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ORIGINAL ARTICLE

Assessing the historical adaptive cycles of an urban social-ecological system and its potential future resilience: the case of Xochimilco, Mexico City

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Abstract

As the bulk of the world's population becomes urban, maintaining urban ecosystem services for environmental and social well-being in cities is crucial. According to resilience theory, maintaining such services requires for a complex adaptive systems perspective that helps in identifying key elements and dynamics behind cross-scale social-ecological interactions. In this context, the objective of this article is to use a resilience "lens" to problematize the imminent loss of an urban wetland using the adaptive cycle model as a heuristic tool. Our case study focuses on the Xochimilco wetland, located in the southern periphery of Mexico City. Xochimilco is characterized by the presence of a complex system of raised bed wetland agriculture (the chinampa system), which was established over 1000 years ago; currently, despite having a recognized cultural and environmental value, it is threatened by increasing urban sprawl, over-exploitation of the aquifer, and water contamination. By conducting a historical analysis of the Xochimilco social-ecological system, we assess how it has gone through phases of the adaptive cycle. As a result, we identify critical elements of the system's historically maintained resilience and main drivers of system change. From such findings, we present some insights on the possibilities of maintaining the system's resilience and guidance for future management strategies for the Xochimilco wetland. Lastly, we reflect on the scope and limitations of using a resilience-based approach and an adaptive cycle analysis for addressing urban sustainability problems, especially in cities in the Global South.

Keywords Urban resilience · Adaptive cycles · Peri-urban · Wetland · Mexico City · Xochimilco

Introduction

Global urbanization, unprecedented in rate and extent, is one of the main drivers behind climate and environmental change (Seto et al. 2010; Romero and Qin 2011). Global urban land cover is expected to nearly triple between 2000 and 2030 (Seto et al. 2012), which increases pressure on terrestrial and aquatic ecosystems within and around cities that provide such ecosystem services as air purification, water provision, climate regulation, and food production. The bulk of the urban

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expansion globally will be in cities in the Global South, which are often located in highly biodiversity-rich areas while also lacking urban planning and infrastructure that can face such rapid urban expansion, and therefore result in rapid ecosystem degradation (Nagendra et al. 2018). In order to maintain or increase the well-being of city residents over time, it is thus crucial to understand the mechanisms that maintain and foster the provisioning of ecosystem services in and around cities of the Global South.

The city fringe, also known as the peri-urban frontier, is one of the main hotspots of dynamic urban land-use change in the Global South (Lerner and Eakin 2011). Additionally, these areas often do not have the capacity to control or regulate environmental externalities as the areas fall through the cracks of traditional urban and rural planning instruments (Allen 2003). Indeed, urban planning in the Global South is often insufficient to meet the demand for communication infrastructure, housing, and industry, and as a result, as new urban and peri-urban morphologies emerge, natural and agricultural areas are replaced with disjointed urban sprawl (Ayllón-García 2016; Nagendra et al. 2018).

In this analysis, we begin with the premise that megacities, i.e., cities with more than 10 million inhabitants, are social-ecological systems (SESs), meaning that they encompass complex interactions between residents, institutions, and natural resources, linked, in part, by governance and management (Bai et al. 2016; Moglia et al. 2018; Pickett et al. 2011; Eakin et al. 2017). Urban SESs function with feedbacks between social and biophysical elements at different scales, which lead to particular system states. Building resilience in cities means that they can withstand shocks and maintain function, with increased flexibility and innovation, and preserving or enhancing ecological and human well-being (Leichenko 2011; Meerow et al. 2016). Identifying pathways to sustainable, resilient cities capable of supporting human well-being, thus call for a perspective of urban resilience that includes an understanding of the diverse socio-political, economic, and ecological drivers of urbanization, especially in the Global South (Ernstson et al. 2010; Moglia et al. 2018; Nagendra et al. 2018; Eakin et al. 2017).

This article presents an exercise in which the resilience "lens" was used to problematize the imminent loss of an urban wetland, using the adaptive cycle model as a heuristic tool (Gunderson and Holling 2002). In this case, the model is not intended to measure the system's resilience and use it as an indicator in the stricter sense, but rather to reflect on the implications of using a resilience-based approach to address complex urban issues and assess their potential future scenarios. We agree with various authors (e.g., Ernstson et al., 2010; Ahern, 2011; Moglia et al. 2018) that this approach is useful when elucidating ways to address urban planning, as it assists in identifying complex trade-offs, pressures and leverage points, and thresholds which may lead social-ecological systems to desirable or undesirable states. However, we also emphasize that the value of this model lies, in large part, in its potential to enable a systematic reflection on how urban problems have been constructed in complex ways, and how they have evolved in the long-term.

Our case study focuses on the history of social-ecological system states in the Xochimilco wetland of the southern periphery of Mexico City, to understand how to foster the future resilience of the area. Xochimilco is characterized by the presence of a complex agricultural system successfully adapted to a lacustrine environment and which was established over 1500 years ago; currently, it is threatened by increasing urban sprawl, over-exploitation of the aquifer, and water contamination (Mazari-Hiriart et al. 2008; Merlín-Uribe et al. 2013a). By providing a historical analysis of complex adaptive cycles, we investigate the social-ecological system of the Xochimilco wetland over time, assess how the system has gone through phases of the adaptive cycle, and identify critical elements of the system's historically maintained resilience. The current Xochimilco social-ecological system is described, drivers behind current changes were identified, and possibilities for maintaining the system's resilience were discussed against the findings in the analysis. Lastly, we discuss the applicability of a historical analysis of adaptive cycles for exploring future scenarios and assessing management strategies in an urban resilience context.

Background

Urban social-ecological systems and regime shifts

The concept of the social-ecological system refers to societies and nature as autonomous but interconnected systems (Berkes and Folke 1998). Resilience is the capacity of a social-ecological system to absorb or withstand perturbations and other stressors while maintaining its structure and functions. It describes the degree to which the system is capable of self-organization, learning, and adaptation (Holling 1973; Gunderson and Holling 2002; Walker et al. 2004). Changes can be triggered by slow variables that affect the system over time but are difficult to detect, such as biodiversity degradation that leads to losses of species which are essential to ecosystem functioning and fast variables that typically are noticeable in a shorter time span, such as floods or heatwaves (Folke et al. 2004). Researchers are only beginning to understand the functions of slow and fast variables, tipping points, and indicators that allow the detection and prediction of shifts in social-ecological systems, such as when urban growth turns from urban densification to urban sprawl or when clear lakes turn turbid after excess nutrient load (Biggs et al. 2012a; Scheffer et al. 2012).

