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Land-cover/use transitions in the binational Tijuana River watershed during a period of rapid industrialization

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Abstract
Question: How do differing social and economic systems affect the dynamics and trajectory of land cover / land use change on similar, neighbouring ecosystems in a time span when an economic industrialization program was enforced?
Location: Tijuana River watershed, located on the border between Baja California, Mexico and California, United States.
Methods: We quantified land use changes between 1970 and 1994 in the Tijuana River watershed. Using aerial photographs and geographic information systems, we elaborated land-cover/use maps and calculated transition probability matrices to describe natural land-cover changes at the landscape level on both sides of the border.
Results: Land cover / land use transitions are mainly driven by urban development on both sides of the border, but exhibit different patterns in each country. The processes seem to be more complex in the Mexican part of the basin, where itinerant land use may revert induced grasslands and rain-fed agriculture into natural communities, than on the US side, where the transition pathways are few and unidirectional.
Conclusions: Despite the need for an integrated planning and management of binational basins and shared water resources, in practice, these goals may be hampered by different economic and social factors triggering land use change within each country.

Keywords: Binational watershed; Geographic information systems; Mexico; Transition model; United States.

Abbreviations: GIS = Geographic information system; LUCC = Land cover and use change; TRW = Tijuana River watershed.

Introduction

The study of land cover and use change (LUCC) processes has become a major topic of environmental research (Houghton 1994; Lee et al. 1995). Its analysis has been based on the quantification of land use and its change over time, using different sources and techniques (Ojima et al. 1994; Lambin 1997). LUCC operates at the landscape level through ecosystem fragmentation, which disrupts environmental functions (Forman 1995; Mas et al. 2004). As semi-natural landscapes become predominant, knowledge of LUCC in human altered ecosystems will play a growing role in the conservation of natural resources (Noss 1996; Schwartz 1997).

In order to study LUCC patterns and processes, Bürgi et al. (2004) suggested the use of the driving forces concept, and identified five main types: natural, socioeconomic, policies, technology and cultural. They also considered that comparative studies on borders are useful to analyse the effects of regulations, subsidies and political systems and that selected periods must reflect a change in the conductive force potential level.

Binational watersheds are ideal study areas, because they may function as split-plots where most natural variables are similar, but where the contrasting economies and social dynamics may operate differently, imposing divergent pressures on shared natural resources. The study of LUCC patterns in watersheds is of particular relevance because it may affect erosion rates (Sah & Shimizu 1998), hydrologic cycles and water availability (Peters & Meybeck 2000).

At the border between Mexico and the United States, environmental research with a binational view has grown substantially during the past decade. Most environmental studies have been oriented towards water resources modelling and management (Frisvold & Caswell 2000; Brown 2003; Van Schoik et al. 2004; Cortés et al. 2005).

Binational geographic information systems (GIS) have been integrated in the Tijuana River watershed (Anon. 2005a) and in the Nogales Watershed (Brady et al. 2002). Other studies have dealt with urban growth and LUCC in Tijuana–San Diego (Herzog 1990) and Ciudad Juárez–El Paso (Peña et al. 2005), with watershed analysis in the San Pedro River Basin (Kepner et al. 2002, 2004; Miller et al. 2002). Mumme (2003) reviewed and analysed policy issues since the 1970s, and concluded that research topics such as natural resource conservation and LUCC deserve more attention.

Urbanization has not been considered a major cause of LUCC as it only accounts for 2% of the world's land surface. In some areas, however, large-scale urbanization and extended peri-urban settlements fragment the landscapes and threaten ecosystem processes (Lambin et al. 2001). Although landscape pattern metrics have been applied to study urban morphology (Luck & Wu 2002; Cifaldi et al. 2004; Seto & Fragkias 2005), most spatial studies are applied to single cities (Jenerette & Wu 2001; Luck & Wu 2002; Herold et al. 2003) or several cities within one country. Physical processes of LUCC and socioeconomic processes that cause certain space configurations have been understudied (Seto & Fragkias 2005).

