Wanping Lake. Today, why did you choose this park over the other parks? ___________________________

P21. What aspects of the Yongding River Ecological Corridor are you dissatisfied with:

☐Water Quality ☐Water Level ☐Air Quality ☐Climate

☐Environment ☐Other_____________________

P22. What is your biggest concern about the future of the Yongding River?

____

You completed the survey. Thank you for your time and cooperation. Good-bye!

N1 问卷编号	

问卷复核	*问卷调查人*	*复核*	*录入*
日期			
签字			

永定河休闲价值及旅游者偏好问卷调查

尊敬的游客：

您好！我们是来自亚利桑那州立大学和中国科学院生态环境研究中心的研究生，本研究旨在收集永定河休闲及旅游者的旅游偏好信息。项目的研究目的是为永定河的管理提供建议。我们对您所提供的意见将全部保密，仅供我们研究分析使用。希望您支持我们的工作，对您的支持表示感谢！

P1． 被访者性别：□男 □女

P2． 您的年龄（12 岁以下终止访问）：
□12 - 20 岁 □21 - 30 岁 □31 - 40 岁□41 - 50 岁 □51 - 60 岁 □60 岁以上

P3． 文化程度：□初中及以下 □高中、高职 □大专、本科 □硕士及以上

P4． 请问您的工作是：
□学生 □老师 □科研人员 □军人 □国家机关、企事业单位职员 □商业、服务业人员 □专业技术人员 □农林牧渔生产人员 □自由业 □离退休人员 □失业 □其它（无法判断，请注明_____）

P5． 请问您的个人月收入（税后收入，包括福利、津贴、奖金等）为？
□无收入 □2000 元及以下 □2,001–3,000 元 □3,001 - 4,000 元 □4,001 - 5,000 元 □5,001 - 6,000 元 □6,001 - 7,000 元

□7,001 - 8,000 元 □8,001 - 9,000 元 □9,001 - 10,000 元
□10,001 - 12,000 元 □12,001 - 15,000 元 □15,000 元以上

P6． 您的常住地址：□北京市____________区 □其它省____________

P7． 永定河建设生态走廊以前（即 2010 年及以前），您每年到永定河的次数：
□0 次 □1 次 □2 次 □3 次 □4 次 □5 次 □6 - 10 次 □10 次以上

P8． 永定河建设生态走廊以后（即 2010 年以后），您每年到永定河的次数：
□1 次 □2 次 □3 次 □4 次 □5 次 □6 - 10 次 □10 次以上

P9． 从您的出发地到永定河，你单程的交通费用是_________元/人，单程距离_________公里，单程花费的时间是_________分钟。

P10． 您今天在永定河逗留的时间是（不包括来回路上花费的时间）：
□少于 30 分钟 □31 - 60 分钟 □1 - 2 个小时 □2 - 4 个小时 □一天

P11． 您到永定河的目的：
□锻炼身体（慢跑，散步，跳舞） □休闲放松 □旅游 □其它：_________

P12． 如果您今天没有到该地旅游，您最有可能干什么？
□工作；□看电视；□做家务活；□购物；□其它

P13． 如果工作的话，您认为今天花在永定河的时间能给您带来_______元的价值。

P14． 您认为永定河生态走廊建设**最**有价值的地方是:
□改善空气质量 □降温作用 □ 提高水资源供给能力 □改善水质
□ 提供了休闲旅游机会 □ 自己或他人有机会利用景观资源
□ 作为一份遗产留给子孙后代
□ 确保景观永远存在 □其他_________

P15． 您认为永定河生态走廊：

□非常不具吸引力 □不具吸引力 □一般 □美 □非常美

P16． 在您休闲旅行的整个过程中，您认为永定河生态走廊的空气质量：

□非常不健康 □不健康 □一般 □健康 □非常健康

P17． 在您休闲旅行的整个过程中，您认为永定河生态走廊的水体质量：

□非常不健康 □不健康 □一般 □健康 □非常健康

P18． 在您休闲旅行的整个过程中，您认为永定河的气候：

□非常热 □热 □暖和 □凉爽 □冷

P19． 在您今天旅行的整个过程中，您的总体感觉如何：

□非常不愉快 □不愉快 □一般 □愉快 □非常愉快

P20． 在永定河有很多公园，比如门城, 莲石, 晓月, 宛平等。请问您为什么选择来这里而不是其它的公园？___________________________

P21． 您对永定河的哪些方面不满意：

□水质 □水量 □空气质量 □气候状况 □周边环境

□其他_____________________

P22． 对于永定河的未来，您最大的担忧是什么？

____

访问到此结束，谢谢您的合作，祝您万事如意，再见！