An increased understanding of social-ecological system states is particularly important in cities, since cities are nested social and ecological systems where interactions between temporal and spatial scales are highly complex (Eakin et al. 2017). Local and global drivers work simultaneously in urban social-ecological systems affecting ecosystems services on which urban services depend (Alberti et al. 2018). Governance, planning, and innovation are needed not only to sustain ecosystem services for the cities, but also to sustain and build resilience, especially in the most vulnerable populations (Diaz et al. 2006; Ernstson et al. 2010). Resilience theory provides some insights to redefine how cities can be managed to cope with disturbances by integrating the shape of the city into the ecosystem landscape at a regional scale in order to have positive feedbacks between both human and environmental systems (Ernstson et al. 2010), and allows complex trade-offs to be considered in decision-making (Moglia et al. 2018).

One of the central aspects of resilience theory is the concept of adaptive cycles, which is the idea that social-ecological systems exhibit dynamic cycles of change, where a system transforms from one state into another (Gunderson and Holling 2002; Fath et al. 2015). Although easier to understand with ecological indicators (i.e., savanna shifts states through desertification), cities are interesting systems to study adaptive cycles, and especially in the peri-urban frontier where dynamic change is taking place. The typical adaptive cycle includes four phases which encompass periods of relative growth, stability, decrease, perturbation, and collapse, identified by phases r (exploitation), K (conservation), Ω (release), and α (reorganization) (Gunderson and Holling 2002). A resilience and adaptive cycle-based approach considers change as the rule and not the exception in systems' dynamics, thus articulates with principles of adaptive management rather than looking for optimal control of the systems' elements and behavior (Anderies et al. 2006). Given the importance of understanding and promoting city resilience, this analysis uses a resilience-based approach to problematize the loss of an urban wetland, using the adaptive cycle model as a heuristic tool, and to reflect on the potential of this perspective for addressing urban sustainability problems.

Case study: the Xochimilco wetland of Mexico City

Mexico City lies in the Valley of Mexico, built on the former lake bed of five brackish and freshwater lakes, and where the old capital of the Aztec Empire, Tenochtitlan, was located. The Xochimilco and Chalco freshwater lakes were used for a sophisticated system of wetland agriculture to sustain the Aztec population, where human-made islands or chinampas separated by canals were used as production sites (González-Pozo et al. 2016). The aquatic and terrestrial systems functioned in symbiosis, making the chinampas highly productive and the societies largely self-sufficient (Rojas 1995). When the Spanish conquered the area, they transformed the villages and the lakes, and wetlands were gradually drained starting in the 1600s. The construction of increasingly sophisticated drainage systems aimed to dry the muddy soil and to protect the emergent city from flooding, irreversibly changed the basin hydrology, and the chinampas drastically declined as an effect (Ezcurra 1990).

Mexico City rapidly expanded between the 1950s until the late 1990s, mostly due to an influx of migrants from rural areas as an effect of industrialization. Currently, the Mexico City Metropolitan Area (MCMA) is a vibrant megacity with 21.3 million inhabitants across three states (Mexico City, the State of Mexico and Hidalgo) (INEGI 2017). Even though the city already has experienced its fastest growth rates, it continues to grow and expand, primarily outwards, and in no small degree uncontrolled, i.e., formal and informal urban sprawl. The city is facing several other challenges, many of them connected to water as Mexico City's location on a lake bed increases the risk of subsidence, a phenomenon that already is causing infrastructural damage, flooding, and a scarcity of potable water (Chaussard et al. 2014).

Xochimilco is the third largest of the 16 municipalities in Mexico City, covering over 125 km^2 or 8.4% of the city's territory, and housing 415,933 inhabitants, 4.7% of the total population of the city (INEGI 2017). It is located in the southeastern zone of the city, originally established at the southern shore of Lake Xochimilco. The area connects the freshwater-producing southwestern catchment area that supplies surface freshwater for irrigation and groundwater aquifer recharge for Mexico City. The landscape in Xochimilco consists of three main regions that are distinguished from the relief, namely, the mountain area, the transition area, and the wetland area, which is the focus of this paper.

Currently, the Xochimilco wetland has a recognized cultural and environmental value and is, at the same time, one of the greatest sustainability challenges of Mexico City. On the one hand, it houses the remnant of the pre-Hispanic chinampa system (raised bed wetland agriculture), it is one of the most important sources of groundwater used for water supply for the city, it serves as a flood regulating area within the basin, it modulates the microclimate, and it is home to endemic species and a passage site for migratory birds, which led to its designation as a World Heritage Site by the United Nations Educational, Scientific and Cultural Organization (Fig. 1). On the other, it is composed of a very diverse mosaic of land uses that includes productive chinampas with different technologies, abandoned land, informal settlements, wetland, canals, and water bodies. It reflects characteristics typical of peri-urban spaces in the Global South, such as high population density, high social inequality, proliferation of irregular human settlements, poor solid and liquid waste management as well as inefficient governance schemes (Wigle 2010; Merlín-Uribe et al. 2013a).