In this article we analyse LUCC patterns and transitions during the Border Industrialization Program (1970–1994) in the Tijuana River watershed (TRW), a binational basin on the Mexico-US border, bridging the states of California and Baja California (Fig. 1). We also examine the contrasting patterns observed north and south of the border, and analyse their main driving forces. This study follows previous research of the TRW bio-history (Ojeda & Espejel in press), in which the main historical events that shaped land cover / landuse patterns and its change were identified. The study period we chose (1970–1994) coincides with the Border Industrialization Program started in Mexico in 1965 (Zenteno & Cruz 1992), which induced accelerated population and industrial growth within the basin, reaching a peak of 20% annual growth in industrial capacity between 1985-1990. Between 1970 and 1994, the number of '*maquiladoras*' (tax-exempt assembly plants of foreign capital located on the Mexican side of the border) increased from 101 to 727. Shortly after 1994, the growth of the maquiladora industry started to dwindle, reaching negative values (–7%) in the 2000–2005 period (Anon. 2005b).

The main question we intended to explore with this study was how differing social and economic systems affect landscape patterns and LUCC in similar, neighbouring ecosystems, in that special time span when the economy of the region was oriented towards industrialization.

Methods

Study area

The TRW is located along the western border between Mexico and the US, covering 4450 km², of which almost 75% belong to Mexico (Fig. 1). Terrain is rolling to hilly, relief amplitude ranges from sea level to nearly 2000 m a.s.l. at its northeastern portion. It is part of the California Floristic Province, one of the world's biodiversity hotspots (Myers et al. 2000). Within the basin, different varieties of mediterranean climate occur, characterized by mild winters and dry summers. Arid mediterranean climate dominates in the lowlands near the sea, where the mean annual rainfall is less than 200 mm and the mean annual temperature is 16 °C. In the highest sierras a more humid and cooler climate prevails, with yearly precipitation reaching 500 mm and mean annual temperature around 10 °C (Anon. 1995). Mixed conifer forest, juniper scrub, chaparral, coastal sage scrub, meadows and riparian land cover naturally inhabit the watershed. Land use (i.e. man-made) categories include urban development, grasslands, irrigated and rain-fed agriculture, and reservoirs (O'Leary 2005).

The watershed falls under the jurisdiction of San Diego County in the US, and the Municipalities of Tijuana and Tecate in Mexico. Population growth rates were 3.0% during the 1970s, and 4.8% in the 1980s and 1990s (3.1% between 2000 and 2005) in the Mexican municipalities (Anon. 2000, 2006a), and 3.2% in the 1970s, 2.9% in the 1980s, 1.2% in the 1990s (1.4% between 2000 and 2006) in San Diego County (Anon. 2006b). On both sides of the border only 1% of the population is related to primary production activities; in Mexico 41% work in the secondary sector (mainly industry) and 52% in services, while in the US 16% work in the secondary sector and 83% in services (Anon. 2000, 2006).

Computing land cover change

We worked with land cover / land use maps derived from black and white US Department of Agriculture 1970 Corona Satellite Photographs (1:20000) for the US part of the basin; black and white 1972 Instituto Nacional de Estadística Geografía e Informática aerial photographs (1: 50000) for the Mexican side of the basin and Nation Oceanographic and Atmospheric Administration 1994 colour aerial photographs for the whole basin.

This study is part of a long-term research programme, which started in the 1930s and aims to monitor trends in LUCC in the basin. For comparison purposes, we adopted the land cover / land use classification developed by O'Leary (2005), combining categories that were not discernible in the oldest aerial photographs (Table 1).

