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Urban expansion into a protected natural area in Mexico City: alternative management scenarios

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Land use change is one of the main stress factors on ecosystems near urban areas. We analysed land use dynamics within Xochimilco, a World Heritage Site area in Mexico City. We used satellite images and GIS to quantify changes in land use/land cover (LULC) from 1989 to 2006 in this area, and a Markov projection model to simulate the impact of different management scenarios through to 2057. The results show an alarming rate of urbanisation in 17 years. LULC change runs in one direction from all other land use categories towards urban land use. However, changes from wetland or agricultural LULC to urban LULC frequently occur through transitional categories, including greenhouse agriculture and abandoned agricultural land. While urbanisation of natural land is often indirect, it is also effectively permanent. Active management aimed at protecting ecologically valuable habitats is urgently needed.

Keywords: land use change; Markov model; *chinampas*; Xochimilco

1. Introduction

In many developing countries, urban growth does not follow a development plan. This is often true even in cases where development plans include legal instruments designed to ensure conservation of critical areas within cities (Musaoglu *et al.* 2006). These plans are simply overwhelmed by demand for housing, communication infrastructure and industry (Lambin *et al.* 2001, Foley *et al.* 2005). Consequently, in the last century large metropolitan areas have expanded into adjacent small rural towns, which previously depended on agriculture as their primary income source. In these cities the landscape is a dynamic mosaic of shrinking rural areas surrounded by growing urban areas (Wigle 2010).

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Changes in land use/land cover (LULC) in urban areas affect the function and services of ecosystems in areas near cities (Lambin *et al.* 2001, Marshall *et al.* 2003, Aspinall 2004). Many of these rural lands provide ecosystem services to the urban areas, such as water, climate, food and culture, thus contributing to the sustainability of the city (Smit and Nasr 1992, Losada *et al.* 2000, Bowler *et al.* 2002, Swinton *et al.* 2007). For example, one of the cultural ecosystem services of these rural areas in Mexico City is the provision of land and water used for traditional forms of agricultural production called *chinampas*. Consequently, Mexico City urbanisation of rural areas is not only affecting ecosystem services such as water provision or local climate modification but also its cultural heritage.

Mexico has been urbanising rapidly. At present more than 63% of the population inhabit 343 cities which have populations larger than 250,000 (Aguilar 2002). To accommodate this rural influx, these cities have changed their landscapes by expanding into the urban-rural periphery (Losada *et al.* 2000). For example, between 1990 and 2000 the population in central Mexico City (which includes the Federal District of Mexico, the D.F.) (Wigle 2010), increased only 1.3%, while the population at the periphery (which includes 40 municipalities of the Estate of Mexico), increased by 2.9% (Aguilar 2008). The population within the D.F. alone (the south-central part of the city) is now more than 8 million people, with more than 20 million people living in the Mexico City metropolitan area (Crotte *et al.* 2011).

Official protected areas in the D.F. make up 88,442 ha (Wigle 2010), including Xochimilco, which is located in the south of Mexico City (SMA 2007). Xochimilco is also listed under the RAMSAR convention because of its high wetland value. The United Nations Educational, Scientific and Cultural Organization (UNESCO) listed this area as a World Heritage site in 1986 because of its biological and cultural attributes (UNESCO 2006). Xochimilco is a managed wetland, in which narrow canals surround land plots, called *chinampas*. This type of managed wetland is considered one of the most diverse and productive agricultural systems known to date (Jiménez-Osornio *et al.* 1990, González-Pozo 2010). *Chinampas* have been cultivated for at least six centuries and reached their maximum development between 1400 and 1600 (Rojas 1991).

However, at present traditional agriculture is not the only activity in the area. The long history of management has produced different types of land use, which are scattered, and there does not seem to be a pattern across the region. Immediate pressures that local decision makers face daily in these rural-urban areas overwhelm any agreed development and conservation plan based on previous ecological, economic or population studies. Therefore, at this spatial and temporal scale land-use changes are driven by individual decisions rather than zoning and land use plans.

For example, declining water quality has reduced traditional agricultural activities, because *chinampas* rely on adequate water quality in the surrounding canals. To maintain agricultural activities, approximately 20 years ago the local government promoted the use of greenhouses among traditional farmers. These facilities are less reliant on surface water quality because they obtain water from the aquifer (UNESCO 2006). As a result of government promotion, part of the traditional agricultural lands have changed to greenhouse land (Siemens 2004, Merlin-Urbe 2009). To service these greenhouses, it is necessary to build houses, communication systems, and water and sewage services, changing the landscape to urban use (Losada *et al.* 1998). Pesticides and herbicides used in greenhouse

agriculture lixivate directly to the canals, which further reduces water quality for the remaining traditional farmers (Torres-Lima and Burns 2002).