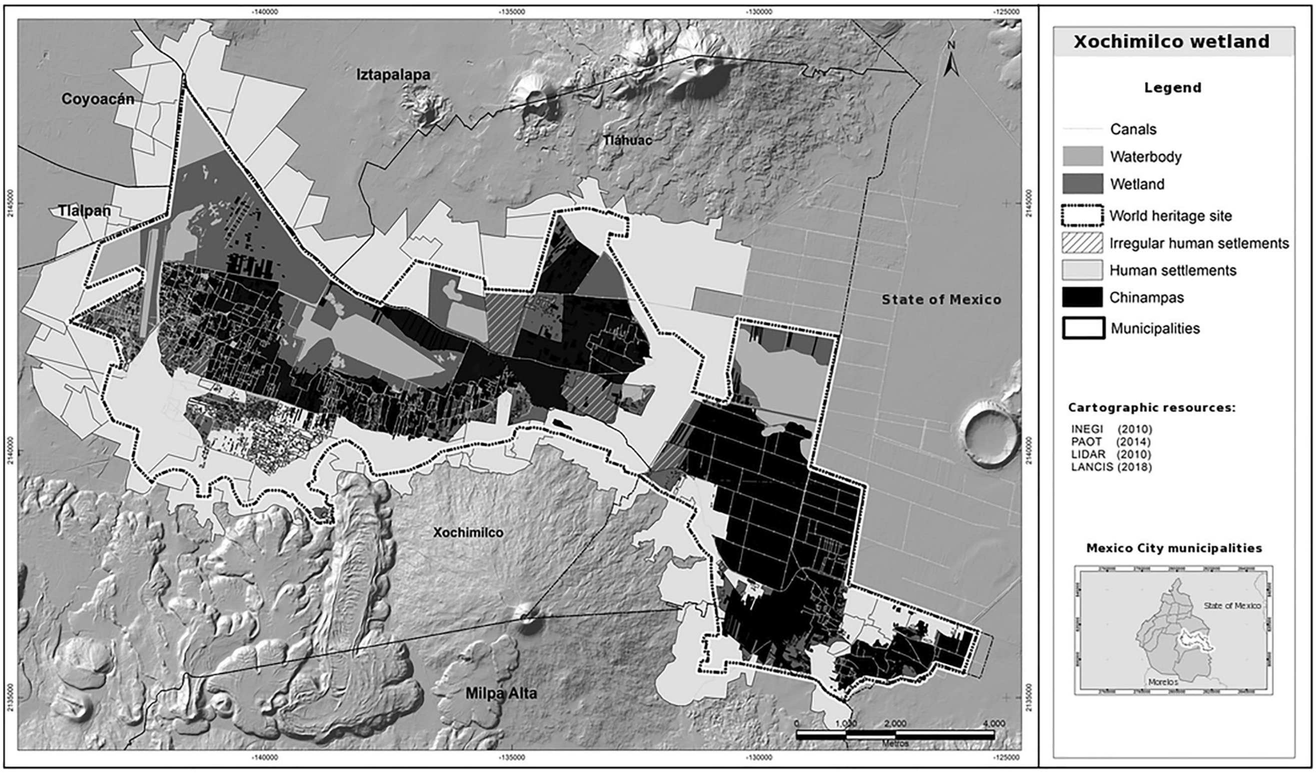

Fig. 1 Map of the Xochimilco World Heritage Site and associated land-cover. Author, Fabiola Gress

The remaining chinampa system is today threatened by new agricultural technology (i.e., greenhouses with agrochemical inputs), intensive groundwater extraction, agricultural abandonment, and contamination. For example, the production area loses 31 ha annually, and the area of greenhouses expands by 14 ha annually (Merlín-Uribe et al. 2013a). The chinampa production area suffers from urban sprawl mainly in the form of informal urbanization. In the Xochimilco municipality, 6% of its conservation area (~ 625 ha) has been transformed into informal settlements (GDF 2012; Wigle 2010).

Methods

This study began with a historical analysis using a complex adaptive systems approach in order to understand the historical resilience states of the Xochimilco wetland, and identifying elements and dynamics that have been central to the social-ecological system's functioning over time. The analysis was based on a critical literature review, field trips to Xochimilco, participant observation for 3 years (2016–2018), and 15 formal and informal semi-structured interviews conducted with four residents, eight farmers, and three representatives of local government institutions. The literature review included scientific articles, books, local conservation and development plans, and gray literature regarding the social and environmental history of the Xochimilco wetland and the chinampa system. The interviews focused on five main topics, i.e., the perceived social and environmental problems in the wetland area; the main challenges for maintaining the traditional chinampa system; the role of local authorities, NGOs, international figures, and farmer's and resident's institutions in the survival/loss of wetlands and traditional agriculture; in the case of farmers, the production process, in the case of chinampa owners, the chinampas characteristics and prospected changes.

The information gathered from the literature review was organized into a matrix of historical events, which allowed the identification of the key historical stages. Through a qualitative analysis, the dynamics of the social-ecological system were identified, including relative growth, stability, decrease, perturbation, and collapse, in each historical stage. Then, the dynamics were then translated into the phases r (exploitation), K (conservation), Ω (release), and α (reorganization) of the adaptive cycle model. The information gathered from the interviews helped to characterize the current social-ecological state of the Xochimilco wetland, and to take into account local actors' perspectives while conducting the historical assessment and reflecting on future perspectives.

The analysis incorporates elements of the social subsystem (i.e., population growth and cultural and identity shifts), the environmental (i.e., water quality and biodiversity), the economic (i.e., productive activities and land values), and the spatial (i.e., trends of land-cover/land-use change and urban area expansion). Of particular interest were those elements that have been critical for (a) crossing tipping points or the point of inflection of the conservation phase to the release phase and (b) overcoming moments of crisis in the reorganization of the SES in phase α. From this approach, we identified key elements for system functioning and historical drivers of system change. The social-ecological system of reference was the traditional chinampa system of the Xochimilco wetland, characterized by highly productive agriculture, a sustainable use of water, an interconnection between the producers and the lacustrine environment, and a strong social and cultural value related to its agricultural identity. Thus, the criteria for considering a shift in the system's state were based on the identification of drastic qualitative or quantitative changes in any of these characteristics.

Results

Historical stages of the Xochimilco wetland as adaptive cycles

In this section, we describe the history of the Xochimilco wetland organized into three main historical stages and their reinterpretation as three adaptive cycles of a SES. Historical stages refer to a series of events that shaped a system's dynamics in a certain period and describe how the system evolved until suffering a major social-ecological change. Each historical stage is then re-explained as an adaptive cycle, describing the transitions between cycle phases (r, K, Ω, and α) and synthesizing key system elements and dynamics. In this analogy, both historical stages and adaptive cycles follow the same temporal continuum; however, adaptive cycles illustrate an iterative dimension of system dynamics over time. As presented below, the analysis showed that the system has been through three adaptive cycles and is currently in the K-phase of a third cycle (Fig. 2).