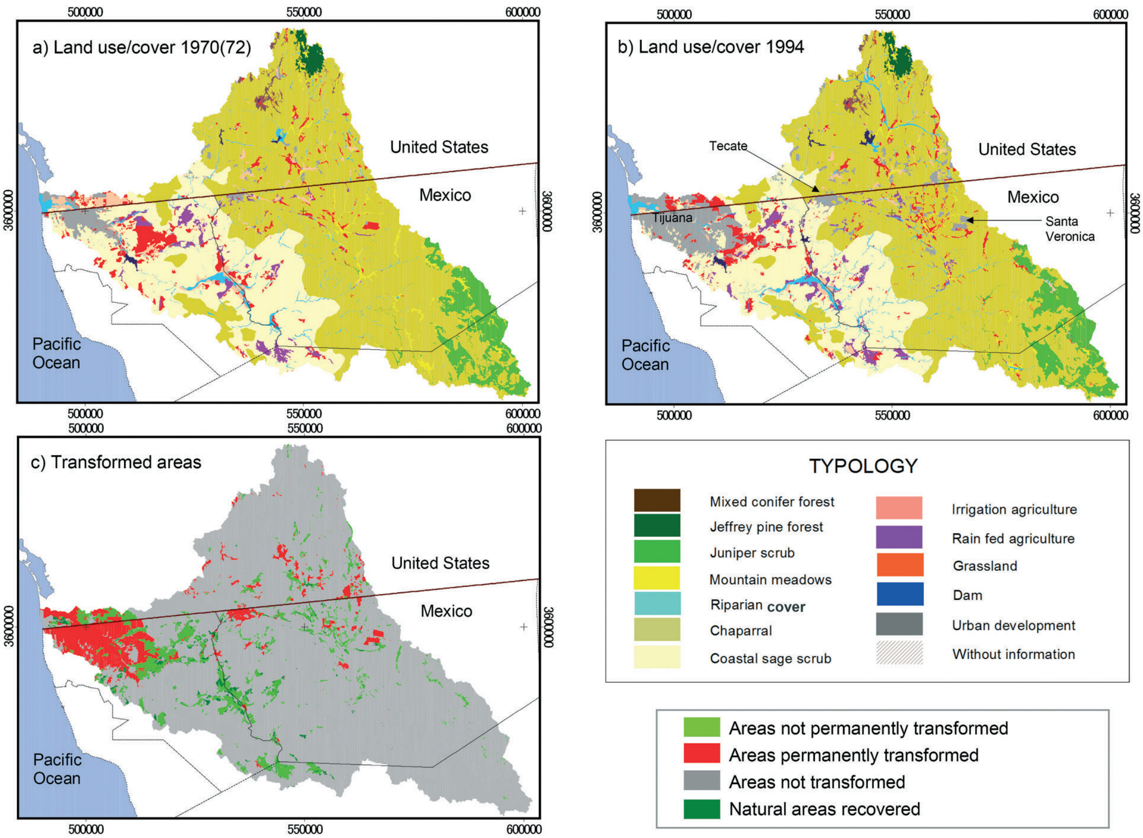

Fig. 1. Land-cover/use in (**a**) 1970-1972, (**b**) 1994 in the Tijuana River watershed and (**c**) areas that were transformed from one land use into another during the 1970-1994 study period. Numbers in the map fringes indicate co-ordinates in the Universal Transverse Mercator system (UTM units).

Aerial photo-interpretation was carried out by means of a mirror stereoscope and using standard interpretation keys (tone, texture, pattern, shape and location of land cover / land use polygons as identified on the images) using the central portion of every photograph to avoid lateral distortion. Stereovision helped us to understand the relevant relationships between land cover and relief, and thus, to differentiate among visually similar cover types. Every interpreted photograph was manually digitized onto a common-base mosaic (scale 1:50000), and corrected using control points in a GIS. To ensure geometric consistency, the different layers were overlaid on a digitally enhanced 1994 SPOT panchromatic image (10 m spatial resolution) and checked thoroughly for consistency. The accuracy of polygon labelling was tested by verifying in the field at least 20% of the interpreted polygons, and corrections were made when needed.

Table 1. Land-cover/use categories.