Illegal housing development, which has been detected in at least 41 ha of the protected area in the past 17 years, has also contributed to urbanisation within Xochimilco. The sewage from these houses goes directly to the wetlands and lakes, further degrading water quality. Such land use changes in Xochimilco appear to be a strong driver of the decline in wetland water quality (Zambrano *et al.* 2009), and are also capable of changing food web connections (Zambrano *et al.* 2010), as well as the distribution of endemic species such as the endangered salamander, axolotl (*Ambystoma mexicanum*) (Contreras *et al.* 2009).

Most of these changes are related to the ecosystem services this wetland provides to Mexico City, such as food provisioning, air quality, favourable climate conditions, soil productivity, flood prevention in extreme rainy seasons, water provision in a city with high hydraulic stress on its water table, cultural ties from local people, and aesthetics and recreation (De Groot *et al.* 2002). Therefore, understanding land use change in Xochimilco is critical to predicting ecosystem service changes that may affect the entire city.

The goal of this research was to evaluate the dynamics of land use change in urban, wetland and traditional agricultural areas of Xochimilco during the period 1989–2006. From the observed land use transition probabilities, we developed a simple Markov model to generate projections based on the assumption that the transition probabilities observed between 1989 and 2006 will carry forward into the future. These projections provide a baseline scenario for understanding the implications of recent development patterns. By modifying the transition probabilities to reflect different management scenarios, we also illustrate alternative paths for management and conservation of this important area.

2. Methods

2.1. Study area

Xochimilco is located 18 km south from the centre of Mexico City and encompasses 12,200 ha of urban area, tourist areas, wetlands, secondary forest and different types of agriculture lands (Wigle 2010). Xochimilco's wetland system consists of 40 km² of canals connecting eight small lakes and two flood plain areas (Zambrano *et al.* 2009). This aquatic ecosystem represents the remnants of a larger system of five lakes: Xaltocan, Zumpango, Texcoco, Xochimilco and Chalco. All of them occupied approximately 1000 km² of the basin of Mexico in the fifteenth century (Rojas 2004).

Intense long-term development activity in Xochimilco has produced a collage of urbanised areas (mostly in the northern region) and rural and agricultural areas (in the central and southern regions). In 1989 a small area in the north of the wetland became an ecological park (Parque Ecológico de Xochimilco, or PEX).

Xochimilco receives water from the water treatment plant called 'Cerro de la Estrella', which feeds the whole aquatic system, including those canals connecting *chinampas* and the wetland, from the southwest and moves to the northeast ending in a connection to the 'Gran Canal', a sewage system for the city. The shallow wetland conditions of this area attract 140 species of migratory birds during winter (UNESCO 2006, Zambrano *et al.* 2009). There are two aquatic endemic species: the axolotl (*Ambystoma mexicanum*) and the crayfish (*Cambarellus montezumae*) (Zambrano *et al.* 2009, Contreras *et al.* 2009).

This research focuses on a polygon of 10,672 ha in the centre of Xochimilco wetland and the urban area around it. Within this area, 2,657 ha (25%) are considered to be Protected Area (SMA 2007), in which land uses are mixed among different types of agricultural, wetland, and forested areas (Aguilar 2008).

2.2. Land use analysis

We used a Landsat 5 TM 30 m multispectral satellite image for 1989 and a Quickbird 2 m multispectral satellite image for LULC classification in 2006. Both images were geo-referenced and radiometrically calibrated to enable comparison between them. For georeferencing, we used orthophotos of the studied area (INEGI 2000). Estimates of transition rates (and their uncertainty) would probably be improved by using images from more than two different years. However, such images are not yet available, and understanding LULC change is an urgent concern. Therefore, we decided to proceed using the best available information.

Polygon delineation of land use classes was based on visual interpretation carried out by a team of biologists and geographers, using criteria such as tone, texture, patterns, edge shape and size, which are more accurate than digital corroboration in complex systems (Chuvieco 2002). To generate the map with polygons of land use in 1989, we used aerial photographs from 1990 (1:12 000) to interpret the 1989 Landsat image at a scale of 1:75 000 (at a higher resolution, visual interpretation becomes difficult). To generate the polygons from the 2006 image, we started with the polygons generated from classification of the 1989 image, matched these polygons to the corresponding area in the 2006 image, and corrected any differences produced by changes in land use over years.

