Environmental Science & Technology

Article

pubs.acs.org/est

Predicting Plant Invasions Following China's Water Diversion Project

Dasheng Liu,[*,†,§] Rui Wang,[‡] Doria R. Gordon,[∥,⊥] Xihua Sun,[#] Lu Chen,[#] and Yanwen Wang[§]

[†]Shandong Institute of Environmental Science, Lishan Lu 50, Jinan 250013, China

[‡]State Key Laboratory for Biology of Plant Diseases and Insect Pests, Institute of Plant Protection, Chinese Academy of Agricultural Sciences, Yuanmingyuan West Road 2, Beijing 100193, China

[§]Ecological Society of Shandong, Zhijinshi Jie 12, Jinan 250012, China

[∥]Environmental Defense Fund, 1875 Connecticut Avenue NW, Washington, DC 20009, United States

[⊥]Department of Biology, University of Florida, Gainesville, Florida 32611, United States

[#]College of Geography and Environment, Shandong Normal University, Wenhua Dong Lu 88, Jinan 250014, China

ABSTRACT: China's South to North Water Diversion (SNWD) project connects portions of the Yangtze River in the south to the Yellow River system in the north, overcoming biogeographic barriers to water movement. The diversion will supply potable water to over 110 million people and provide multiple other socioeconomic benefits. However, an inadvertent negative impact of this connection includes creation of conduits for species invasions. Alligator weed (*Alternanthera philoxeroides*), water hyacinth (*Eichhornia crassipes*), and water lettuce (*Pistia stratiotes*) are the only aquatic plant species on China's shortlists for special control. These species are mainly invasive in the Yangtze River basin. If these species are able to invade the SNWD and further spread via the SNWD, they have the potential to alter water supply, including water quantity and quality, as well as local ecology and agriculture, threatening the goals of the diversion. Understanding the full potential for these species to invade northern China is critical to early management decisions to avoid costly negative impacts. We used Maxent modeling to evaluate the probability that each of these species might become invasive in the receiving water regions. The models predict that all three species will be able to expand their ranges northward, with alligator weed and water hyacinth having the greatest potential for range expansion. These results suggest the need for prevention, monitoring, and management strategies for these species to reduce the risk and costs of impacts.

INTRODUCTION

Biological invasions are causing global environmental and economic damage,[1] including threats to global biodiversity through alteration of the structure and function of ecosystems and ecological interactions that have developed over evolutionary time scales.[2−7] Multiple studies have demonstrated the cost-effectiveness of early prevention and management of biological invasions.[8−10] Preemptively predicting where biological invasions may occur is crucial to developing successful monitoring programs and management strategies.

Meeting water supply needs is an increasing concern throughout the world.[11] One common response to enhance navigation and access to water is through diversion of waterways to areas of need.[12−14] The South to North Water Diversion (SNWD) in China is one such project (Figure 1). SNWD consists of eastern, middle, and western routes designed to alleviate water supply problems in northern China by transferring water from the lower, middle, and upper reaches of the Yangtze River in southern China.[15] SNWD is intended to supply potable water to 110 million people, including 7 million who have suffered from consuming high-fluorine and brackish water.[16] Moreover, the groundwater overdraft situation in northern China will gradually be alleviated as a result of this project.[16] In addition to water supply improvements, SNWD may also help reduce the rate of land subsidence in Beijing,[17] which has been attributed to groundwater withdrawals. The eastern and middle routes of SNWD have been in use since December 2013 and December 2014,[16,18] respectively, while the western route is still being planned.

Human-made waterways have become conduits for species invasions in multiple locations.[13,14,19] The SNWD establishes water flows between historically biogeographically independent river basins. As a result, aquatic invaders may spread passively, carried by the water via hydrochory,[20−22] through the SNWD[23] if environmental conditions in the north are suitable. Currently, many more non-native plant species have invaded southern than northern China.[24−27] However, while multiple risks associated with the SNWD have received attention,[28,29] risk assessment of biological invasions has not.

Three non-native aquatic plants, alligator weed (*Alternanthera philoxeroides* (Mart.) Griseb.), water hyacinth (*Eichhornia crassipes* (Mart.) Solms), and water lettuce (*Pistia stratiotes* L.),

Received: November 4, 2016
Revised: December 8, 2016
Accepted: January 6, 2017
Published: January 6, 2017