Land-cover/use	Categories
Forest	1. Mixed conifer forest
	2. *Pinus jeffreyi* forest
Riparian vegetation	3. Riparian vegetation
Scrubs	4. *Juniperus* scrub
	5. Coastal sage scrub
	6. Chaparral
Grasses	7. Mountain meadows
	8. Grasslands
Agriculture	9. Irrigated agriculture
	10. Rainfed agriculture
Water bodies	11. Reservoirs
Urban development	12. Urban development

The following landscape analyses were performed on the basis of patch number and area (Forman 1995): (1) area of each land cover (S_i); (2) number of patches in each land cover category (N_i); (3) perimeter shape ratio; i.e. total perimeter for the category (P_i) divided by the perimeter of a circle with the same area and equal to $P_i/2\sqrt{(\pi S_i)}$ and (d) rate of change in land cover [$C = (\log S_{i2} - \log S_{i1})/(t_2 - t_1)$], where S_{i2} is the area of land cover i at time 2, and S_{i1} is the area of the same land cover at time 1, t_2 y t_1 are the time dates. Rates of change were calculated both for the area of each land cover/use category and for the number of its patches, to respectively estimate expansion or retraction of different land cover / land use types, and their fragmentation.

Calculating transition matrices

In order to describe the land cover / land use dynamics, we constructed Markovian transition matrices, considering landscapes as land cover / land use mosaics that can change dynamically, from and towards different land cover / land use categories. The probability that an area with land cover / land use belonging to category *i* may experience a transition into another category *j* is calculated as the ratio of the area that did change from *i* to *j* between 1970 and 1994, divided by the original amount of land cover category *i* at the beginning of the study period:

$$P_{ij} = S_{ij\,(1994)} / S_{i\,(1970)}, \text{ where } \Sigma_i P_{ij} = 1. \quad (1)$$

Transitions were evaluated in terms of both geometric and thematic consistency. Small differences in polygon area (< 0.02% for the whole basin) originating from tracing errors in polygon boundaries were not taken into account.

Results

The maps in Fig. 1 show land cover / land use in 1970-1972 and 1994, and the changes undergone in this period in the TRW. As expected in a basin with the marked elevation changes and coastal-inland climate gradients as our study area, there was a gradient of natural land cover types from the highest peaks to the lowlands (Fig. 1). On the US side, the highest areas within the basin are occupied by mixed conifer and *Pinus jeffreyi* (Jeffrey pine) forests. The highlands on the Mexican side are mostly covered by *Juniperus* scrub, and on both sides the high elevation valleys and plains harbour mountain meadows. Following the elevation gradient downwards, the basin's slopes are mostly covered by chaparral, a particular type of sclerophyllous scrub, and further down, where the coastal fogs of the Pacific Ocean hit the land, chaparral becomes replaced by coastal sage scrub, which is richer in succulents and herbaceous growth forms. Finally, riparian land cover is found along intermittent *arroyos* or creeks at different altitudes, driven by moisture and water availability.

The first apparent feature observed in our data is that the complexity of the network of observed transitions is much greater in Mexico, with more transition pathways between different land cover / land uses than on the US side of the basin. Overall, natural land cover lost 253 km^2 in the basin, of which 202 km^2 (80%) were lost in Mexico (Tables 4 and 5). However, 55 km^2 of natural land cover were also recovered from abandoned grasslands and agricultural fields, returning chiefly to secondary chaparral, coastal sage scrub and mountain meadows. Most of this recovery (90%), however, was observed in Mexico, while in the US, natural land cover loss was almost irreversible. Globally, the rate at which natural land cover classes were lost in Mexico (0.4%) doubled that of the US (Table 2). Correspondingly, the rate of growth of anthropogenic land cover classes in Mexico was also higher than in the US (1.7% vs 1.2%).

In 1972, urbanization covered 2.4% of the basin; by 1994 it had extended to over 6.9%. Urban areas increased more than 200 km^2 in the whole basin, 74.7% of which developed in Mexico, in 85 patches. In the US, urban development only contributed 87 km^2, but was split into 110 patches (Tables 2 and 3). The perimeter shape ratio of urban patches was also different in each country: 13.8 and 17.0 in 1970 and 1994, respectively, in the US; and 8.3 and 10.7 in Mexico. In the US, urban areas expanded at an annual rate of 3.7%, mostly over

Table 2. Land-cover/use (km^2) and annual rate of change (%) in the Tijuana River watershed.