Ground truthing of the LULC classifications from the 1989 image was based on orthophotos of the studied area (INEGI 2000). To ground truth the 2006 LULC classifications, we conducted field observations at 200 random sites within the study area in 2007. In this field validation, we performed individual interviews with local farmers using maps, images and pictures. We also interviewed key informants, such as historians and social leaders of the community, with historic knowledge of the area for land use interpretations for both years.

Interpretation of the satellite imagery resulted in two maps with nine LULC categories based on human activities (urban or agriculture) and type of cover (wetlands, vegetation or forest). We used the urban category (URB) for land with housing and other human activities such as commerce and industry. We divided agricultural areas into three categories based on their production method: conventional agriculture (CA), *chinampa* agriculture (CHI) and greenhouse agriculture (GH). Two of the agricultural categories also occurred in a transitional state, *chinampa* agriculture in transition (CHT) and conventional agriculture in transition (CAT). The transition category was applied to areas having many small patches from another category, which suggest a land use change was in progress. The wetland (WET) land cover category included any type of aquatic system (temporary or permanent lakes and canals). Terrestrial ecosystems were divided into secondary forest (SF) (reforested areas) and scrub and grasslands (SG) (abandoned areas or without any current use) (Table 1).

From the maps produced from 1989 and 2006 imagery, we generated two raster datasets containing the land use categories described above at a resolution of 20 m using ArcGIS 9.3. This resolution was appropriate for the studied area and land use

Table 1. Description of land use/cover classes.

Urban (URB)	Land with houses, pavement and communication infrastructure with public services.
Conventional agriculture (CA)	Agriculture without irrigation, food crops such as corn and beans.
<i>Chinampa</i> agriculture (CHI)	Traditional agriculture in which a plot of land is surrounded on at least three sides by canals with water and trees <i>ahuejotes</i> (<i>Salix boplandiana</i>) at the edges. The <i>chinampas</i> are generally used to grow vegetables such as lettuce and purslane.
Greenhouses (GH)	Industrialised agriculture with buildings and facilities; greenhouses are made of plastic and steel. Devoted to production of flowers such as poinsettia and tulips.
<i>Chinampa</i> agriculture in transition (CHT)	<i>Chinampas</i> with at least 25% abandoned or urbanised land.
Conventional agriculture in transition (CAT)	Agriculture lands abandoned or with at least 25% of area with houses.
Wetlands (WET)	Any water body (temporary or permanent) within the study area (canals, lakes and inundated areas) less than 3 m depth.
Secondary forest (SF)	Reforested areas, mainly urban parks.
Scrub and grasslands (SG)	Terrestrial lands without any agricultural or urban activity. Vegetation is scrub and grass. Also includes abandoned lands.

categories in order to maintain real boundaries between entities or polygons (Berry 1995). We processed these raster datasets to generate a change detection matrix, which included each land use category and its area obtained from the 1989 and 2006 images. Changes were computed by means of a cross-tabulation of the LULC change from 1989 to 2006, using IDRISI Kilimanjaro.

2.3. Management projections

We used a Markov projection model to extrapolate LULC changes observed between 1989 and 2006. Such models permit prediction of general patterns of LULC change in the whole system, but they are not spatially explicit. In Xochimilco, fine scale patterns of LULC change are difficult to predict as they are largely a function of individual decisions rather than zoning and development planning (see above). Spatially explicit models are useful to understand land use changes and generate projections, but they require a detailed and quantitative understanding of the drivers of land use change. Such knowledge is not available in this particular case.

We calculated a land use transition matrix based on comparisons of the categorised images in 1989 (t1) and 2006 (t2). This transition matrix was used in a Markov model to generate a baseline projection (BSL), assuming no change in transition rates from the first two periods. This is a plausible scenario considering that Mexico City's population growth is stabilising as it reaches the limits of water and land availability.