DOI: 10.1021/acs.est.6b05577
Environ. Sci. Technol. 2017, 51, 1450−1457

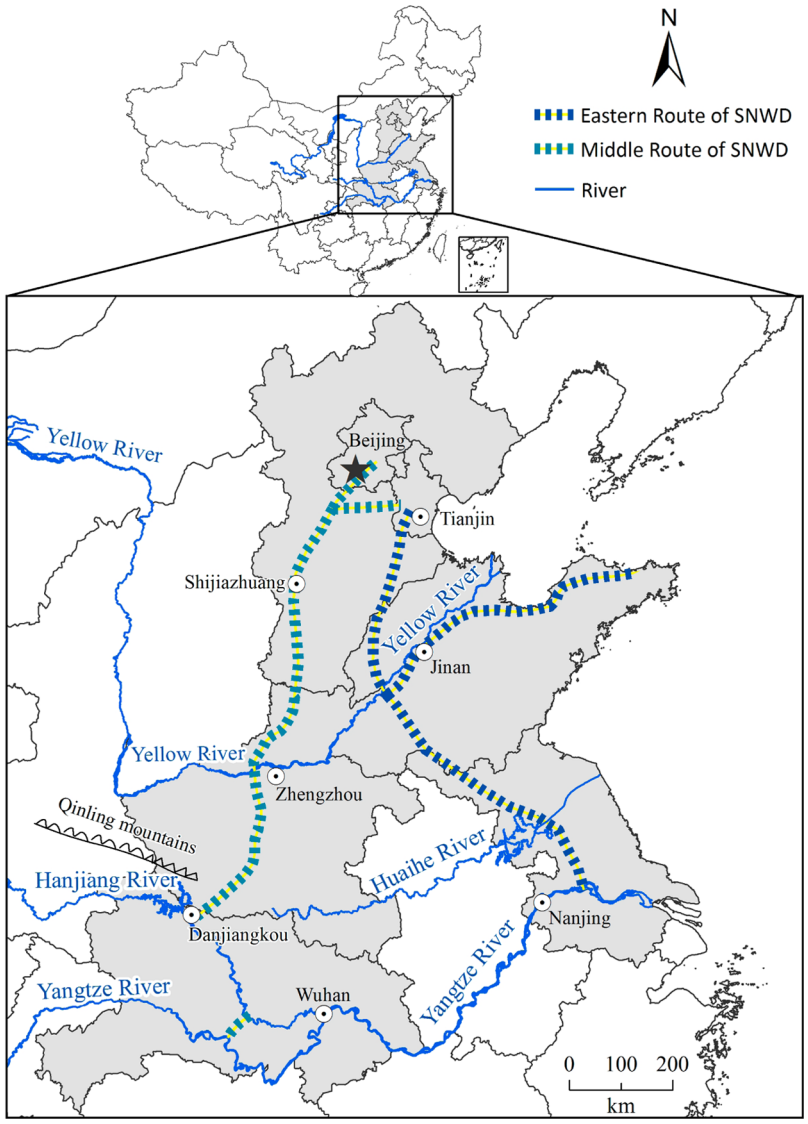

Figure 1. Eastern and middle routes for SNWD in China. The eastern route transfers water from Yangzhou, Jiangsu Province in the lower reach of the Yangtze River. The middle route diverts water from the Danjiangkou reservoir on the Hanjiang River in the Hubei Province which is the tributary of the middle reach of Yangtze River; its second stage will allow the transfers of water directly in the middle reach of the Yangtze River. Jinan, Nanjing, Shijiazhuang, Zhengzhou, and Wuhan are the capital cities of the Shandong, Jiangsu, Hebei, Henan, and Hubei Provinces, respectively.

are of particular concern. These species are the only aquatic plants included on China's first (alligator weed and water hyacinth)[30] and second (water lettuce)[31] shortlists of invasive species requiring special control. All three species have been cultivated widely for forage in southern China.[32−34] This cultivation, their floating habit, and clonal reproduction are the sources of their extensive distribution in the region. The development of dense vegetation mats on water bodies impairs navigation and water flow, causes flooding, alters water quality and quantity, and threatens native biodiversity.[35−40] In southern China, this damage by alligator weed and water hyacinth is reported to annually cost 600 million RMB (US$90 million) and 10 billion RMB (US$1.5 billion), respectively.[41,42] For the former species, losses on agricultural lands represent a significant portion of these costs.[43,44] These species also have a consistent history of becoming invasive in many regions of the world[45] and are widely predicted to become invasive in new habitats.[46] If the species invade the expansive receiving water areas in northern China, the damage consequences are likely to be of the same magnitude as seen to southern China and other areas of the introduced ranges around the world.

Because the species have demonstrated tolerance to cold temperatures elsewhere in the invaded range, they may survive and grow in higher latitudes.[47] This potential has already been realized for alligator weed, which has now invaded Shandong Province, northern China,[48,49] a range expansion not predicted by earlier work.[50] Understanding the full potential for these species to invade northern China's waterways is critical to early management decisions to avoid costly negative impacts.

Ecological niche modeling has been used to evaluate the potential habitat for species in a new location.[51−55] We used the maximum entropy (Maxent) model to predict the potential northern distributions of the three invaders. Maxent has been demonstrated to have greater precision than other niche modeling approaches[53] and has been used for habitat suitability projections for other invasive species.[54,55]

DOI: 10.1021/acs.est.6b05577
Environ. Sci. Technol. 2017, 51, 1450−1457

MATERIALS AND METHODS

South to North Water Diversion. In the eastern plains of China, the largest rivers flow from west to east. The Yangtze River is the longest river, followed by the Yellow River (Figure 1). The Huai River - Qinling Mountains line is generally regarded as the dividing line between northern China and southern China, and it also approximates 0 °C degree January mean temperature isotherm and 800 mm precipitation isohyet.[56,57] The SNWD eastern route transfers water from Yangzhou, Jiangsu Province in the lower reach of the Yangtze River. One branch flows northward through the Shandong and Hebei Provinces to Tianjin, while another flows through the eastern part of Shandong.[15,58] The SNWD middle route diverts water from the Danjiangkou reservoir on the Hanjiang River in the Hubei Province which is the tributary of the middle reach of Yangtze River and flows northward through the Henan and Hebei Provinces to Beijing and Tianjin (Figure 1). The second stage will allow the transfers of water directly from the middle reach of the Yangtze River.[15,58] The construction of the eastern and middle routes of SNWD began in 2002, and they have been in use since December 2013 and December 2014,[16,18] respectively. According to Office of the SNWD Commission of the State Council of China, the SNWD will annually divert 44.8 billion cubic meters of water when completed.[58]

Model Species. *Alligator Weed (Alternanthera philoxeroides (Mart.) Griseb.).* Alligator weed (Amaranthaceae) is native to the Parana River region of South America (Figure 2).[59,60] This weed grows in both aquatic and terrestrial habitats and can also invade farm lands. Its stems are hollow and buoyant and form floating mats that expand over surfaces of all types of waterways, making them practically impenetrable.[35] The floating sections from broken stems are able to establish readily on moist soil.[35] Alligator weed was introduced to mainland China in 1940 by the Japanese in Shanghai[32] and further distributed across southern China for forage in the 1950−1960s.