	US			Mexico		
	1970	1994	Rate (%)	1972	1994	Rate (%)
Mixed conifer forest	23.01	22.16	-0.2	-	-	
Pinus jeffreyi forest	39.39	39.22	0.0	-	-	
Juniperus scrub	-	-		260.67	228.52	-0.6
Chaparral	879.91	846.06	–0.2	1 504.54	1 468.43	-0.1
Coastal sage scrub	78.62	70.80	–0.4	1 028.76	950.63	–0.4
Riparian vegetation	35.35	31.03	–0.5	61.63	79.65	1.2
Mountain meadows	16.92	17.37	0.1	54.04	31.14	–2.5
Grassland	45.81	58.85	1.0	139.28	132.59	–0.2
Irrigation agriculture	52.00	27.55	–2.6	39.31	34.22	–0.6
Rainfed agriculture	0.00	0.00		77.45	87.26	0.5
Urban	35.62	87.04	3.7	69.62	221.02	5.3
Reservoirs	3.94	10.20	4.0	4.84	7.39	1.9
Total	1 210.56	1 210.29		3 240.14	3 240.85	
Total natural	1 073.20	1 026.64	–0.2	1 405.10	1 289.94	–0.4
Total anthropogenic	137.37	183.64	1.2	330.50	482.48	1.7

Table 3. Number of patches within different land-cover/use categories at the Tijuana River watershed.

	US 1970	US 1994	US Rate (%)	Mexico 1972	Mexico 1994	Mexico Rate (%)
Mixed conifer forest	20	20	0.00	-	-	-
Pinus jeffreyi forest	3	3	0.00	-	-	-
Juniperus scrub	-	-	-	46	82	2.63
Chaparral	26	38	1.58	49	60	0.92
Coastal sage scrub	8	10	0.93	28	46	2.26
Mountain meadows	33	33	0.00	68	84	0.96
Grassland	79	69	-0.56	240	443	2.79
Irrigation agriculture	71	73	0.12	53	53	0.00
Rainfed agriculture	-	-	-	79	122	1.98
Urban	77	110	1.49	50	85	2.41
Reservoirs	15	15	0.00	1	2	3.15

chaparral, irrigated agriculture and grasslands (Tables 2 and 4). Urban expansion in Mexico was much faster (5.3%) and expanded chiefly over coastal sage scrub, chaparral and induced grasslands, but also impacted heavily on other natural land cover types (Tables 2 and 5). As a sink land use category, urban development did not undergo further conversions; for all practical purposes it is an irreversible state.

Other anthropogenic land uses, such as irrigation and rain-fed agriculture and grasslands, that covered almost 7.9% of the basin, reduced their area slightly to 7.6% by 1994. Irrigation agriculture decreased in area in both countries, mainly in the US, but not so their number of patches, which increased in the US and were maintained in Mexico (Tables 2 and 3). Grasslands increased in area, but the number of patches decreased in the US. In contrast, in Mexico, grassland area decreased and patch number increased (Tables 2 and 3).

Patches increased in almost all land cover / land use types on both sides of the border, with the exception of induced grasslands in the US. In Mexico, fragmentation rates on natural ecosystems were much faster, and were especially high in the *Juniperus* scrub and the coastal sage scrub, while in the US the most severely fragmented natural land cover type was the chaparral (Table 3).

Table 4. Land-cover/use transitions for the US part of the Tijuana River basin between 1970-1994 in km^2. The values in parentheses indicate the transition probabilities, and the values in bold indicate the diagonal of the transition matrix.