We then modified land use transition rates to generate projections simulating conservation and restoration strategies. The general assumption of the four projections is based on the idea that a healthy agricultural activity (socially and economically) will help to strengthen rural barriers, thus containing the pressure to urbanise the area. In other words, a wealthy farmer would not abandon his lands. The restoration of the wetland will be a natural barrier for any urbanisation attempt. We generated the following projections:

- (1) Protection of conventional agriculture lands (PCA). This strategy promotes conventional agriculture using economic subsidies. There are many governmental programmes (local and federal) promoting agricultural activities and payment for ecosystem services.
- (2) Preservation of *chinampa* agriculture (PCHA). This strategy is based on the development of local markets to encourage people to return to agricultural activities by increasing their income, generating a fair market (Valiente *et al.* 2010). In recent years there has been a growing movement to preserve the area by encouraging producers to sell their products directly to consumers.
- (3) Actively increasing wetland areas within a conservation area (IWE). This strategy is based on hydrological programmes to capture water during the rainy season, avoiding inundations in lowlands in Mexico City, and storing the water for the dry season. This project is now in its initial stages.
- (4) A complete ecosystem management strategy that includes all of the other three strategies together to promote the provision of ecosystem services (ESPL). This strategy attempts to find optimal trade-offs in management of these different land uses. This is the most difficult programme since most of the stakeholders must agree.

To understand the system response for each management programme, we simulated each scenario across varying degrees of protection from 0% (no change from the baseline) to 100% (the probability of change to a particular land use was set to one). For example, under a scenario of 50% protection of wetlands, all transition rates from wetland to another land use category were reduced by 50% and the probability of land remaining as wetland was correspondingly increased. Therefore the sum of transition rates from wetland remained equal to one. In the ESPL scenario, we modified transition rates for all three categories simultaneously. Results for each scenario are plotted across varying degree of protection (0–100%).

3. Results

Land use images in 1989 showed urban areas surrounding agricultural lands and natural and secondary vegetation covers (Figure 1). The percentage of area occupied by urban lands (URB) was 46.7%, conventional agriculture (CA) occupied 24.4% and wetlands (WET) occupied 12.4%. Other land uses had lower proportions such as *chinampa* agriculture (CHI) with 7.4%; scrub and grasslands (SG) with 4.8%; conventional agriculture in transition (CAT) at 1.9%; secondary forest (SF) at 1.1%; *chinampa* agriculture in transition (CHT) 1.2%; and greenhouse agriculture (GH) at only 0.02% (Table 2). These percentages changed in 2006 with an increase of URB to 57.2%, SG increased to 4.9%, while CAT and SF decreased to 3.6 and 4.5%. The area occupied by GH in 2006 was 100 times larger than in 1989, increasing to almost 2.3% of the total area. Other land uses decreased, such as CA 12.8%, WET 6.2% and CHI to 2.5% (Table 2 and Figure 2).

Cross-tab matrix analysis (Table 3) and a transition probability diagram (Figure 3), give a path of land use change between categories. For example, 371.48 ha of the *chinampa* agriculture (CHI) changed to transitional state (CHT) and 85.44 ha of land in this transitional state changed to greenhouse agriculture, which the transition probabilities suggest will ultimately convert to urban land use (Figure 3).

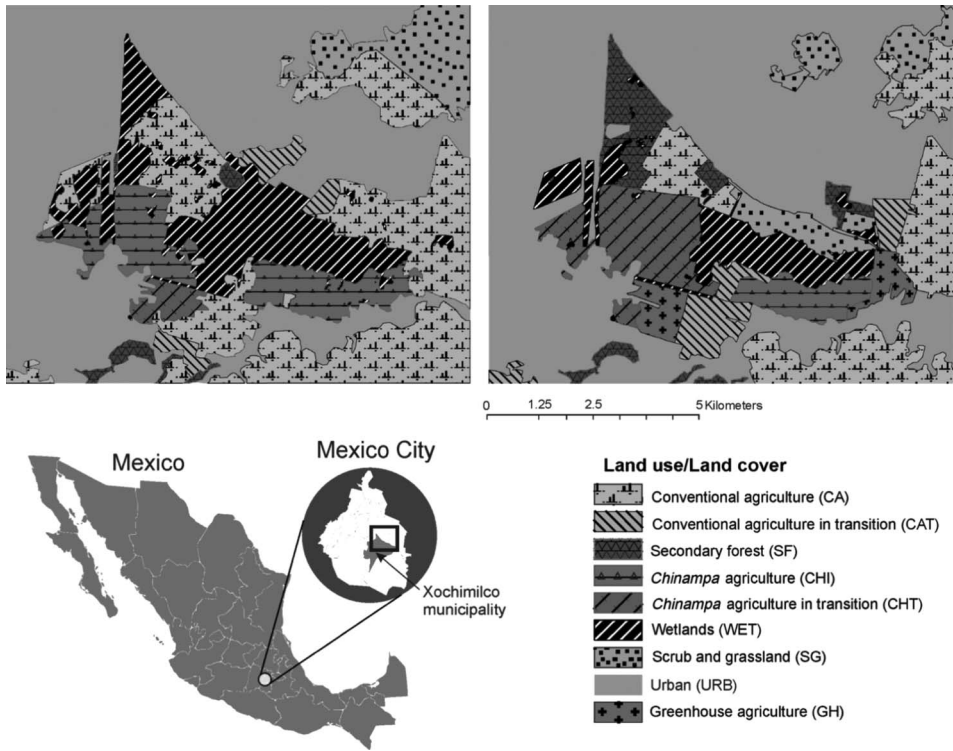


Figure 1. Land use/land cover change at Xochimilco between 1989 and 2006.