Alligator weed is currently invasive and poses significant ecological and economic problems. The species causes annual losses in China of 600 million RMB (US$90 million).[41] Alligator weed has now invaded the Xiaqing River, 500 km north of the Yangtze River in northern China's Shandong Province.[48,49]

Water Hyacinth (Eichhornia crassipes (Mart.) Solms). Water hyacinth (Pontederiaceae) is considered to be one of the world's top ten worst weeds.[61] This perennial herb is native to Brazil, South America (Figure 2) and has an erect, free-floating, stoloniferous, growth form with buoyant leaves.[36] Water hyacinth invades still and moving waters, with thick growth that can cause flooding and impair flows among other impacts.[36] The species was introduced into China in 1901 as an ornamental plant[33] and has been cultivated widely as a forage in southern China since the 1950s. Like alligator weed, water hyacinth has created significant ecological problems, causing annual losses of 10 billion RMB (US$1.5 billion).[42]

Water Lettuce (Pistia stratiotes L.). Water lettuce (Araceae) is native to South America (Figure 2). The species was introduced in China during the 16th century and was recorded in 1593 in the medical work "Compendium of Materia Medica".[34] Water lettuce is a floating, herbaceous hydrophyte, consisting of free-floating rosettes of many leaves that inhabits still and slowly flowing waters.[37] Like water hyacinth, water lettuce can impede navigational channels and water flow for irrigation and flood control.[37−39] Water lettuce was also cultivated as a forage in southern China in the 1950−1970s. Like the other species, water lettuce has become a problematic invader and is now on the second shortlist of invasive species requiring special control in China.[31]

Species Distribution Data Source. The occurrence data for modeling species distribution should include both the geographic distribution and the breadth of environmental gradients occupied by the species (e.g., cover the full range of environments tolerated by the species). We used native and introduced range occurrence data from the Global Biodiversity Information Facility (GBIF; http://data.gbif.org/), Chinese Virtual Herbarium databases (http://www.cvh.ac.cn/), and China Specimen Resources Sharing Platform for Education (http://mnh.scu.edu.cn), for this analysis (Figure 2). Additional records were obtained from the Herbarium of National Taiwan University (http://tai2.ntu.edu.tw/ebook.php), local floras, and field surveys (e.g., our field investigations of alligator weed in Xiaqing River basin and Weishan Lake basin, Shandong province). Occurrence data were carefully screened as described elsewhere.[62,63]

Maxent Modeling. We modeled the potential ranges of alligator weed, water hyacinth, and water lettuce using the Maxent (Version 3.3.3 k; Princeton University, Princeton, NJ, USA) maximum entropy method.[53] Maxent integrates species presence with environmental data to produce habitat suitability predictions[64] and has been used for projecting potential distributions of multiple plant species.[54,55]

We implemented and validated Maxent for each of the three species as documented by Qin et al.,[65] using occurrence points from the native and invaded ranges. We used a cumulative output format with a 0 to 100 range, indicating unsuitable to optimal habitat, respectively, resulting in presence/absence maps for each species using the minimum training presence.[64,65]

Receiver operating characteristic curves were used to evaluate the predictive power of the models following O'Donnell et al.[66] The closer the area under the curve (AUC) to 1.0 is, the better the fit of the Maxent results to environmental conditions as reflected by the validation data set (25% of the occurrence data).[67]

Environmental Variables for Modeling. We characterized the environmental characteristics of the native and invaded ranges of all three species by obtaining 20 climatic and topographic variables from the WorldClim 1.4 database (Version 1.4, http://www.worldclim.org). Nineteen variables were bioclimatic: monthly temperature and precipitation data were used to develop annual and seasonal trends in local climate. The single topographic variable reflected local elevation at a spatial resolution of five arc min. All these variables were considered as candidate predictors. We used a jackknife approach to identify those environmental data layers that most contributed to accuracy of the Maxent predictions,[53] eliminating variables that contributed <5% (Table 1).[65]

RESULTS

After data screening, 783 global records remained for alligator weed, of which approximately 25% were from its native range, 2125 for water hyacinth with ca. 24% from its native range and 1344 records for water lettuce with ca. 28% from its native range. All three species are now present on multiple continents; the global distributions of water hyacinth and water lettuce are more extensive than that of alligator weed (Figure 2). In China, the main distributions of the three species are in the southern region, including the middle and lower reaches of the Yangtze River, the area from which water is being diverted to the north.