US 1970-1994	Mixed conifer forest	*Pinus jeffreyi* forest	Chaparral	Coastal sage scrub	Riparian vegeta-tion	Mountain meadows	Grass-land	Irrigation agri-culture	Urban devel-opment	Reservoir
Mixed conifer forest	**21.70 (0.918)**	-	-	-	-	-	-	-	-	-
Pinus jeffreyi forest	-	**39.22 (1.000)**	-	-	-	-	-	-	-	-
Chaparral	1.93 (0.082)	-	**838.66 (0.958)**	-	1.47 (0.041)	-	1.04 (0.023)	-	-	-
Coastal sage scrub	-	-	-	**70.07 (0.901)**	-	-	-	-	-	-
Riparian vegetation	-	-	-	-	**27.84 (0.781)**	-	-	3.51 (0.069)	-	-
Mountain meadows	-	-	-	-	-	**16.76 (1.000)**	-	1.08 (0.021)	-	-
Grassland	-	-	5.54 (0.006)	5.78 (0.074)	-	-	**38.91 (0.851)**	9.06 (0.178)	-	-
Irrigation agriculture	-	-	2.55 (0.003)	-	-	-	-	**23.52 (0.462)**	-	-
Urban development	-	-	27.23 (0.031)	1.88 (0.024)	1.20 (0.034)	-	5.80 (0.127)	13.68 (0.269)	**35.84 (1.000)**	-
Reservoir	-	-	1.16 (0.001)	-	5.13 (0.144)	-	-	-	-	3.92 (1.000)

Table 5. Land-cover/use transitions for the Mexican part of the Tijuana River basin between 1972-1994 in km². The values in parentheses indicate the transition probabilities, and the values in bold characters indicate the diagonal of the transition matrix.

Mexico 1972-1994	*Juniperus* scrub	Chaparral	Coastal sage scrub	Riparian vegetation	Mountain meadows	Grassland	Irrigation agriculture	Rainfed agriculture	Urban development	Reservoir
Juniperus scrub	**200.25 (0.769)**	21.98 (0.015)	-	-	5.94 (0.104)	-	-	-	-	-
Chaparral	55.28 (0.212)	**1391.32 (0.926)**	2.70 (0.003)	6.76 (0.110)	5.39 (0.095)	4.98 (0.036)	-	1.20 (0.016)	-	-
Coastal sage scrub	-	16.99 (0.011)	**891.58 (0.867)**	7.81 (0.127)	-	24.68 (0.177)	1.64 (0.042)	7.93 (0.103)	-	-
Riparian vegetation	1.43 (0.005)	13.87 (0.009)	13.09 (0.013)	**40.23 (0.655)**	2.70 (0.047)	2.37 (0.017)	4.64 (0.118)	2.11 (0.027)	-	-
Mountain meadows	2.15 (0.008)	2.72 (0.002)	-	-	**25.81 (0.453)**	-	-	-	-	-
Grassland	1.40 (0.005)	27.50 (0.018)	26.73 (0.026)	1.51 (0.025)	14.61 (0.256)	**46.33 (0.333)**	1.49 (0.038)	13.67 (0.178)	-	-
Irrigation agriculture	-	1.00 (0.001)	1.48 (0.001)	-	2.53 (0.044)	3.97 (0.028)	**17.14 (0.436)**	7.01 (0.091)	-	-
Rainfed agriculture	-	6.69 (0.004)	11.72 (0.011)	3.11 (0.051)	-	18.82 (0.135)	11.08 (0.282)	**35.98 (0.468)**	-	-
Urban development	-	21.04 (0.014)	79.47 (0.077)	2.03 (0.033)	-	38.09 (0.274)	3.33 (0.085)	9.00 (0.117)	**69.46 (1.000)**	-
Reservoir	-	-	1.50 (0.001)	-	-	-	-	-	-	**4.84 (1.000)**

Discussion

As would be expected in an area where secondary and tertiary economic activities dominate, urbanization accounted for the larger transformations. On both sides of the border in the TRW, grasslands and agriculture were the forestates of urban development. Within the basin, urbanization showed two different patterns. One was the enlargement of existing patches, mainly on the Mexican side, eastwards along the international border, southwards along the Pacific coast and to the southeast along the Tijuana River. This growth took over grasslands, coastal sage scrub and riparian zones, interrupting the continuity of these ecosystems between Mexico and the US. The second pattern was formed by the development of scattered urban patches, growing over riparian habitats and chaparral in Mexico and widely spread in the US over grasslands and chaparral (Fig. 1). The higher perimeter ratio of the urban area in US reveals the higher fragmentation of urban patches on this side.