Table 2. Area measurements of land use/cover change within study area for 1989 and 2006.

Land use/cover	1989		2006	
	Area (ha)	Area (%)	Area (ha)	Area (%)
Urban (UR)	4984.36	46.7	6107.22	57.2
Conventional agriculture (CA)	2603.78	24.4	1364.73	12.8
Chinampa agriculture (CHI)	788.92	7.4	262.00	2.5
Greenhouse agriculture (GH)	2.00	0.0	244.36	2.3
Chinampa agriculture in transition (CHT)	130.71	1.2	652.52	6.1
Conventional agriculture in transition (CAT)	201.64	1.9	381.14	3.6
Wetland (WT)	1322.84	12.4	661.75	6.2
Secondary forest (SF)	121.43	1.1	480.21	4.5
Scrub and grassland (SG)	516.44	4.8	518.19	4.9
Total	10672.12	100.00	10672.12	100.00

From this matrix, a projection to the year 2057 (i.e. three 17-year time intervals beyond 2006) gives contrasting results depending on the scenario chosen. The baseline scenario (BSL), using the same trend of the previous 17 years, projects all LULC categories of ecological importance, such as conventional agriculture, *chinampa* agriculture and wetlands, will all but disappear (Figure 4a). Agricultural land use areas increased between 1989 and 2006 but are expected to slowly decline as

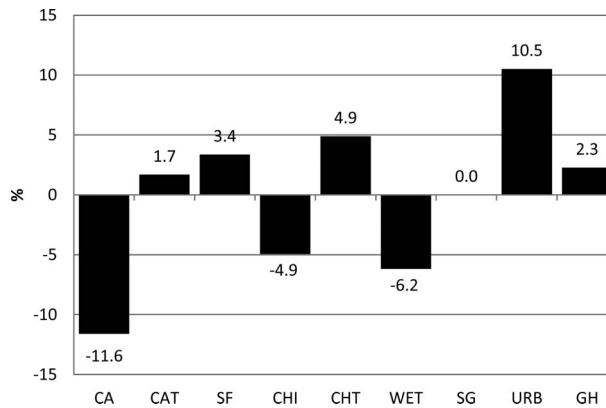


Figure 2. Land use/cover change between 1989 and 2006. Negative values are losses. Conventional agriculture, *Chinampa* agriculture and wetlands are the land uses with more losses, some of this missing area changed to urban, which increased by 10.5% in the study area. Notes: Abbreviations: Urban (URB); Conventional agriculture (CA); *Chinampa* agriculture (CHI); Greenhouses (GH); *Chinampa* agriculture in transition (CHT); Conventional agriculture in transition (CAT); Wetlands (WET); Secondary forest (SF); Scrub and grasslands (SG).

Table 3. Cross-tabulation. Area of land use/land cover that changed between 1989 (columns) versus 2006 (rows).

2006	1989									Total
	CA	CAT	SF	CHI	CHT	WET	SG	URB	GH	
CA	1134.71	0.0	0.21	0.22	0.0	71.79	157.72	0.04	0.04	1364.73
CAT	337.14	0.0	0.0	26.33	2.83	14.56	0.0	0.15	0.13	381.14
SF	208.45	0.0	97.33	0.62	0.0	172.7	0.0	1.08	0.03	480.21
CHI	7.37	0.0	0.0	244.8	0.0	9.63	0.0	0.13	0.07	262.0
CHT	72.96	0.0	0.0	371.48	32.05	175.95	0.0	0.08	0.0	652.52
WET	72.52	0.0	0.1	49	0.0	539.99	0.0	0.12	0.02	661.75
SG	93.09	3.16	0.0	0.0	0.0	186.78	235.08	0.05	0.03	518.19
URB	595.98	197.25	23.79	41.73	10.39	130.39	123.64	4982.55	1.5	6107.22
GH	81.56	1.23	0.0	54.74	85.44	21.05	0	0.16	0.18	244.36
Total	2603.78	201.64	121.43	788.92	130.71	1322.84	516.44	4984.36	2.0	

Notes: Abbreviations: URB, Urban; CA, Conventional agriculture; CHI, *Chinampa* agriculture; GH, Greenhouse; CHT, *Chinampa* agriculture in transition; CAT, Conventional agriculture in transition; WET, Wetland; SF, Secondary forest; SG, Scrub and grassland. Values are area (hectares) that changed from one class to another. For example, 244.8 ha of land classified as CHI in 1989 remained as CHI in 2006, while 371.48 ha of this land were converted to CHT and 54.74 ha to GH.

their primary sources (conventional agricultural lands) are reduced. If recent trends continue, by 2057 we expect urban areas will cover most of the 10,000 ha study area.