DOI: 10.1021/acs.est.6b05577
Environ. Sci. Technol. 2017, 51, 1450−1457

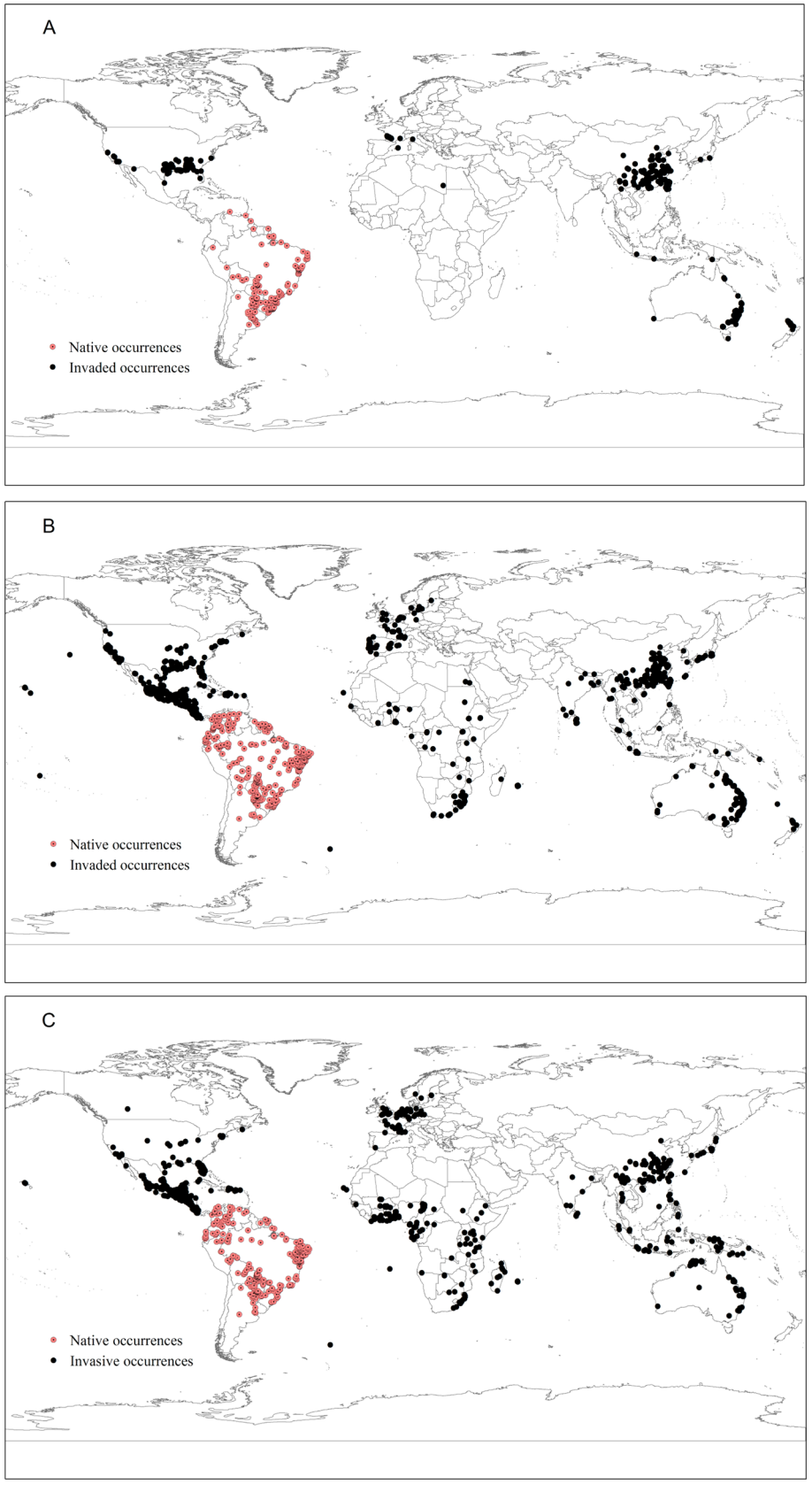

Figure 2. World distribution records of alligator weed (a), water hyacinth (b), and water lettuce (c).

Receiver operating curves of the Maxent models revealed accurate prediction of suitable new habitat for the three species: AUC values for alligator weed, water hyacinth, and water lettuce were 0.934 (SD = 0.011), 0.869 (SD = 0.007), and 0.879 (SD = 0.008), respectively. Different environmental variables contributed to the significant model for each of the three species (Table 1).

DOI: 10.1021/acs.est.6b05577
Environ. Sci. Technol. 2017, 51, 1450−1457

Table 1. Contribution of Environmental Variables to the Maxent Models for Alligator Weed, Water Hyacinth, and Water Lettuce in China, Excluding Variables Explaining <5% of the Total Variation[a]

alligator weed		water hyacinth		water lettuce	
variable	percent contribution	variable	percent contribution	variable	percent contribution
bio11	22.7	bio1	32	bio7	33.7
bio17	15.0	bio11	15.6	bio12	18.6
bio19	13.8	bio12	15.3	bio1	13.5
bio1	12.1	bio16	11.8	alt	8.5
bio4	7.0	alt	7.4	bio10	6.4
bio14	6.7			bio11	5.8
bio9	5.4				

[a]Variable definition: bio1, annual mean temperature; bio4, temperature seasonality (standard deviation × 100); bio7, temperature annual range (bio5-bio6); bio9, mean temperature of driest quarter; bio10, mean temperature of warmest quarter; bio11, mean temperature of the coldest quarter; bio12, annual precipitation; bio14, precipitation of driest month; bio16, precipitation of wettest quarter; bio17, precipitation of driest quarter; bio19, precipitation of the coldest quarter; alt, altitude.

Our results suggest that all species will be able to disperse into favorable more northern habitats but that alligator weed will show the greater range expansion (Figure 3). The Maxent models identified that more than 80% of the total area of SNWD can support populations of alligator weed, water hyacinth, and water lettuce. Areas unsuitable for invasion are mainly located north of Beijing and Hebei province (Figure 3).

The low, moderate, and high suitability areas were different for the three weeds (Figure 3). Most of the area within the two receiving water provinces, Henan and Shandong, are suitable for alligator weed and water hyacinth at moderate and high levels. Only one province, Henan, is suitable for water lettuce at those levels. Generally, the predicted suitability showed a decreasing tendency from south to north along the water diversion routes. Importantly, almost all the area impacted directly by the diversions is suitable for the three species (Figure 3).

DISCUSSION

Our models indicate that large areas of northern China, including most areas of Henan and Shandong Provinces and the southern part of Hebei Province, are suitable for all three species, particularly for alligator weed and water hyacinth (Figure 3). These results suggest that the water transfer between South China and North China will likely result in long-distance dispersal of these invasive species, which will then be able to persist and spread. It should be noted that alligator weed was first detected via our field survey in northern China from the SNWD waterway in late 2015 and the summer of 2016 (see TOC graphic). Management of that invasion should be a priority to avoid the costly impacts currently restricted to southern China.

As in southern China and other areas of the introduced ranges around the world, the north is now threatened with development of dense vegetation mats on water bodies that impair navigation and water flow, cause flooding, alter water quality and quantity, and threaten native biodiversity.[35−40] Furthermore, agricultural production of the receiving water provinces may be at risk. Henan and Shandong Provinces produce 9.5% and 7.5% of the total national grain output, respectively, putting them second and third in productivity in China.[68] Average losses from alligator weed to vegetable production in southern China range from 5 to 15% and can exceed 20%.[43] The species is also responsible for yield reductions of 63% in sweet potato and 45% in rice.[44] Our results indicate the necessity of both weed management and