In the US the more dispersed urban pattern was driven by a combination of population growth, socio-economic encouragement of suburban growth, policies empowering local governments combined with lower taxes in rural areas and infrastructure construction; mainly highways, water and drainage, and other services (Ojeda & Espejel in press). In Mexico, a more compact and continuous urban pattern was driven mainly by population growth, especially of migrants in search of work, job creation policies (such as Border Industrialization Program, Zenteno & Cruz 1992), poor infrastructure investment that pushes newcomers to be near the limits of urbanization and lack of law enforcement preventing illegal land use change (Ojeda & Espejel in press; Velázquez et al. 2005). Indeed, almost 50% of the city's area has an irregular settlement origin (Alegría & Ordoñez 2005).

The dynamics of the transformation process was much simpler in the US than in Mexico (Tables 4 and 5). The observed differences possibly reflect a series of driving forces, such as diverging urbanization growth patterns, different grazing practices in each country, the active role played by itinerant rain-fed agriculture and induced grasslands in Mexico (which allows the recovery of natural vegetation), and some conservation policies applied in the US that contribute to reduce the number of transformation pathways undergone by natural areas.

On both sides of the border, scrublands were the main source of land cover change, in part because they cover most of the watershed area and especially because they dominate in the flat lowlands where development has priority. During our study period, *Juniperus* scrub in Mexico changed mainly towards chaparral – its natural neighbour that takes over when *Juniperus* cover decreases as a result of wildfires and/or cutting for fuel and for the construction of ranch fences by the local populations (Minnich & Franco-Vizcaíno 1998). Chaparral and coastal sage scrub, the dominant categories in the basin's scrublands, had a more dynamic and diverse contribution to land cover transitions; transforming to every other land use type. Quantitatively, however, their reduction was chiefly driven by urban development, which occurred largely at the expense of chaparral in the US and of coastal sage scrub in Mexico. Quantitative and qualitative changes in chaparral composition and structure are caused by *ranchero*s, who deliberately burn the scrub to improve browsing and livestock access, and by agricultural burns that increase without control (Minnich & Franco-Vizcaíno 1998). During our study period, some chaparral and coastal sage scrubs in Mexico were recovered from abandoned agriculture plots and induced grasslands, a process observed only in very small areas in the US (Table 5).

Coastal sage scrub is a unique type of land cover as it contains a great number of endemic species (Oberbauer 1999; Riemann & Ezcurra 2005). Besides its diverse conversions to all kinds of land use, it has been used for cattle grazing since colonial times, with browsing preferences resulting in selective removal of some shrub species, and with the introduction of exotic species to make it more palatable for livestock (Minnich & Franco-Vizcaíno 1998). Burning practices are also common in this land cover type, and although it is resilient under periodic fire (O'Leary 1990), recurrent intervals of less than five to ten years will degrade it and lead to the dominance of non-native grasses, often promoted by open-range, transhumance cattle grazing (Malanson 1984; Minnich & Franco-Vizcaíno 1998).

In our data set, riparian land cover appears to have grown substantially between 1970 and 1994. This effect, however, is probably due to the 1992–1993 El Niño phenomenon, when the rainy season almost doubled the long-term precipitation mean (Anon. 2004) enhancing the development of foliage and biomass along water courses. In spite of this apparent increase in riparian land cover, urbanization was a major cause of its destruction on both sides of the border. Additionally, in the Mexican portion of the basin, rain-fed agriculture expanded over fluvial terraces to benefit from water courses, thus taking over riparian land cover (Table 5).

Induced grasslands can replace any type of land cover, and thus play an important role in the landscape. During our study period they expanded mainly over chaparral and coastal sage scrub, or they developed on abandoned agricultural plots (Tables 4 and 5). In Mexico their decrease in area and increase in patch numbers were due either to their abandonment followed by recovery of natural cover in some patches, or to their occupation by urbanization. In the US, grassland areas merged as they extended, leading to a reduction in the number of patches (Fig. 1). Because induced grasslands form open, highly-disturbed and biologically poor sites, they are sought after by development projects, and constitute one of the early stages leading towards urbanization on both sides of the border.