In the protection of conventional agriculture scenario (PCA) (Figure 4b), the area of this land use category was conserved. However, all other categories except urban were reduced, particularly the *chinampa* agriculture. In the *chinampa* protection scenario (PCHA), land devoted to *chinampas* increased 10-fold with 100% protection relative to the baseline projection. Wetland was unaffected; transitional *chinampa* agriculture (CHT) and urban areas decreased substantially

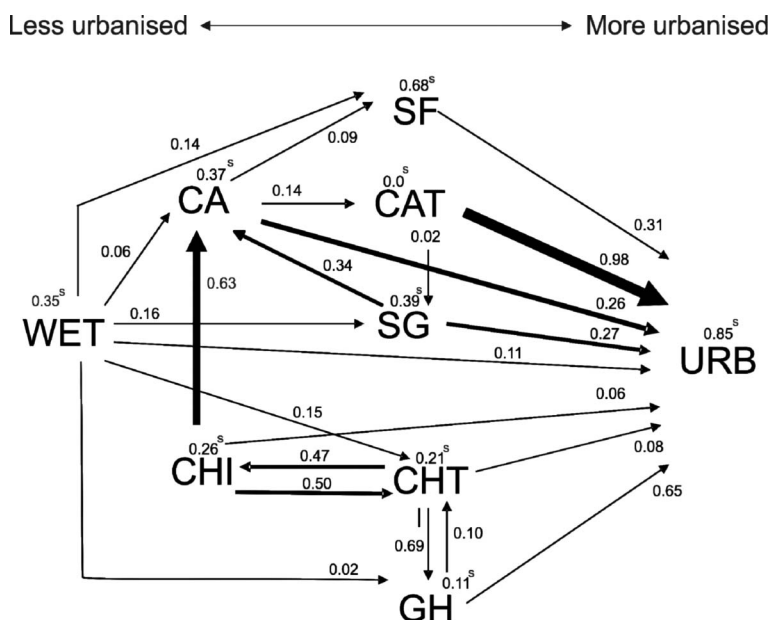


Figure 3. Primary relationships in land use/land cover change dynamics. The diagram shows the probability that one land use/land cover change to another, for example, CHI (*chinampas*) has 50% probability to change to CHT (*chinampas* in transition), CHT has 69% to change to GH (Greenhouse) and GH has 65% to change to URB (urban). Arrows indicate transitions between land use category. Gross lines indicate higher values of transition rate. Values indicate transition probabilities. Superscript 'S' indicates probability of remaining with no change. CA (Conventional Agriculture), CHI (*Chinampa* Agriculture; WET (Wetlands); SF (Secondary Forest); CAT (Conventional Agriculture in Transition); CHT (*Chinampa* Agriculture in Transition); SG (Scrub and Grassland); GH (Greenhouses); URB (Urban).

relative to the baseline scenario (Figure 4c). In the increased wetland scenario (IWE), wetland loss stopped at high levels of protection while conventional agriculture lands were relatively unaffected (Figure 4d). In this scenario, the urban growth rate was also reduced and transitional *chinampa* agriculture had a significant reduction relative to the baseline scenario. In the last scenario (ESPL), where conventional agriculture, *chinampa* agriculture and wetlands were conserved equally, growth of urban areas in Xochimilco nearly stopped and transitional lands decreased significantly (Figure 4e). However, none of the three protected categories increased as much as they did under scenarios in which they were each the sole focus of protection.

4. Discussion

The process of urbanisation at the edge of Mexico City is similar to cities where rural and natural areas have been replaced by urban land (Kumar 2009, Torres-Vera *et al.* 2009, Yan *et al.* 2009). A land use comparison between 1989 and 2006 shows a reduction in wetlands and *chinampa* agriculture, and consequently a reduction in the ecosystem services these land types provide, which is close to US\$30 million in a preliminary study using only three services: water quality, biodiversity and carbon capture (Aguilar *et al.* in revision).