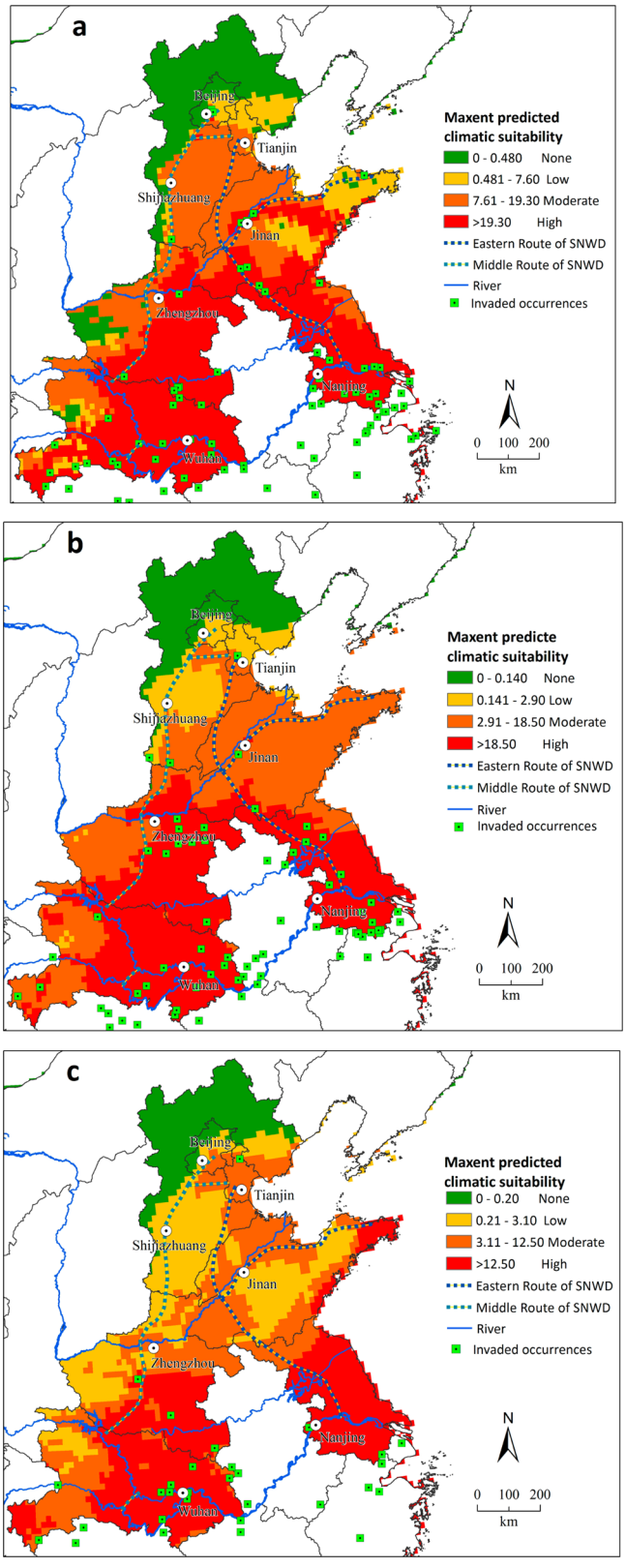

Figure 3. Maxent-predicted potential distribution of alligator weed (A), water hyacinth (B), and water lettuce (C) in the SNWD range (eastern and middle routes).

DOI: 10.1021/acs.est.6b05577
Environ. Sci. Technol. 2017, 51, 1450−1457

education efforts to inform local populations about the potential impacts to agriculture in Henan, Shandong, and other provinces of northern China.

China is not the only location that has seen the negative impacts of these species. One of the best studied invasions of water hyacinth is from Lake Victoria, East Africa, where the species impacted water quality, water supply, disease incidence, navigation, energy generation, and fisheries, negatively impacting communities across the basin.[69,70] Water lettuce has had similar impacts in the Lake Victoria basin and other watersheds. All three of the species studied here are globally harmful invaders, with alligator weed apparently having greater impacts in China than in other regions.[71] Water lettuce and alligator weed have become more prevalent in lakes in Florida (USA) when water hyacinth was controlled.[71]

While large areas of northern China are currently suitable for the three species, their potential distribution is likely to expand further north than the models suggest as temperatures increase in the 21st century.[72] Warming is likely to promote a shift or extension of species' ranges toward higher latitudes.[73] Concern about range shifts resulting from either or both of longer growing seasons and warmer winters has been identified for all three species in North America.[47,74] Control costs may also increase where populations are no longer largely controlled by freezing conditions.[74]

The predicted potential distribution for these three invasive plants does not necessarily mean that these species will successfully invade or damage specific areas of northern China. However, model results may be used to predict species distributions across broad geographic regions from which no samples have been collected, complementing and targeting field surveys which are costly, labor-intensive, and time-consuming. Understanding the most vulnerable areas will allow their prioritization for early detection and rapid response efforts. A recent study of structured expert judgment for the Chicago Area Waterway may provide a helpful approach to developing monitoring and management efforts.[19] Although eradication of these species in China is unlikely, newly establishing small populations are more successfully controlled,[75,76] which could prevent species from causing the scale of damage seen in Lake Victoria and Southern China. Most of the species distribution data and environmental variables that are required here can be downloaded from public data Web sites, facilitating these management actions.

These analyses also have relevance for the potential spread of other invasive species, like *Lepisosteus sp.* and *Pomacea canaliculata*, in the Yangtze River basin.[77−79] In North America, similar constructed waterways between the Mississippi River and Great Lakes basins have facilitated movement of multiple species, with significant impacts in both basins.[80,81] Losses from invaders introduced to this system through ship ballast alone are estimated at US$138 million or more annually.[82] Thus, the impacts of the SNWD on the species investigated here are likely a significant underestimate of overall potential invasion impacts: other species of concern in southern China should be added to these three for prevention and early detection efforts.

Because cultivation of the three species modeled in this effort is no longer permitted[30,31] and northern China has more temperate growing conditions, this invasion will theoretically be slower than that in southern China. However, the northward water flow of SNWD presents a rapid potential driver for the spread. These factors, combined with monitoring based on the model results presented here, should facilitate effective control efforts. As the eastern and middle routes of SNWD are already in use,[16,18] such efforts should be rapidly implemented to preclude costly impacts for both the 110 million people and the natural systems dependent on this water.

AUTHOR INFORMATION

Corresponding Author

*Phone: +86 531 86103303. Fax: +86 531 86103386. E-mail: liu_sdiep@126.com.