Historical stage 1. The pre-Hispanic and early colonial period (late 1300s–early 1700s)

The first wave of massive construction of the chinampas occurred between 1426 and 1467 (Calnek 1972), coinciding with the peak of the Aztec Empire. Chinampa agriculture evolved into a highly productive and efficient system that included not only the cultivation of agricultural products but also their transportation and distribution through a complex network of canals extending through the city of Tenochtitlan, the capital of the Aztec Empire. The chinampa system produced approximately 50% of the food consumed by the population of the Basin of Mexico (Ezcurra et al. 2006). It is estimated that at its peak, the area of chinampas reached an extension of over 116 km^2 (Armillas 1971). This system was

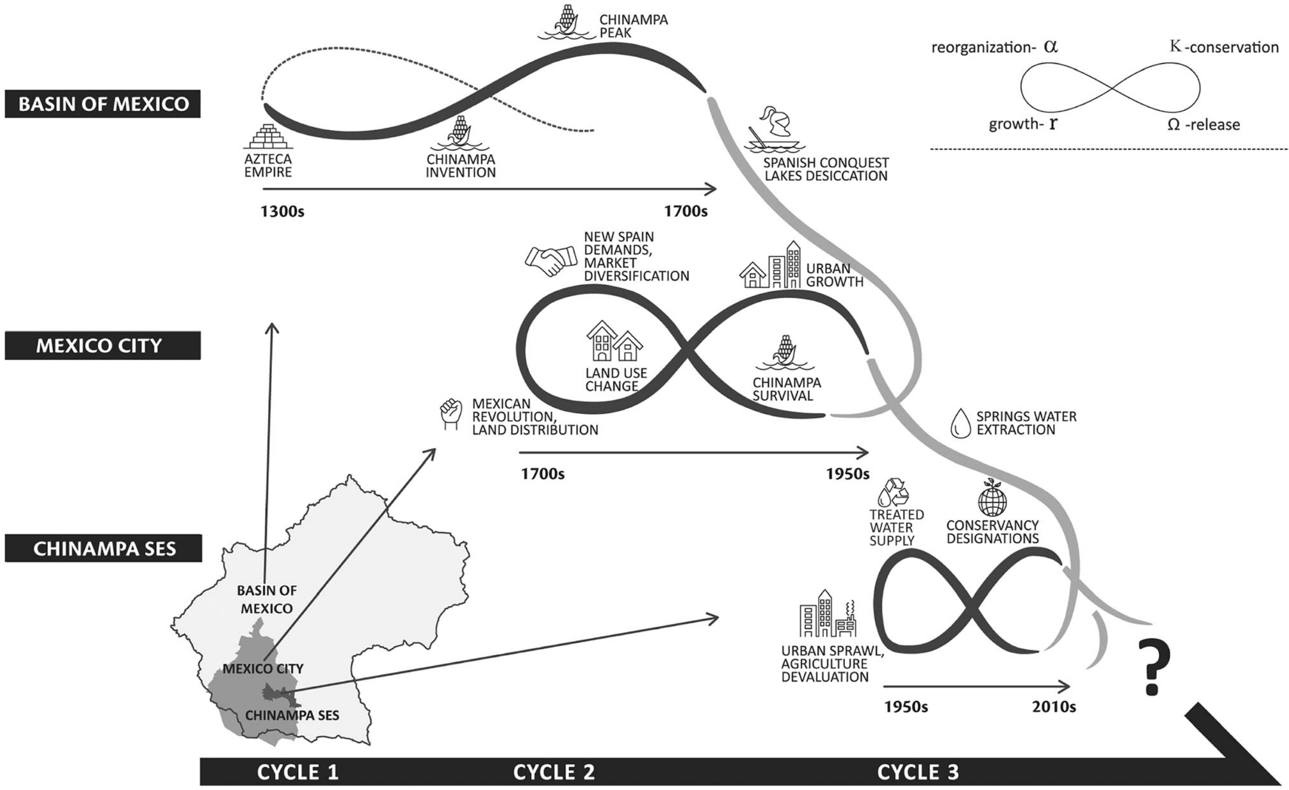

Fig. 2 Adaptive cycles of the Xochimilco wetland occurring at different temporal (axis *x*) and spatial scales (axis *y*) from the 1300s until 2019

important not only for its productive capacity but also for the efficiency of the canal network that enabled the communication as well as the distribution and exchange of products across the lake territory.

Spanish conquerors invaded Tenochtitlan in 1521. Being unable to adapt to a wetland-based way of life; the conquerors transformed the environment to make it drier and more suitable for the construction of the Spanish city model. The Spanish conquest severely affected the functioning of the lakes and ultimately led to reduction of the water levels within the basin. This first serious impact, the destruction of the pre-Hispanic hydraulic system, triggered a series of severe floods during the second half of the sixteenth century that turned water into the main enemy of the new city. In 1607, the first of several drainage projects with the objective of eliminating the risk of flooding in the city and draining the muddy subsoil from the bottom of the lake began in the Basin of Mexico (Ezcurra 1990). Although these projects were concentrated in the northern part of the city, the lakes of the South, including Xochimilco, were severely affected, and therefore the chinampa system was reorganized to be concentrated in the remaining lakes.

Adaptive cycle 1

The first adaptive cycle of the system corresponds to the historical stage 1. This cycle includes the origin of the chinampa system in the Basin of Mexico (r phase); its development, expansion and peak production (r-K transition), and the first system collapse (K-Ω transition). The system collapse can be derived from the disappearance of a significant part of the system due to the desiccation of the northern lakes. The cycle concludes with the spatial reconfiguration of the system concentrated in the southeastern portion of the basin (Ω-α transition), into a new spatial configuration in which the system continued to be functional (α-r transition).

