Land and water use changes in the US–Mexico border region, 1992–2011

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Abstract

The linkages between land and water use are often neglected when considering resource management. Here, we examined regional changes in land and water use along the US–Mexico border in the decades following the North American Free Trade Agreement, using bi-national land cover maps from 1992–2011, a process-based hydrology and irrigation model driven with long-term meteorological data, and agricultural production and urban water demand statistics. During the study period, land and water use in the region partially re-oriented around the needs of US cities, leading to crop to urban conversions and water savings in the US, while agricultural and urban expansion in Mexico resulted in local aquifer exploitation and reduced river flows. We identified that land uses with lower rates of water consumption (urban in US and agriculture in Mexico) expanded more than those with higher demands (irrigated agriculture in US and urban in Mexico) due to the water scarcity in the region. This resulted in divergent trends in the US and Mexico that in aggregate has led to an unsustainable trajectory in land and water resources.

Introduction

Land and water resources are under increasing pressures from population growth and the expansion of agricultural, pastoral and urban land uses [1, 2]. Because of global trade, land and water resources are increasingly used together to produce commodities that are consumed in distant locations, resulting in the virtual export of land and water [3–6]. Thus, remote drivers or teleconnections increasingly influence local decisions related to land and water use as well as the local resource competition occurring between cities, agriculture, ranching and other sectors [7]. This is anticipated to be keenly acute in the arid and semiarid regions of the world where competition for water resources significantly impacts land use decision-making [8, 9].

One region where water scarcity may influence land and water use changes is the 3200 km long border between the United States and Mexico (figure 1), which is characterized by arid and semiarid ecosystems and frequent droughts [10]. On both sides of the border, rapidly-growing urban centers and their economic activities compete with rainfed and irrigated agriculture, ranching, and natural ecosystems for obtaining water resources on extensive open lands [11, 12]. To meet these demands, aquifer over-exploitation has led to declines in regional groundwater levels [13, 14], while water shortages in transboundary rivers, such as the Rio Grande and Colorado River, have led to both international disputes [7, 15, 16] and examples of cooperation [17].

A major shift in the trajectory of the US–Mexico border was prompted by the 1994 North American
Free Trade Agreement (NAFTA) through spurred urban and agricultural development. While prior work has discussed the environmental impacts of NAFTA [7, 18], there has been a limited quantification of the interrelated land and water use changes in the region. Thus, we posed the following questions: (1) how has land use changed following NAFTA (1992–2011)? (2) Did land use conversions impact water supply and demands? (3) Are there implications for the sustainability of the US–Mexico border region?

To answer these questions, we employed the Variable Infiltration Capacity (VIC) model [19], extended with an irrigation module [20] and a model of urban water consumption. Three regional land use maps for years 1992, 2001, and 2011 were obtained from bi-national land cover datasets. To isolate anthropogenic changes from natural changes by superimposing the urban, cropland, and rainfed pasture extents from 1992 and 2011 onto the extents of natural land covers from 2001. Water use and hydrologic fluxes reported from simulations for each land cover map are the mean values over the entire period.

Methods

Hydrologic simulations were conducted with the process-based, VIC hydrologic model [19], version 4.2, extended with an irrigated agriculture module [20]. Simulations covered the period 1980–2013 at 1/16th degree spatial resolution, using gridded daily meteorology [21], disaggregated to hourly resolution via the methods of [22]. The study domain consisted of states in the US and Mexico contained between 20° and 37° N latitude and 93° and 123° W longitude, plus southern portions of California and Nevada (figure 1). Land cover maps for the years 1992, 2001, and 2011 were derived from the USGS National Land Cover Database [23] and for the years 1993, 2002, and 2011 of the INEGI Uso del Suelo y Vegetación map [24], reconciled to a consistent set of classes (table S1 is available online at stacks.iop.org/ERL/13/114005/mmedia), and aggregated to area fractions at 1/16th degree (6 km). Anthropogenic changes were isolated from natural changes by superimposing the urban, cropland, and rainfed pasture extents from 1992 and 2011 onto the extents of natural land covers from 2001. Water use and hydrologic fluxes reported from simulations for each land cover map are the mean values over the entire period.