ORCID

Dasheng Liu: 0000-0001-8394-7619

Author Contributions

D.L., R.W., and D.R.G. contributed equally to this work.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by Shandong Science and Technology Program (2009GG10008014), China Water Project (Huaihe River 2009ZX07210-009), National Nature Science Foundation of China (31471827), and National Key Technology Research and Development Program of China (2015BAD08B03). We thank Z. M. Lin for assistance with data collection. We are grateful to Drs. Christer Nilsson, David Horvath, and Kevin E. McCluney for reviewing the outline and earlier draft of the manuscript. Thanks are also due to our peer reviewers for comments.

REFERENCES

(1) Cohen, A. N.; Carlton, J. T. Accelerating invasion rate in a highly invaded estuary. *Science* **1998**, *279*, 555−558.

(2) Lyons, K. G.; Schwartz, M. W. Rare species loss alters ecosystem function-invasion resistance. *Ecol. Lett.* **2001**, *4*, 358−365.

(3) Levine, J. M.; Lavorel, S. Mechanisms underlying the impacts of exotic plant invasions. *Proc. R. Soc. London, Ser. B* **2003**, *270*, 775−781.

(4) Asner, P.; Vitousek, P. M. Remote analysis of biological invasion and biogeochemical change. *Proc. Natl. Acad. Sci. U. S. A.* **2005**, *102*, 4383−4386.

(5) MacDougall, A. S.; Turkington, R. Are invasive species the drivers or passengers of change in degraded ecosystems? *Ecology* **2005**, *86*, 42−55.

(6) Traveset, A.; Richardson, D. M. Biological invasions as disruptors of plant reproductive mutualisms. *Trends Ecol.* **2006**, *21*, 208−216.

(7) Ehrenfeld, J. G. Ecosystem consequences of biological invasions. *Annu. Rev. Ecol. Evol. Syst.* **2010**, *41*, 59−80.

(8) Waage, J. K.; Reaser, J. K. A global strategy to defeat invasive species. *Science* **2001**, *292*, 1486.

(9) Leung, B.; Lodge, D. M.; Finnoff, D.; Shogren, J. F.; Lewis, M. A.; Lamberti, G. An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. *Proc. R. Soc. London, Ser. B* **2002**, *269*, 2407−2413.

(10) Keller, R. P.; Lodge, D. M.; Finnoff, D. C. Risk assessment for invasive species produces net bioeconomic benefits. *Proc. Natl. Acad. Sci. U. S. A.* **2007**, *104*, 203−207.

(11) Yeston, J.; Coontz, R.; Smith, J.; Ash, C. A thirsty world. *Science* **2006**, *313*, 1067.

(12) Changnon, S. A.; Changnon, J. M. History of the Chicago diversion and future implications. *J. Great Lakes Res.* **1996**, *22*, 100−1818.

(13) Kingsford, R. T. Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecol.* **2000**, *25*, 109−127.

(14) Galil, B. S.; Nehring, S.; Panov, V. Waterways as invasion highways−Impact of climate change and globalization. In *Biological*