In this cycle, the evolution of the system to one highly efficient in terms of yields, use of environmental resources, use of space and methods of transportation, and distribution of agricultural products characterize the r-K transition. We identified two elements that are particularly important for this transition: (1) the emergence of a symbiotic relationship between the chinampa system as a food source and the food consumption by the inhabitants of Tenochtitlan, and (2) the optimal functioning of the canal network, which was fundamental to achieve the efficiency that characterized the system in pre-Hispanic times. The key element that triggers the K-Ω transition in this cycle is a drastic change in the hydrology of the basin, derived from the intentional draining process for the construction of the new Spanish city.

Historical stage 2. Late colonial period, Mexican independence, Agrarian Reform, and Mexico City expansion (early 1700s–1950s)

During the colonial period, drainage efforts continued while the canal system connecting the chinampa areas with the capital city remained active. Although reduced in size, the chinampa production system was maintained during Spanish rule; despite the adversities, the productive system was enriched with agricultural varieties brought from Europe and the symbiotic relationship continued between the chinampas and Mexico City consumption. The chinampa, designed as an agricultural production system, proved crucial for the colony's survival after the conquest, since European farming systems were not suitable for the environmental and topographical conditions of the Basin of Mexico. This also explains the fact that large landholdings for farming (haciendas) were never developed in this area and, as a result, indigenous populations had the primary influence on the landscape (González-Pozo et al. 2016).

Mexico became independent in 1821, and the national and local administrative processes subsequently changed. In the post-colonial era, population growth in lakeside settlements was already a factor, disturbing the natural hydrology and environmental condition of the wetlands as they were being transformed into land intended for human settlements, rainfed agriculture, and livestock exploitation (Ezcurra 1990). Despite the political, demographic, and environmental change, the Xochimilco wetland remained a chinampa agricultural area dedicated to the production of vegetables and flowers, and the canals remained the primary way to transport goods and people (Sanders 1976). In 1850, the first steam line connecting Xochimilco with the center of Mexico City was inaugurated, which further intensified the communication between these two areas (González-Pozo et al. 2016).

Towards the last decades of the nineteenth century, because of territorial and population growth, Mexico City's metropolitan area began to exhaust its local sources of water supply. A study from 1883 concluded that the only solution to the city's water needs was to bring water from the springs of the southern region of Xochimilco to supply the city (Hernández 2003; Peñafiel 1884). The effective usurpation of water from the Xochimilco springs began at the end of the nineteenth century with the construction of the "Gran Acueducto" (the great aqueduct was built to take spring water from Xochimilco and transfer it to the center of the city), marking the end of a stage of survival of the chinampa system and the beginning of a phase of deterioration that would advance at an unprecedented rate. The Xochimilco water extraction for the public supply of Mexico City increased until reaching the point where the inhabitants of Xochimilco did not have the necessary water supply to satisfy their basic needs nor maintain their productive activities. Between 1954 and 1958, the canals became practically dry (Arechiga 2004; Romero 2004).

At the same time, the Mexican Revolution led to land redistribution across the country and encouraged smallholder agriculture. However, a set of changes in the Agrarian law incorporated between 1930 and 1950 made it more difficult to get land titles in the chinampa production area. The difficulty of titling land coupled with the unstoppable growth of Mexico City led to a critical period for the chinampa system characterized by a sharp devaluation of agricultural land and a steep increase in its value as housing land.

Adaptive cycle 2

The second adaptive cycle begins with the reorganization of the system after the first collapse (α). Key elements for the reorganization were: (1) the permanence of the southern lakes and the survival of the local canal network due to a concentration of the drainage efforts to the northern part of the basin, (2) the efficiency of the pre-Hispanic agricultural production system versus that of the Spanish, and (3) the importance of the area of the southern lakes as food supplier for the city.

The r-K transition of the second adaptive cycle begins in the eighteenth century, when the chinampa system, in its new spatial configuration concentrated in the southeastern end of the Basin of Mexico, begins to flourish. This transition corresponded, on the one hand, to the recovery of the agricultural system's efficiency and the increase of its complexity as a result of the diversification of crops, technologies, and abilities developed by the chinampa producers, combined with the increasing importance of the canal network, which was the basis of transport and commerce. On the other hand, it corresponded to the K phase of this transition, as administrative changes linked to the Agrarian Reform paradoxically complicated the legal situation of many chinampa areas, federal policies promoted other forms of agriculture, and Mexico City grew spatially and demographically, which increased the demand for water and land for urban uses. These factors increased the system's vulnerability in the face of internal and external pressures. In this context, one critical element to detonate the inflection towards the second collapse (K-Ω) is the decision of local authorities to pipe the Xochimilco springs to supply water to central Mexico City. Systemic collapse, as such (Ω), is reached with the drainage of the canals in the 1950s.

Historical stage 3. The urban demographic explosion, environmental crisis, and recovery efforts (1950s to present)

In 1959, Mexico City's government tried to compensate for the damage to the Xochimilco canal network by supplying partially treated sewage water to the canals. The poor water quality caused such social discontent that the government began the operation of the first wastewater treatment plant, the "Cerro de la Estrella," to supply the lake area with cleaner water. Although the improvement in water quality was incipient, this process allowed agriculture to remain in the area (Merlín-Uribe 2009). However, in a parallel process, the canals that connected the Xochimilco wetland area to Mexico City had been turned into paved avenues by 1950. The terrestrial roads, coupled with the country's growing road network, led to the arrival of agricultural goods from outside the city, which created an increasingly competitive market for chinampa farmers (González-Pozo et al. 2016).

The industrialization of Mexico in the twentieth century resulted in massive migration of peasants to large cities. In Mexico City, immigration became especially evident in the periphery, leading to informal human settlements, without services and land title, in ecological and agricultural areas that included the wetlands (Canabal et al. 1992). In the 1960s, the urban area of Mexico City grew by 47% and reached Xochimilco for the first time (ibid.). Over this period, the main impacts on water quality were linked to the scarce water flow within the canals system derived from increasing water extraction, and with the waste and sewage discharged directly into the canals in the settlements without sewer systems (Canabal et al. 1992; Aguilar et al. 2006; Zabaleta 2010). Among the consequences of water extraction, it was recorded that by the 1970s, some of the chinampa land had become saline with a low productivity leading to a drastic decline of the agricultural population in the chinampa area (Merlín-Uribe 2009). The incorporation of rural spaces into the city also caused a transition of livelihoods from agriculturally based to industrial- or service-based livelihoods, and consequently a devaluation of peasant farming. This situation greatly impacted the younger generation to opt out of agriculture and led to the diversification of land uses in traditional chinampa areas.