Seasonal cycles of land cover characteristics were derived from the moderate resolution imaging spectrometer products [25]. Soil parameters were derived from the Digital Soil Map of the World [26]. Irrigated and planted fractions were obtained from MIRCA2000 [27] and bias-corrected on a state-wide basis to match areas given by the years 1992, 2002, and 2012 of the USDA National Agricultural Statistics Service [28] and the years 1993, 2002, and 2011 of the SAGARPA Anuario Estadístico de la Producción Agrícola [29]. Agricultural trade statistics were obtained from the USDA Global Agricultural Trade System database [29]. For each major crop category, water use in each grid cell was computed by multiplying the simulated irrigation withdrawal in the cell by the share of statewide irrigated area devoted to that crop. Nationwide fractions of land and water used for
Export-oriented production were computed as the ratio of tonnage exported to tonnage produced. These fractions were then applied to the cultivated and irrigated areas and water use estimates of these crop categories in each cell. To account for uncertainty in the source locations for exports from Mexico, a second set of land and water fractions were computed assuming all exports were produced within the domain. The fraction of irrigation drawn from groundwater was taken from the Global Map of Irrigated Areas [31]. Urban water withdrawals were estimated using population counts from the years 1990, 2000, and 2010 of the US Census Bureau [32–34] and the INEGI Censo de Población y Vivienda 2010 [35], along with per capita domestic and commercial water withdrawals from the USGS National Water Information System [36] and the CONAGUA Atlas del Agua en México 2012 [13], and assigning all withdrawals to urban areas. Consumptive water use was calculated by multiplying urban and agricultural withdrawals obtained from the simulations by factors of 0.33 and 0.8, respectively, based on the ratios of mean consumptive use to mean withdrawals for these categories in USGS water use records [36]. The resulting agricultural and urban water use was evaluated as described in appendix. Relative to government records, simulated statewide agricultural withdrawals had bias and RMSE of $-20\%$ and $28\%$ in Mexico and $+9\%$ and $14\%$ in the US. Simulated urban withdrawals had bias and RMSE of $-1.7\%$ and $7.1\%$ in Mexico and $3.3\%$ and $6.4\%$ in the US. However, it should be noted that government records may also contain substantial yet poorly-defined errors [36, 37]. Model performance in simulating streamflows in the region has been investigated previously [25].

Results

Land use changes

Changes in land use from 1992–2011 differed markedly across the US–Mexico border (figure 2, tables S2 and S3). The US portion of the region primarily experienced widespread urban expansion (16 000 km$^2$, or +24%) on
the fringes of major cities, notably around Phoenix, Dallas, Houston, and Los Angeles. A substantial expansion of croplands (6800 km²) in the High Plains of TX, OK and NM (state abbreviations denoted in figure 1) was mostly canceled by crop to urban land conversion (5000 km²) around the major cities, resulting in a modest net crop expansion of 1800 km² (+1%). Despite this net increase, the area of irrigated cultivation declined by 4000 km², primarily west of 100° W longitude (figure S1). Rainfed pastures also declined by 5800 km² (−6%), primarily in TX. The net expansion of anthropogenic land covers resulted in the loss of 10 000 km² of shrub/grassland and 1900 km² of forest areas in the US from 1992–2011.

In contrast, the Mexican portion of the region experienced less urban expansion in terms of absolute area (2900 km², or +60%), but a substantial increase in cropland area (18 000 km², or +14%) and a large northward shift in pastures (net increase of 3300 km², or +0.5%). Natural landscapes were converted to pasture and cropland, including 18 000 km² of shrub/grassland and 7000 km² of forest, primarily in the Sierra Madre Occidental (SMO). Cropland and pasture expansions were uneven across Mexico, with crop area growth concentrated in CHH, ZAC and SIN, and pasture expansion mostly in SON, northern NLE and TAM. Cropland extents declined in western SON, where they were replaced by pasture, and around Torreon in DUR and COA. Pasture extents were reduced in DUR, southern TAM and other sites further south. Importantly, irrigated agriculture consuming surface or groundwater resources (figure S1) expanded by 6000 km². Crop-urban conversions occurred over 1200 km² as compared to 5000 km² in the US.

Water use changes
The divergent trends in land use change within the US and Mexico had important consequences for simulated consumptive water use (figure 3, tables 1, S4). In the US, population growth and accompanying urban expansion increased water use by 1.3 km³ yr⁻¹ (+39%, note that 1 km³ is 810714 acre-feet), but the decline in the extent of irrigated agriculture reduced the total water use by 4.0 km³ yr⁻¹ (−8%), for a net reduction of 2.7 km³ yr⁻¹ (−5%). For comparison, the long-term mean annual flow in the Colorado River is 17 km³ yr⁻¹ [38]. Reductions in cotton in the High Plains and central AZ,
Irrigation also impacted net runoff reduction in the amplitude of the seasonal cycle of ET. By 0.17 and 0.92 km$^3$ yr$^{-1}$, correspondingly, to a net rise in consumption of 3.3 km$^3$ yr$^{-1}$ (+16%). Increases in irrigation water use were concentrated in SIN, CHH, and TAM (2.8, 1.5, and 0.5 km$^3$ yr$^{-1}$), accompanied by declines elsewhere. These changes were the result of several different transitions. First, in the 1990s, summer crops declined dramatically due to whitely infestation of soy in the Yaqui Valley and SIN and due to groundwater overdraft and soil salinization in BCS, western SON, DUR and COA. Second, a corresponding shift to durum wheat production increased winter irrigation in SIN and the Yaqui Valley during the 2000s, while irrigated agriculture expanded significantly in CHH and TAM (figure S1).