DOI: 10.1021/acs.est.6b05577
Environ. Sci. Technol. 2017, 51, 1450−1457

Invasions; Nentwig, W., Eds.; Springer: Berlin Heidelberg, 2008; pp 59−74.
(15) Wang, Y.; Yang, Y. South-to-North Water Transfers project of China. *Yangtze River* **2005**, *36* (7), 2−6.
(16) Office of the South-to-North Water Diversion Project Commission of the State Council of China. http://www.nsbd.gov.cn/zx/zxdt/201312/t20131209_292368.html.
(17) Chen, M.; Tomás, R.; Li, Z.; Motagh, M.; Li, T.; Hu, L.; Gong, H.; Li, X.; Yu, J.; Gong, X. Imaging land subsidence induced by groundwater extraction in Beijing (China) using satellite radar interferometry. *Remote Sens.* **2016**, *8* (6), 468.
(18) Office of the South-to-North Water Diversion Project Commission of the State Council of China. http://www.nsbd.gov.cn/zx/zxdt/201512/t20151217_407224.html.
(19) Wittmann, M. E.; Cooke, R. M.; Rothlisberger, J. D.; Lodge, D. M. Using structured expert judgment to assess invasive species prevention: Asian carp and the Mississippi-Great Lakes hydrologic connection. *Environ. Sci. Technol.* **2014**, *48*, 2150−2156.
(20) Johansson, M. E.; Nilsson, C. Hydrochory, population dynamics and distribution of the clonal aquatic plant. *J. Ecol.* **1993**, *81*, 81−91.
(21) Nilsson, C.; Brown, R. L.; Jansson, R.; Merritt, D. M. The role of hydrochory in structuring riparian and wetland vegetation. *Bio. Rev.* **2010**, *85*, 837−858.
(22) Säumel, I.; Kowarik, I. Propagule morphology and river characteristics shape secondary water dispersal in tree species. *Plant Ecol.* **2013**, *214*, 1257−1272.
(23) Liu, D. S. New problem of the environmental impact assessment of water diversion construction projects - Biological invasions. *Chin. Environ. Impact Assess.* **2006**, *51*, 11−15.
(24) Liu, J.; Liang, S.; Liu, F.; Wang, R.; Dong, M. Invasive alien plant species in China: Regional distribution patterns. *Divers. Distrib.* **2005**, *11*, 341−347.
(25) Weber, E.; Sun, S. G.; Li, B. Invasive alien plants in China: Diversity and ecological insights. *Biol. Invasions* **2008**, *10*, 1411−1429.
(26) Feng, J.; Zhu, Y. Alien invasive plants in China: Risk assessment and spatial patterns. *Biodivers. Conserv.* **2010**, *19*, 3489−3497.
(27) Wu, S. H.; Sun, H. T.; Teng, Y. C.; Rejmanek, M.; Chaw, S. M. Patterns of plant invasions in China: Taxonomic, biogeographic, climatic approaches and anthropogenic effects. *Biol. Invasions* **2010**, *12*, 2179−2206.
(28) Liu, H.; Geng, L. H. *Risk Management of the South-to-North Water Transfer Project: Key Technology Research*; China Science Press: Beijing, China, 2011.
(29) Liu, H.; Geng, L. H. Risk Management of the South-to-North Water Transfer Project. *South to North Water Transfers and Water Sci. & Technol.* **2010**, *8* (4), 1−6.
(30) State Environmental Protection Administration of China and Chinese Academy of Sciences, *The Announcement About the First List of Invasive Species in China*. 2003.
(31) State Environmental Protection Administration of China and Chinese Academy of Sciences, *The Announcement About the Second List of Invasive Species in China*. 2010.
(32) Diao, Z. S. *Aquatic Weeds in China*; Chongqing Publishing Press: Chongqing, China, 1990.
(33) Ding, J. Q. Water hyacinth. In*Invasive Alien Species in China*; Li, Z. Y., Xie, Y., Eds.;China Forestry Publishing Press: Beijing, China, 2002; pp 188−189.
(34) Jin, X. F. Water lettuce. In *Invasive Alien Species in China*; Li, Z. Y., Xie, Y., Eds.; China Forestry Publishing Press: Beijing, China, 2002; p 187.
(35) Buckingham, G. R. Alligator weed. In *Biological Control of Invasive Plants in the Eastern United States*; Driesche, R. V., Blossey, B., Hoodle, M., Lyon, S., Reardon, R., Eds.; USDA Forest Service: Washington, DC, 2002; pp 5−15.
(36) Center, T. D.; Hill, M. P.; Cordo, H.; Julien, M. H. Water hyacinth. In *Biological Control of Invasive Plants in the Eastern United States*; Driesche, R. V., Blossey, B., Hoodle, M., Lyon, S., Reardon, R., Eds.; USDA Forest Service: Washington, DC, 2002; pp 41−64.
(37) Dray, F. J.; Center, T. D. Water lettuce. In *Biological Control of Invasive Plants in the Eastern United States*; Driesche, R. V., Blossey, B., Hoodle, M., Lyon, S., Reardon, R., Eds.; USDA Forest Service: Washington, DC, 2002; pp 65−78.
(38) Attionu, R. H. Some effects of water lettuce (*Pistia stratiotes*, L.) on its habitat. *Hydrobiologia* **1976**, *50*, 245−254.
(39) Bruner, M. C. Water-lettuce, *Pistia stratiotes* L. *Aquatics* **1982**, *4* (4), 14.
(40) Hill, M. P. The impact and control of alien aquatic vegetation in South African aquatic ecosystems. *Afr. J. Aquat. Sci.* **2003**, *28*, 19−24.
(41) *Invasive Alien Species in China*; Li, Z. Y., Xie, Y., Eds.; China Forestry Publishing Press: Beijing, China, 2002.
(42) Xie, Y. H.; Yu, D. Propagation, ecology and management of Water hyacinth. In *Biology Invasions: Theory and Practice*; Xu, R. M., Ye, W. H., Eds.; China Science Press: Beijing, China, 2003; pp 186−218.
(43) Yin, R. G. The occurrence and hazard of *Alternanthera philoxeroides* in vegetable land. *Chin. Weed Sci.* **1992**, *1*, 13.
(44) Liu, J.; Huang, J. H. Introducing alien plants with caution and avoiding negative effects. *Chin. Plant Prot.* **2002**, *28* (4), 51−53.
(45) Charudattan, R. Are we on top of aquatic weeds? Weed problems, control options, and challenges. In *BCPC Symp. Proc. No. 77: The World's Worst Weeds*; Riches, C. R., Eds.; The British Crop Protection Council: Farnham, Surrey, U.K., 2001; pp 43−68.
(46) Gordon, D. R.; Gantz, C. A.; Jerde, C. L.; Chadderton, W. L.; Keller, R. P.; Champion, P. D. Weed Risk Assessment for Aquatic Plants: Modification of a New Zealand system for the United States. *PLoS One* **2012**, *7* (7), e40031.
(47) Adebayo, A.; Briski, E.; Kalaci, O.; Hernandez, M.; Ghabooli, S.; Beric, B.; Chan, F.; Zhan, A.; Fifield, E.; Leadley, T.; MacIsaac, H. Water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes*) in the Great Lakes: playing with fire? *Aquat. Invasions* **2011**, *6*, 91−96.
(48) Liu, D. S.; Zhang, B.; Liu, R. H.; Zhang, X. J. A study on the invasion and control strategies of an invasive species *Alternanthera philoxeroides* in Xiaoqing River. *Shangdong Environ.* **2006**, *1*, 27−28.
(49) Liu, D. S.; Hu, J. F.; Horvath, D. P.; Zhang, X. J.; Bian, X. Y.; Chang, G. L.; Sun, X. H.; Tian, J. Invasions and impacts of alligatorweed in the upper Xiaoqing River Basin of Northern China. *J. Aquat. Plant Manage.* **2012**, *50*, 19−24.
(50) Julien, M. H.; Skarratt, B.; Mayald, G. F. Potential geographical distribution of alligator weed and its biological control by Agasicles hygrophila. *J. Aquat. Plant Manage.* **1995**, *33*, 55−60.
(51) Peterson, A. T. Predicting the geography of species' invasions via ecological niche modeling. *Q. Rev. Biol.* **2003**, *78*, 419−433.
(52) Herborg, L. M.; Rudnick, D. A.; Siliang, Y.; Lodge, D. M.; MacIsaac, H. J. Predicting the range of Chinese mitten crabs in Europe. *Conserv. Biol.* **2007**, *21*, 1316−1323.
(53) Phillips, S.; Anderson, R.; Schapire, R. Maximum entropy modeling of species geographic distributions. *Ecol. Modell.* **2006**, *190*, 231−259.
(54) Barnes, M. A.; Jerde, C. L.; Wittmann, M. E.; Chadderton, W. L.; Ding, J.; Zhang, J.; Purcell, M.; Budhathoki, M.; Lodge, D. M. Geographic selection bias of occurrence data influences transferability of invasive *Hydrilla verticillata* distribution models. *Ecol. Evol.* **2014**, *4*, 2584−2593.
(55) Trisurat, Y.; Alkemade, R.; Arets, E. Projecting forest tree distributions and adaptation to climate change in northern Thailand. *J.Ecol. Nat. Environ.* **2009**, *1*, 55−63.
(56) Zhao, J. *China Physical Geography*; Higher Education Press: Beijing, China, 1995.
(57) Ren, M. E. *China Physical Geography Outline*; The Commercial Press: Beijing, China, 2004.
(58) Office of the South-to-North Water Diversion Project Commission of the State Council of China. http://www.nsbd.gov.cn/zx/gczs/200603/t20060302_188126.html.
(59) Maddox, D. M. Bionomics of an alligators weed flea beetle, *Agasicles sp*. in Argentina. *Ann. Entomol. Soc. Am.* **1968**, *61*, 1299−1305.
(60) Vogt, G. B.; McGurie, J. U., Jr.; Cushman, A. D. Probable evolution and morphological variation in South American *Disonychine*