In 1985, an 8.1 magnitude earthquake devastated Mexico City, affecting the Xochimilco wetland in two main ways: one, it activated a geological fault line that crosses the lacustrine zone, which led to some cracks and differential subsidence in the chinampa area affecting canal levels; and two, many families moved to Xochimilco from the city center, most of whom were affected by the earthquake (Romero 2004). As a result of the seismic disaster, the Mexican government agreed to two Technical Cooperation Programs with the United Nations Food and Agriculture Organization (FAO), which concluded in 1987, and led to the creation of the "General Rescue Plan of Xochimilco." Over the following years, different international institutions recognized the Xochimilco wetland's ecological and cultural value. In 1987, UNESCO declared the remnants of the chinampa area of Xochimilco a World Heritage Site, and it was also included in Mexico City conservation area. In 1992, a natural protected area was created; in 2004, it was declared a Ramsar (Convention of Wetlands) site; and in 2017, it was designated as a Globally Important Agricultural Heritage System by the FAO. Under all of these designations, 80% of the wetland area became legally protected, which helped to decelerate, to a certain extent, the urbanization process and led to the official publication of the Management Plan for Xochimilco in 2006 (GDF 2006).

Meanwhile, the green revolution of Xochimilco agriculture, which began in the early 1990s, acted as a crucial driver for significant changes in the traditional agricultural techniques. The technological development increased product yields, diversified agricultural activities including horticulture and planting of ornamental plants, diversified job opportunities, and promoted agriculture as a means to preserve the area. However, it also exacerbated environmental problems and eroded the link between the farmer and the cultural significance of the chinampas (Merlín-Uribe 2009).

Since the 1980s, the discourses that underlie conservation strategies in the area changed, moving from one of protection through policy instruments to one of sustainable use that gives greater importance to the participation of local actors such as farmer associations and NGOs. Valuing the ecological and cultural features of the chinampa has been increasingly recognized as a wetland conservation strategy. While the first rescue actions involved the expropriation of chinampa land to create an ecological park operated by the government, initiatives since then have increasingly turned to suggest reviving traditional farming techniques, for example, to meet the demand for organic products in the city.

Adaptive cycle 3

In the third cycle, post-collapse reorganization (α) is based on the water replenishment to the canal network through the supply of treated water, which although not in the best condition allowed the system to recover functionality. In this cycle, the r-K transition begins at a time of explosive urban growth associated with massive rural-urban migration. At this stage, numerous families from other regions arrived, the lack of clarity in the land titling and tenure leads to the proliferation of informal settlements, land speculation in Xochimilco continued to increase, the value of agricultural land decreased rapidly, and a mixture of land uses spread.

The Mexico City earthquake of 1985 marks the beginning of the phase K of the third cycle, leading to the first attempts of “rescuing” Xochimilco. The phase K, in which the system is located at the time of writing this article, is characterized by the creation of various public policy instruments aimed at recovering and preserving Xochimilco wetland, which coexist with pressures such as urban expansion, the continuous groundwater extraction for urban supply, environmental degradation, and a decreased interest in engaging in agriculture. Despite these pressures, the system remains relatively functional; however, the size of the area continues to decrease. Table 1 summarizes the interactions between fast and slow variables through each adaptive cycle, as well as the main drivers of transitions between cycles and reorganization processes.

Drivers and thresholds of change

The Xochimilco wetland illustrates that despite the pressure of urbanization in one of the largest metropolitan regions in the world, some elements have allowed the system to survive for more than 700 years. According to our analysis, some of these key elements in its persistence are (a) the continued existence of a market for chinampa products, mainly in Mexico City; (b) the efficiency of the traditional system, its relatively low cost of production, and the fact that it hardly requires external agricultural inputs, which has made it possible for local producers to keep farming despite challenging economic, political, and environmental conditions; (c) the high social and cultural value of chinampa agriculture, which helps explain the interest of chinampa producers in maintaining agriculture; and (d) the multifunctional nature of the traditional system that combines agricultural productivity with the maintenance of a healthy lacustrine environment and diverse ecosystem services, which has in turn led different actors and institutions to show interest in its survival.

Although the social-ecological system of Xochimilco persists, it is not necessarily following a sustainable path or contributing to the resilience of Mexico City, since the system exhibits environmental degradation. The future of a sustainable Xochimilco wetland depends on its resilience, understood as an attribute that changes over time and scale, but further interventions and management needs to be based on an understanding of possible regime shifts and should address key variables for change to which the system will need to respond. Then, learning from past events in the SES resilience can allow for the emergence of strategies to move the system towards sustainable trajectories through active management (Walters 1986).

The historical adaptive cycles analysis illustrates those main elements interacting in different system states and provides some insights into future trajectories of the Xochimilco wetland. In this case study, the resilience and adaptive cycles approach shows a time and space compression in the context of urban encroachment and its impacts on the social-ecological system (Fig. 2), highlighting the fact that current decision-making is taking place in an extremely dynamic context that is a result of the historical interaction of the system elements.

Recognizing that Xochimilco’s SES identity and multifunctionality is defined by its capacity to be productive (i.e., having chinampas, water for irrigation, farmers, market), to maintain the ecological processes of the wetland (i.e.,

Table 1 Slow and fast variables by adaptive cycle, and drivers of transitions from the origin of the chinampas to the present