Hydrologic budget changes
Changes in land and water use had relatively minor impacts on the overall hydrologic budget due to their limited extent (2% of total area). However, local effects from irrigation and deforestation were sizable in some areas (figure S2). Irrigation affected evapotranspiration (ET), with annual ET decreases of 1.2 km$^3$ yr$^{-1}$ (−0.2%) in the US and increases of 3.1 km$^3$ yr$^{-1}$ (+0.6%) in Mexico. In SIN, a shift from summer to winter crops led to +10% in winter ET and an 8% reduction in the amplitude of the seasonal cycle of ET. Irrigation also impacted net runoff ($Q_{\text{net}}$), which increased by 0.3 km$^3$ yr$^{-1}$ in the US and decreased by 0.5 km$^3$ yr$^{-1}$ in Mexico. Changes in $Q_{\text{net}}$ and irrigation were positively correlated where irrigation used groundwater (CHH, AZ, SON and High Plains) and negatively correlated where surface water supplies were drawn upon (SIN). This led to local effects that might differ from regional totals. For instance, a shift from groundwater to surface water irrigation in COA and NLE reduced simulated flows to the transboundary Falcon Reservoir by 0.09 km$^3$ yr$^{-1}$, and expansion of surface water use reduced irrigation return flows into the Rio Conchos, upstream of the Amistad Reservoir, by 0.04 km$^3$ yr$^{-1}$.

 Anthropogenic deforestation occurred primarily in Mexico within the SMO, leading to compensating effects on surface water resources. In contrast with irrigation-induced changes, deforestation reduced annual ET and increased annual $Q_{\text{net}}$ via changes in ecosystem water use. Over Mexico, conversions of forests into rainfed pastures and croplands increased $Q_{\text{net}}$ by 0.17 and 0.92 km$^3$ yr$^{-1}$, respectively. In particular, deforestation in the Rio Yaqui, Rio Conchos, and other basins in the SMO (figure S2) caused $Q_{\text{net}}$ to increase by 0.62 km$^3$ yr$^{-1}$ (+6%). Reductions in ET in all of these basins were approximately equal to the increases in $Q_{\text{net}}$, but amounted to a small portion of annual ET (−0.2%). In the Rio Conchos, forest-crop conversion led to an increase in $Q_{\text{net}}$ of 0.22 km$^3$ yr$^{-1}$, more than compensating for the increased withdrawals for surface water irrigation, for a net increase of 0.18 km$^3$ yr$^{-1}$ into the Amistad Reservoir. However, deforestation increases in river flows (0.58 km$^3$ yr$^{-1}$) were counteracted by increases in irrigated agriculture downstream that had a net effect of reducing river flows in Mexico overall by 0.49 km$^3$ yr$^{-1}$.

Discussion
Cross-border differences in agricultural land and water use
Irrigated agriculture followed different trajectories on either side of the border from 1992–2011, with decreases in the US and increases in Mexico (figure 4, table S2). Export-oriented cultivation of irrigated and rainfed fruits and vegetables in Mexico for NAFTA markets (of which the US comprised 93%) expanded by an estimated 2000–4000 km$^2$ of land use, resulting in a simulated increase of 0.4–0.8 km$^3$ yr$^{-1}$ of water use within the domain, depending on how much was sourced from northern Mexico. Trade of irrigated bulk commodities such as winter wheat with non-NAFTA countries led to an additional 1300 km$^3$ and 0.8 km$^3$ yr$^{-1}$ of land and water use exported virtually from Mexico. The remaining expansion, consisting of 12 700–14 700 km$^2$ of cropland and 1.3–1.7 km$^3$ yr$^{-1}$ of water use, addressed food needs in Mexico, including irrigated feed cultivation for livestock. Agricultural changes also occurred in Mexico in response to environmental degradation, for example in cropland-pasture conversions in western SON which encouraged irrigated cropland expansions in other areas (figure 5). In contrast, although fruit and vegetable cultivation expanded in the US, urban expansion and field fallowing led to a net reduction of irrigated cropland (−1300 km$^3$).

Cross-border differences in urban land and water use
Urban growth also exhibited different trajectories on either side of the border from 1992–2011, with about five times the urban expansion area in the US (figure 4, table S2). Moreover, US cities preferentially expanded into surrounding croplands at higher rates, particularly in AZ and NM (figure S3). Despite widespread use of urban irrigation [8], US cities had substantially lower simulated and recorded water use rates than irrigated agriculture [44], such that crop-urban conversion yielded large water savings. For instance, the urban growth rate of 65% in AZ resulted in a large reduction in cropland area (−8%) and the transfer of 0.69 km$^3$ yr$^{-1}$ of agricultural water to urban use. In contrast, higher population densities in Mexican cities...
led to higher simulated values of urban water use rates per unit area than in US cities, despite lower per capita water consumption (123 and 204 l d\(^{-1}\) in Mexico and US, respectively)\(^{[13, 36]}\), such that crop-urban conversion in Mexico yielded smaller water savings or even net losses.