DOI: 10.1021/acs.est.6b05577
Environ. Sci. Technol. 2017, 51, 1450−1457

flea beetles (Coleoptera: Chrysomelidae) and their Amaranthaceous hosts. *USDA Technol. Bull.* **1979**, *1593*, 148.
(61) Holm, L. G.; Plucknett, D. L.; Pancho, J. V.; Herberger, J. P. *The World's Worst Weeds: Distribution and Biology*; University Press: Honolulu, HI, 1977.
(62) Hijmans, R. J.; Schreuder, M.; De la Cruz, J.; Guarino, L. Using GIS to check co-ordinates of genebank accessions. *Genet. Resour. Crop Evol.* **1999**, *46*, 291−296.
(63) Sheppard, C. S. How does selection of climate variables affect predictions of species distributions? A case study of three new weeds in New Zealand. *Weed Res.* **2013**, *53*, 259−268.
(64) Phillips, S. J.; Dudik, M. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography* **2008**, *31*, 161−175.
(65) Qin, Z.; DiTommaso, A.; Wu, R. S.; Huang, H. Y. Potential distribution of two Ambrosia species in China under projected climate change. *Weed Res.* **2014**, *54*, 520−531.
(66) O'Donnell, J.; Gallagher, R. V.; Wilson, P. D.; Downey, P. O.; Hughes, L.; Leishman, M. R. Invasion hotspots for non-native plants in Australia under current and future climates. *Global Change Biol.* **2012**, *18*, 617−629.
(67) Fielding, A. H.; Bell, J. F. A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environ. Conserv.* **1997**, *24*, 38−49.
(68) National Bureau of Statistics of China. *China Statistical Yearbook 2014*; China Statistics Press: Beijing, China, 2014.
(69) Mailu, A. M.; Ochiel, G. R. S.; Gitonga, W.; Njoka, S. W. Water hyacinth: an environmental disaster in the Winam Gulf of Lake Victoria and its Control. *Proc. Ist IOBC Water Hyacinth Working Group* **2000**, 101−105.
(70) Mailu, A. M. Preliminary assessment of the social, economic and environmental impacts of Water Hyacinth in the Lake Victoria basin and status of control. In *Biological and Integrated Control of Water Hyacinth, Eichhornia crassipes, ACIAR Proceedings 102, Australia*; Julien, M. H., Hill, M. P., Center, T. D., Jianping, D., Eds.; 2001; pp 130−139.
(71) Lacoul, P.; Freedman, B. Environmental influences on aquatic plants in freshwater ecosystems. *Environ. Rev.* **2006**, *14* (2), 89−136.
(72) Meehl, G. A. et al. Global Climate Projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L., Eds.; Cambridge University Press: Cambridge, UK and New York, NY, 2007; pp 749−845.
(73) Parmesan, C.; Yohe, G. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **2003**, *421*, 37−42.
(74) Hellmann, J. J.; Byers, J. E.; Bierwagen, B. G.; Dukes, J. S. Five potential consequences of climate change for invasive species. *Conserv. Boil.* **2008**, *22*, 534−543.
(75) Rejmánek, M. Invasive plants: approaches and predictions. *Austral Ecol.* **2000**, *25*, 497−506.
(76) Moody, M. E.; Mack, R. N. Controlling the spread of plant invasions: the importance of nascent foci. *J. Appl. Ecol.* **1988**, *25*, 1009−1021.
(77) Liu, F. Alien fish and their damage in Yangtze River basin. *China Nature* **2014**, *2*, 38−40.
(78) Li, X. H.; Hu, Y. C.; Song, H. M.; Wang, P. X.; Wang, X. J.; Mu, X. D.; Liu, C.; Luo, J. R. Invasion and Monitoring Methods of *Pomacea canaliculata* for in China. *Chin. Agr. Sci. Bull.* **2009**, *25* (14), 229−232.
(79) Chen, J. Z.; Shen, G. M.; Meng, S. L.; Qu, J. H. Investigation and study on the aquaculture alien species in the lower reaches of Yangtze River. *Chin. Agr. Sci. Bull.* **2010**, *26* (3), 315−319.
(80) Lawrie, A. H. The sea lamprey in the Great Lakes. *Trans. Am. Fish. Soc.* **1970**, *99*, 766−775.
(81) Nalepa, T. F.; Hartson, D. J.; Gostenik, G. W.; Fanslow, D. L.; Lang, G. A. Changes in the freshwater mussel community of Lake St. Clair: From unionidae to *Dreissena polymorpha* in eight years. *J. Great Lakes Res.* **1996**, *22*, 354−369.
(82) Rothlisberger, J. D.; Finnoff, D. C.; Cooke, R. M.; Lodge, D. M. Ship-borne nonindigenous species diminish Great Lakes ecosystem services. *Ecosystems* **2012**, *15*, 1−15.

DOI: 10.1021/acs.est.6b05577
Environ. Sci. Technol. 2017, 51, 1450−1457