Adaptive cycle	Slow variables	Fast variables	Collapse for a transition to Ω	Process for reorganization (Ω-r)
1 (r-K-Ω) From late 1300s to early 1700s	Creation, expansion, and peak of the chinampa system in the Basin of Mexico (r-K phase)	The building of a Spanish model city over the old Tenochtitlan	An irreversible disturbance of the hydrological conditions in the Basin of Mexico	Diversification of chinampa products Preservation of chinampa system in the southeastern part of the basin
2 (-r-K-Ω) From early 1700s to1950s	New politics supporting rainfed agriculture and land redistribution Urban growth and increased water demand	Conflicts over property rights Consolidation of road network Piping of Xochimilco's water	Decreased value of agricultural land Extreme water scarcity in the canal system and affectations in water quality Drastic changes in agricultural products market	Protests against water extraction Supply of treated wastewater into the canals
3 (-r-K-Ω) From 1950s to the present	Migration processes (rural-urban and city center-periphery) Devaluation of peasant livelihoods The Green Revolution and the Sustainable Development discourses appear	Mexico City limits reach the Xochimilco area, emerging a very complex peri-urban fringe The 1985 earthquake International cooperation to protect Xochimilco environmentally and culturally	Local collapses related to Land value shift (from agricultural land to housing land) Conservationist rhetoric with little interest in agriculture Drastic social and demographic change (livelihood change, generational shifts, migration)	Elements that allow for the system to persist Recognition of agriculture as a conservation strategy, reinforced by NGOs and academics Alternative urban markets for chinampa products

keeping its biodiversity, water retention) and its cultural value and identity, we identified a set of drivers that have recurrently influenced the system states over time. Although these drivers tend to be correlated and are impossible to tease out completely, they can serve as a first step for assessing system functionality, and its monitoring may help to anticipate thresholds for future regime shifts. These key drivers are water quantity and quality, the existing markets for chinampa products, the sociocultural value of chinampa agriculture, social organization in favor of traditional agriculture, and local effects of global and regional forces (such as policies and climate change). We suggest that such drivers should become the main targets for public policy aimed at building resilience towards a sustainable trajectory in the Xochimilco wetland, which can also have an impact in Mexico City since they are nested systems.

Water quantity and quality

As shown in the historical analysis, the observed regime shifts were driven mostly by two drastic changes in the hydrological subsystem that supports the chinampa agriculture and hence the ecosystem's function. One was the desiccation of the lakes during the Spanish Conquest, and the second, the piping of the natural springs that naturally recharged the canal system. Both decisions occurred in a short temporal scale and affected spatially the whole social-ecological system of Xochimilco. Currently, local decisions are slowly affecting water quantity and quality. As informal urbanization increases, it also discharges sewage and solid waste into the canals. At the same time, agricultural intensification expands and relies on agrochemicals. Thus, water quality is increasingly unfit for agricultural use and maintaining habitat for native organisms (Mazari-Hiriart et al. 2008; Merlín-Uribe et al. 2013b). One obvious connection between drivers is that without an adequate quantity and quality of water, agriculture cannot be sustained. Hence, it is also essential to address socio-institutional drivers, such as market access for producers and traditional agro-ecological techniques, that would positively affect water quality.

Markets for chinampa products

Chinampa production survived during the second adaptive cycle due to the diversification of its products to sustain the Spanish and Mexican demands. Currently, chinampa production does not supply most of Mexico City's food demand, which is mainly fulfilled by products that come from the nearest states to the capital and are sold in the central distribution center in the city and through supermarkets with their own supply chains. Additionally, due to the erosion of this symbiosis between Xochimilco and Mexico City, all chinampa producers must pass through several intermediaries and receive relatively low prices for their products. Some studies suggest that local demand and shifts in consumer habits are a factor that could retain or even expand agriculture in peri-urban areas (Lerner and Eakin 2011). In this particular case, the increased demand of chinampa products can also encourage farmers and consumers to demand local authorities that they provide sufficient and high-quality water for irrigation. Some local NGOs are working with farmers and urban consumers in Mexico City to create new market chains through local consumption and organic produce to fuel traditional chinampa agriculture and contribute to environmental conservation (i.e., Villagrán et al. n.d., Toyzan 2015). The creation of new networks between consumers and farmers enhance connectivity, which is a key element to boost sustainable cities (Ahern 2011; Anderies et al. 2006; Walker et al. 2006). Consequently, one window of opportunity for agricultural retention could come from urban residents involved in movements that value local products.

Socio-cultural value of agriculture

The socio-cultural value of the chinampa system seems to be one of the main reasons why it has persisted for the last 700 years. However, as is the case in agricultural systems throughout the world, farming has become devalued as younger generations engage in other activities and diversify their livelihoods (Elias et al. 2018; Kay 2015; Lerner et al. 2013). In the case of Xochimilco, agriculture is not as profitable as other urban employment options, which reduces interest in farming. This highlights the importance of the current work that civil society organizations do through environmental education programs, conservation initiatives, and organic farming advocacy since it contributes to shifting the vision of Xochimilco. The revaluation of chinampa agriculture through innovation in the production chains could promote the engagement of young farmers, and thus result in the maintenance of the system in its current conservation phase (K) or even to move towards a reorganization phase (a) without having to experience a collapse (Ω), as Moglia et al. (2018) suggest.

Social organization for agricultural retention

The revaluation of the chinampa as an agricultural unit must be accompanied by the recognition of the current ecological value as an ecosystem services provider, and the inclusion of various social actors to activate a governance process that could recover the system through new forms of adaptation. Nonetheless, the social fabric of the system is currently eroded since different actors base their decisions on individual rather than collective gain (see Eakin et al. 2019). For example, concerning land use, after the Mexican Revolution and the subsequent Agrarian Reform, land tenure became either communal or private. Since that shift, families have been dividing and distributing land to the younger generations, but with the abandonment of agricultural activities and the economic impossibility of acquiring land in urban areas for housing, they built houses in the chinampas. Building on chinampa land, which is technically a protected area, is not allowed but it is often not sanctioned by the authorities because it is linked to corruption as local politicians look the other way in exchange for votes (Aguilar 2008; Wigle 2010; Lerner et al. 2018). This mixture of different stakeholders and interests and institutional inconsistencies makes it more challenging to manage resources or guiding drivers towards a desirable sustainable pathway.