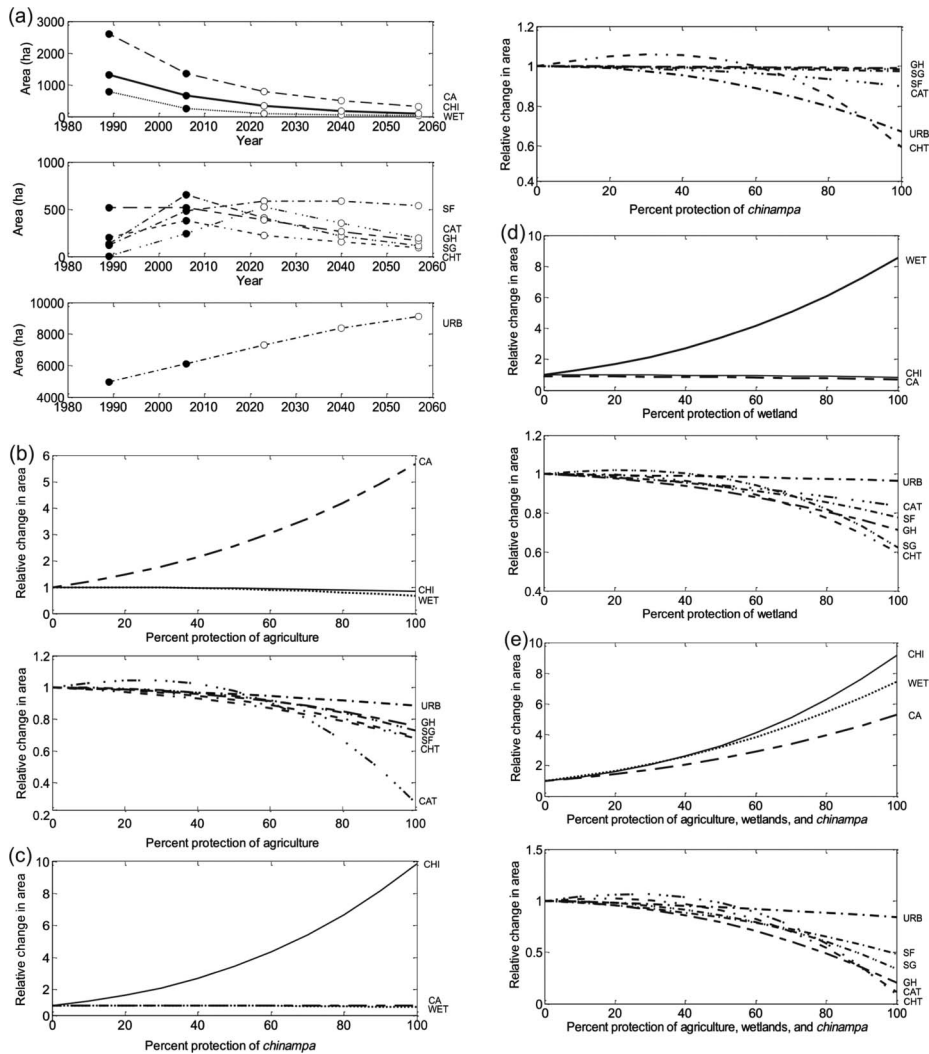


Figure 4. Land use/land cover scenarios projected from land use dynamics between 1989 and 2006. (a) Scenario BSL – Baseline scenario. Filled circles: observed during land use/land cover change evaluation and open circles: projected to 2050. (b) Scenario PCA – Protection of conventional agriculture land; (c) Scenario PCHA – Improving conditions to impulse *Chinampa* agriculture; (d) Scenario IWE – Wetland increase and (e) Scenario ESPL – increase wetlands, agricultural land, and *chinampa* agriculture. Predicted changes in the area of the following land use land cover types as the percentage of protection of agricultural lands increases from 0% to 100%. Lines: CA (Conventional agriculture); CHI (*Chinampa* agriculture); WET (Wetlands); SF (Secondary forest); CAT (Conventional agriculture in transition); CHT (*Chinampa* agriculture in transition); SG (Scrub and grassland); GH (Greenhouses); URB (Urban). See Line Legend to right of graphs. All areas are presented relative to the area expected under the baseline scenario (observed 1989–2006 transition probabilities).

4.1. Land use changes

Since 1989, the urban area in Xochimilco increased by nearly 1000 ha, mostly from conversion of conventional agricultural land. This change has been masked by

transitional land use categories, evident in the transformation of 250 ha from *chinampa* agriculture to conventional agriculture in transition.