### The role of water scarcity and management

A number of factors may have contributed to differing rates of urban and agricultural expansion in the US and Mexico, including cross-border differences in affluence, car ownership, the proportion of workforce employed in agriculture, and trends in beef consumption\(^{[43, 45-47]}\). However, the evolution of land use in the region suggests that water scarcity and management also played major roles. Among water-intensive land uses (table S4), those with the lowest water consumption rates per unit area expanded the most within each country (figure 5). For example, in the US, the expansion of cities with lower water consumption than irrigated agriculture (water savings of 191 mm yr\(^{-1}\) per unit area) was favored. Expansion of agriculture in Mexico with a lower water use than cities also followed this trend, with crop-urban conversions resulting in water cost of 20 mm yr\(^{-1}\) per unit area. Indeed, growing cities in Mexico have sought additional water resources through other means, for example via inter-basin transfers or groundwater exploitation\(^{[48, 49]}\). Cross-border differences in water management may have also exacerbated these land use trends. To conserve groundwater through the water savings associated with crop-urban conversion, Arizona passed the 1980 Groundwater Management Act, prohibiting the establishment of irrigated agriculture on new lands\(^{[14]}\). In contrast, in Mexico, groundwater resource

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**Figure 4.** Urban and irrigated agricultural land use areas (10\(^3\) km\(^2\)) in the US and Mexico over the period 1992–2011, with the major resource exports of land and water use indicated with arrows. *Individual data for US unavailable for 1992.

**Figure 5.** Changes in urban and cropland areas (10\(^3\) km\(^2\)) between 1992–2011 as a function of their 1992 annual water use per unit area (mm yr\(^{-1}\)). Horizontal bars denote changes in water use per unit area arising from crop to urban conversions in each country.
allocations for agricultural use have been poorly monitored and enforced [37, 40], leading to a more hospitable environment for expanded irrigated agriculture.

**Conclusions**

Land and water use in the US–Mexico border region has followed an unsustainable trajectory from 1992–2011 in several respects. First, rapid urbanization in the US and agricultural expansion in Mexico led to a substantial reduction of natural resources and ecosystems, primarily in Mexico. Due to the arid and semiarid climate in the region, increases of agricultural and urban water use in Mexico were sustained by widespread aquifer depletions that led to saltwater intrusion and soil salinization [13]. Irrigation expansions also reduced flows into transboundary reservoirs on the Rio Grande during the time that Mexico failed to meet obligatory deliveries [16]. Since deforestation counteracted some of these irrigation-induced reductions, it is clear that land and water management are inextricably linked across the US–Mexico border in a complex fashion. Second, while NAFTA is recognized as the first major trade agreement to include environmental provisions [50], the coordination of joint land and water resources for the arid and semiarid region appears to have been lacking. As a result, unexpected outcomes have occurred, including an increased dependence in the region on food production from unsustainable groundwater resources in Mexico [37] and the ‘hardening’ of water demand by crop-urban conversion in the US [51]. The outsourcing of water-intensive food production from the US to Mexico has obscured the regional environmental impacts of local land and water management policies, giving the illusion of sustainability locally [3, 14]. Ongoing renegotiations of NAFTA could be an opportunity to improve bi-national sustainability through new policies that recognize the consequences of US–Mexico trade on land and water resources.

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**Appendix**

Evaluation of simulated agricultural withdrawals against available records from the years 1990, 2000, and 2010 in the US [36] and the year 2011 in Mexico [13] yielded a bias of −20% over the Mexican states and +43% over the US states in the study area, respectively (table S4, figure S4). However, the bias in the US was dominated by high values of saturated hydraulic conductivity in the High Plains in Texas. An additional bias came from California in 2010, in which the reported irrigated area was similar to that in years 1990 and 2000, but the reported irrigation withdrawal was 30% less than those in 1990 and 2000. Excluding the values from Texas in all years and California in 2010 led to a bias of 9% in the US. Model errors as a percentage of government totals had an area-weighted RMSE of 28% in Mexico and 14% in the US. Simulated urban withdrawals had smaller errors because they were constructed from nationwide means of government records alone. For the year 2010, simulated urban withdrawals had a bias and RMSE of −1.7% and 7.1% in Mexico and 3.3% and 6.4% the US (table S4). The negative bias in Mexico was the result of errors in assignment of some urban areas along the US–Mexico border to the US. The positive bias in the US was primarily the result of government records not always including all components of urban use (residential, commercial and golf).

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