Global and regional forces

The international and national denominations for the chinampa system have attracted attention for its ecological and cultural value, which in turn has been a key factor in maintaining it in the conservation phase. However, urbanization and the loss of agriculture along with social-ecological degradation continue, and the risk of Xochimilco to lose its denominations is latent. Additionally, forces such as climate change increase the vulnerability of the system, reducing its ability to adapt to rapid changes and events like frosts, intense droughts, and severe floods. Therefore, current global and regional discourses could push the political agenda towards more sustainable actions as long as it includes local participation. For example, if the population of Mexico City demands more local organic products, this could represent an opportunity to create new markets for farmers, encouraging them to change their practices while giving their products an added value. Another opportunity is presented through eco and agro-tourism, since Xochimilco is a popular tourist destination but more ecologically oriented tourism is not well-developed. These actions can adjust the system for future stress and serve as strategies that can lead to the system's resilience and capacity to manage regime shifts.

The more in-depth exploration of the drivers of regime shifts in the Xochimilco wetland presented in this analysis shows an example of social-ecological interdependencies. Therefore, it is possible to argue that innovative interventions targeting those particular drivers can trigger cascading reactions that might result in a transformative process towards a sustainable state as Anderies et al. (2006) suggest. In other words, in order to formulate sustainable strategies for the system, one must understand connections between drivers and the possible effects and trade-offs that can exist among them.

The illustration of the historical context and its analysis with an adaptive cycle and resilience approach is useful to identify the drivers of change and the subsequent possible futures of the system. In order to recognize possible future scenarios, it is crucial to consider that there are several stakeholders with different interests and motivations, which can influence the thresholds for a regime shift. Therefore, it is essential to analyze further how decision-making processes are made in order to propose more sustainable trajectories. For example, how can farmers continue to adapt and preserve the wetland agriculture when water quality is unsuitable for agriculture or market prices are too low to invest in farming? Understanding motivations and decision-making processes can lead to interventions that can provoke a regime shift (i.e., transformation) to a state that could be more sustainable (Chelleri et al. 2015).

Future management regimes of the Xochimilco SES, like other urban SES in the Global South, should address the demands that the system will need to respond to, such as urbanization and climate change, and the functions that are critical to maintaining ecosystem services for the city and to foster system resilience. In this case, drivers or systemic elements discussed above are fundamental to propose strategies that should aim to: 1) halt urbanization, 2) sustain the water supply with a suitable quality for irrigation that would also help the recharge of the aquifer in the long term, 3) promote new markets for producers, and 4) promote land-use planning that integrates different stakeholders in the face of global changes. If this is not achieved, then the system may fall into an unsustainable trajectory, probably towards the loss of the Xochimilco wetland, and hence city resilience.

Conclusions

The current remnant of the Xochimilco wetland is still highly resilient, albeit in an undesirable system state and with an unknown future trajectory. The variables that we identify through the adaptive cycles analysis have different effects on the dynamics of the system depending on the specific spatial and temporal scale in which they are observed. This type of historical evaluation can help to understand the trade-offs between the variables, and the approach can be useful in the planning of future interventions. From a resilience perspective, such interventions can be directed, on the one hand, to minimize the consequences of a new collapse, or on the other, to foster a transition to a phase of reorganization in which premeditated innovation strategies direct the trajectory of the system towards a more sustainable and desirable state. Therefore, it is crucial that further resilience-oriented strategies for Mexico City, as for other cities undergoing rapid change and facing uncertain futures, consider a historical analysis and explore scenarios based on maintaining crucial functions of the system.

The Xochimilco case study shows that complex urban problems can desegregate and organize into a relatively “simple” series of events for allowing systematic reflection on system dynamics and elements behavior over time. By doing this, our analysis shows that building urban resilience requires a social-ecological systems perspective on urban problems, as well as a deliberate interest in understanding the fast and slow variables that underlie them. A resilience and adaptive cycles approach will not automatically determine optimal solutions for such problems. However, it certainly can provide valuable insights for urban planning by revealing key system elements and cross-scale interactions that might be neglected by more narrow and single goal–oriented perspectives. Furthermore, it can provide a broader framework for evaluating specific management strategies.

The historical assessment also revealed an acceleration in the SES’s dynamics over time, while the first cycle lasted about 400 years, and the second one about 250, it has taken less than 80 years for the system to reach the critical K phase of the third cycle. We think this feature might be a recurrent characteristic of SES that gain significant complexity over time (see, for example, the case of the Galápagos SES in González et al. 2008) and consider that in the absence of strategic management measures, such behavior increases the system’s risk of losing resilience. Cities and their peri-urban fringe, especially in the Global South, are a very good example of this situation as they face continued expansion and population growth, accompanied by rapid socioeconomic, cultural, environmental, and technological changes. As the world population increases its concentration in cities, such acceleration must be acknowledged by decision makers in order to better design and assess the outcomes of urban resilience strategies.

From this analysis, we also reassert the importance of considering multifunctionality as an intrinsic characteristic of urban SES, as authors like Anderies et al. (2006), Ahern (2011) and Biggs et al. (2012b) have clearly stated. The evaluation of the functionality of a system will always depend on the context, on what is considered desirable at a given time. Thus, planning for uncertain futures must consider that normative frameworks are also dynamic and therefore, should aim to preserve and nurture as many system functions as possible, considering as well that diversity is key for the system’s ability to continually adapt and transform. In the case of Xochimilco, previous interventions were guided by a single-path vision of the wetland, such as excluding agriculture from conservation strategies or the promotion of greenhouse agriculture as the new development paradigm for the region. Although they proved to be relatively successful in solving particular problems in a given context, in the long term they led to the erosion of the system’s resilience, which is crucial for the sustainability of the Xochimilco wetland and Mexico City as a whole.

Lastly, we recognize that one of the main challenges for resilience-based approaches is its ability to articulate the analysis of system elements and dynamics with a critical understanding of the processes that underlie them; important criticisms have been made regarding the lack of attention of such frameworks in, for example, power disparities or marginalization processes among actors that can be crucial for shaping system states. In fact, the Xochimilco case study is a good example of how a historical adaptive cycles assessment can lead to unresolved questions regarding governance and power struggles over water and territory in Mexico City. To this point, we acknowledge that resilience theory has not developed to critically analyze the behavior of a system's elements, but rather to enrich—and even shift—the way in which we understand social-ecological interactions in a very broad sense. Thus, we consider that the potential of this approach for shedding light on key aspects of such complex interactions is a valuable contribution, as well as a helpful way to orient further analysis, which would certainly benefit from the use of explicitly critical and less abstract framings.

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