Irrigated agriculture was less dynamic, but decreased giving space to urban development and grasslands. In Mexico, because of the high cost of irrigation water and of the growing demand of water for urban use, many irrigated agricultural areas retreated to rain-fed farming during our study period. In the US, reductions in irrigated farmlands were caused by a shift in the production, starting in the 1950s, from field crops to nurseries, flowers and intensive cultivation farms, including small scale vegetable producers that benefit from the urban proximity and produce more per acre (Sokolow 2004).

Relying only on rainy seasons, rain-fed agriculture played a key role in the dynamics of the Mexican landscape during our study period, but not in the US, where it is not practiced. Usually small patches of natural land cover are cleared for cultivation (mainly oat, barley and maize, according to Anon. (1995) or to allow the growth of induced grasslands; after one or two cropping seasons they are abandoned, shifting spatially with time. The shifting of rain-fed agriculture occurs because of its reliance on modest and erratic precipitation, marginal soils for agricultural practices and lack of relatively flat terrains. This type of itinerant agriculture may allow the recovery of natural land cover as long as the agricultural plot is surrounded by natural patches that allow re-colonization.

According to Velázquez et al. (2005), in Mexico there is a 'passive' recovery of natural land cover due in part to the abandonment of small patches of land by farmers who migrate to urban areas or to the US, or to small scale conservation actions; and to the socioeconomic conditions in which *ejidos* and communities (common property land) live. In our study area this process was also associated to the spatial shifting of rain-fed and induced grassland cultural practices.

Conclusions

Transition networks were different on each side of the border, and were closely linked to contrasting policies and land use practices during the selected time period which was based on the industrialization by the *maquiladora* economy (Zenteno & Cruz 1992). Because of this, the main change that occurred over the entire basin was caused by urban development, although with different patterns on each side of the border, driven by a different combination of social, demographic, and policy factors.

Shifting rain-fed agriculture in Mexico, or suburban development in the US, are some prime examples of the influence of societal patterns on natural land cover change. In political terms, the lax enforcement of land use plans in Mexico, compared to the US, is quite evident.

As a whole, on the US side of the basin, LUCC followed a simpler path, with major changes concentrated on chaparral and irrigated agriculture, being rapidly transformed into urban developments with induced grasslands as an intermediate stage. In the Mexican part of the basin the process was more complex; mostly because of the itinerant practices of rain-fed agriculture and grassland management, on the one hand, and of unchecked, badly planned, and very rapid urban development on the other.

In Mexico, rain-fed agriculture, which is very dynamic in time and space, played a key role and explained the much more complex LUCC patterns. Grasslands also added complexity and risk into the system dynamics; in Mexico their growth and productivity is governed by burning practices, while in the US burning is not a management tool.

The dynamic complexity of the land use mosaic imposed by Mexican itinerant land use is perceptible in other types of natural land cover such as, for example, the exploitation and subsequent recovery of *Juniperus* scrub, or the use of mountain meadows and riparian land cover for cattle grazing during rainy years. Recovery of natural vegetation occurs mostly on the Mexican side of the border driven by the shifting practice of rain-fed agriculture and grasslands. In the US natural protected areas imposed limits to LUCC in some parts of the basin.

Further research may consider the analysis of ongoing LUCC paterrns, including the role that shifting rain-fed agriculture and induced grasslands may play in the recovery of chaparral and coastal sage scrub in the Mexican side of the basin. In addition, another potential research path could be the development of different scenarios for mid and long-term study for both sides of the basin and the basin as a whole.

In conclusion, our research suggests that, despite the need for an integrated planning and management of binational basins and shared water resources, in practice, these goals are hampered by the role played by different factors triggering land use change within each society. In any case, the challenge remains to build shared approaches and tools for planning and public policy formulation.

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