The path of land use change appears to flow from less managed land use (wetland) to urban, transitioning through categories such as conventional agriculture and *chinampas*. As these rural lands are abandoned, they do not go directly to urbanisation but to transitional categories or secondary forest. Therefore, a global change to urban use is a clear pattern over the years, but causes seem to be masked by transitional categories. These intermediate categories play an important role in land use change by facilitating urbanisation in protected wetland and agricultural areas. A wetland area that is protected from direct urban development can pass through transitional stages that result in eventual urbanisation after a few years. Transitional stages confirm the abandonment of agricultural lands, which is part of a positive feedback loop (Prol-Ledesma *et al.* 2002).

The conversion of wetlands to transitional LULC categories is one of the most conspicuous and worrying changes in this process because wetlands provide many ecosystem services to the area. For example, wetlands increase water quality for *chinampa* agriculture. Wetlands also have an active role in maintaining the microclimate of the city.

Secondary forest coverage increased substantially between 1989 and 2006 due to the creation of the Ecological Park of Xochimilco (PEX) in 1993. This park included the reforestation of 1,100 ha of agricultural land and produced 3,000 ha of protected wetlands and traditional agricultural lands (UNESCO 2006).

4.2. Future projections of the land use

Land use projections suggest that at the current rate of urbanisation, most of the areas providing ecosystem services will disappear by 2057. Their reduction follows a pattern of exponential decay, while the transitional categories increase in the first years before slowly declining. Therefore, in the near future land abandonment will be intensified for a short period of time, reducing the capacity of the system to provide services. However, lands from these transitional stages can be restored to their previous categories, which will allow time to create management programmes. This baseline projection serves as a point of comparison for management scenarios in which specific land use categories are protected.

Matrix interactions in the projection scenarios in which conventional agriculture, traditional agriculture or wetlands are protected seem to have a similar behaviour. The chosen category grows fast while the rest of the categories are depleted at different speeds but in similar ways. This is possibly explained by the type of interactions and rates of transition these categories have, which are quite similar. However, the projection in which protection of *chinampas* is encouraged seems to produce a higher reduction of urban lands (relative to the baseline scenario) than the others. Therefore, protection of *chinampas* could be one of the most effective ways to reduce urban growth in the area. The small area occupied by greenhouses increased significantly in proportion. Greenhouse LULC went from almost zero to 231 ha in just two decades. The transition probabilities suggest that greenhouse land will change to urban, supporting the idea that this type of agriculture is the base for urbanisation in the area.

4.3. Management policies

Programmes that promote a return to *chinampa* agriculture or reinforce protected areas by implementing wetland conservation policies seem to be effective in the reduction of the urban growth. Agricultural activities in restored *chinampas* can provide ecosystem services to the city such as food, water infiltration, microclimate regulation, and carbon capture and storage (if compost is used as a fertiliser).

All of the conservation scenario projections show a reduction of transitional land use categories and therefore a reduction in urbanisation, as most urbanisation occurs via these transitional categories. One useful tool for slowing the conversion of agricultural lands is through conservation marketing programmes that create refuges for axolotl in canals surrounding *chinampas* by increasing water quality (Valiente *et al.* 2010). A market premium for local products can encourage the return of traditional agriculture activities and therefore increase the area devoted to this type of land use (Von Bertrab and Zambrano 2010).

Land use analyses that improve understanding of drivers such as transitional categories and the conservation of areas as ecosystem service providers (Bolund and Hunhammar 1999, Rotmans *et al.* 2000) are the cornerstones for managing urban growth. Ecosystem services provide greater wealth to society in the long term (Bolund and Hunhammar 1999). Xochimilco also provides economic benefits through tourism and traditional agriculture. In this context, conserving this area not only maintains ecosystem services but also cultural heritage (Smit and Nasr 1992, Chiesura 2004, Tweed and Sutherland 2007) and endemic species.

Xochimilco seems to be moving directly to urbanisation by the accelerated rate of land use change. The general pattern observed over the study period was the conversion of wetlands to urban lands, with intermediate steps of temporary agricultural areas and secondary forest. Greenhouse development also reduces the land area devoted to *chinampa* agriculture and promotes indirect urbanisation. However, projections suggest that policies in which there is wetland conservation and protection of *chinampas* and conventional agriculture could reduce urbanisation in Xochimilco. Conservation strategies should incorporate the added value of products from the *chinampas*, and promote agricultural land use as an alternative to activities such as tourism or housing.

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