1. Introduction

The lake system and surrounding mountain ranges of the Basin of Mexico, in the central highland region of the Trans-Mexican Volcanic Belt, bore witness to human activities at least from the Early Holocene. In more recent times, two complex prehispanic mesoamerican urban societies developed within this scenario: Teotihuacan (2nd-7th centuries AD) and Tenochtitlan (14th-early 16th centuries AD).

Results from several decades of paleoethnobotanical and geoarchaeological investigation in the Basin of Mexico, together with information from ethnohistorical and historical documents contribute towards a better understanding of the ecodynamics of this region and the complex interrelationships among environmental characteristics and the history of human occupation. The Teotihuacan Valley (Figure 1a) in particular provides a detailed case study in which many aspects of landscape change over the past three millennia have been documented.

We begin with a hypothetical reconstruction of vegetation types, based on altitude, humidity, soil characteristics and the ecological requirements of the native plants that conform each group, thought to represent the general conditions of the study area at the time of the earliest settlement by permanent agricultural communities (ca. 1150 B.C., Sanders et al. 1979) shown in Figure 1b. Modern distribution of primary vegetation and soils in the semi-arid Teotihuacan region (Castilla and Tejero 1987, Rzedowski et al. 1964, Rzedowski 1977, Rzedowski 2001), macro- and microbotanical remains recovered from excavated archaeologica contexts and soil profiles (McClung de Tapia 1987, Adriano and McClung de Tapia 2008, McClung de Tapia et al. 2008, McClung de Tapia and Adriano 2012), and geoarchaeological and paleoenvironmental studies in adjacent areas of the Basin of Mexico (Cordova 1997, Cordova and Parsons 1997, Frederick 1997, Lozano-García and Ortega-Guerrero 1998) provide the evidence upon which the proposed reconstruction is based.

Elevation and soil characteristics typical of semi-arid climatic conditions favored the development of the following vegetation communities: Pine and mixed pine/oak forest (2500-3050 m); Oak scrub (2400-2500 m); Xerophytic scrub (2300-2400 m); Grassland (2300-2300 m); Aquatic and marsh vegetation (2230-2240/2250 m), and Gallery (2250-2300 m). With the exception of pine and pine/oak forest, these communities are present today although their distribution is significantly limited.
Figure 1a. The Basin of Mexico and the Teotihuacan Valley: 1b. Hypothesized primary vegetation in the Teotihuacan Valley, Mexico. Maps by Rodrigo Tapia-McClung
2. Vegetation Change and Human Settlement in the Teotihuacan Valley

Vegetation change through time is not only a consequence of climate change, but also reflects modifications in landscape use by human communities. Agricultural systems evolved in the study region as population and the number of settlements increased. Irrigation systems (Charlton 1990, Nichols 1987, Nichols et al. 2001) and terracing (Charlton 1970, Sanders et al. 1979) were likely developed during the Classic (Teotihuacan) period to fulfill the need for subsistence products. Estimates of regional carrying capacity, between approximately 40,000-50,000 inhabitants (Charlton 1970, Lorenzo 1968), suggest that a large proportion had to have been obtained from adjacent regions. Depending upon the agroecological system in use, regional biodiversity was necessarily affected by the increase in settlement and the expansion of cultivation. While it is possible that different management techniques were developed, the intensification of agricultural production undoubtedly affected the habitats of plant and animal taxa. The use of forest resources for construction and fuel over several centuries necessarily impacted the vegetation as well, although periods of abandonment may have permitted intermittent forest regeneration.

Detailed surface survey to locate evidence for prehispanic settlements was undertaken in the 1960s (Sanders 1965). Population estimates for human settlements corresponding to different occupation phases (Sanders et al. 1979, Gorenflo and Sanders 2007), are considered together with estimates of the potential productivity of cultivated plants (maize and others) in the area within which settlements were located, to assess the area affected by human activities. A model of resource production/exploitation and its effect on natural vegetation in the region at different moments in the prehispanic past was developed. Earlier work by Gorenflo and Gale (1986) explored patterns of spatial association between prehispanic settlement location and potential subregional agricultural productivity in the Teotihuacan Valley, Mexico. This paper considers how settlement location may inform studies of vegetation, and hence, landscape change through time.

Settlement location and potential productivity allow us to explore how human communities may have “disturbed” the surrounding landscape as a consequence of both routine and exceptional exploitative practices. We estimate the minimum area affected by human activities, assuming a broad definition of subsistence that includes food procurement as well as production.

Gorenflo and Gale (1986) used values for potential productivity levels associated with particular subregions of the study area (Table 1), based on cultivation techniques and humidity regimes assumed to have been in use in prehispanic times (Sanders et al. 1979, Evans 1980).

<table>
<thead>
<tr>
<th>Subregion</th>
<th>Agricultural strategy</th>
<th>Annual maize productivity (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin soil alluvium (2240-2300 masl, soil depth &lt;1m)</td>
<td>Rainfall dependent</td>
<td>500</td>
</tr>
<tr>
<td>Deep soil alluvium (2240-2290 masl, soil depth&gt;1m)</td>
<td>Permanent irrigation</td>
<td>1400</td>
</tr>
<tr>
<td>Deep soil alluvium (2290-2300 masl, soil depth &gt;1m)</td>
<td>Floodwater irrigation</td>
<td>1000</td>
</tr>
<tr>
<td>Lower piedmont (2260-2340 masl)</td>
<td>Floodwater irrigation</td>
<td>800</td>
</tr>
<tr>
<td>Middle piedmont (2350-2499 masl)</td>
<td>Floodwater irrigation</td>
<td>800</td>
</tr>
<tr>
<td>Upper piedmont (2500-2699 masl)</td>
<td>Rainfall dependent</td>
<td>500</td>
</tr>
<tr>
<td>Sierra (≥ 2700 masl)</td>
<td>Nonarable</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1. Environmental categories, agricultural strategies and potential maize productivity in the Teotihuacan Valley (based on Sanders et al. 1979, Evans 1980, Gorenflo and Gale 1986, McClung de Tapia et al. 2008).
Figure 2a. Teotihuacan period agricultural expansion in the Teotihuacan Valley, México, showing cumulative effects from the time of initial settlement in the region (ca. 1150 BC) through the Classic period (AD 600/650): 2b. Aztec period agricultural expansion in the region, showing cumulative effects from the time of initial settlement in the region through the Late Postclassic period (ca. 1150 BC – AD 1519). Maps by Rodrigo Tapia-McClung.
Here we use population figures for prehispanic settlements assuming an approximate annual requirement of 200 kg of maize per capita. The area in hectares required to produce sufficient maize for the population of each site was estimated, based on the potential productivity of the subregion within which each site is located, as indicated in Table 1, and considering the hypothesized population for each site (Gorenflo and Sanders 2007). We employed a circular configuration of the area for each site corresponding to the presumed maize requirements for the population. The radius was calculated for each area based on population size and the radii were then used to determine buffers surrounding each site as an estimate of the minimum area impacted by agricultural activities. We interpret these areas as zones in which natural vegetation was affected by human activities, a proxy for impact on the natural biodiversity of the region.

This procedure was repeated for each of the major prehispanic occupation phases described in the Teotihuacan Valley for which digital settlement data are available. Figure 1b represents the hypothetical distribution of vegetation types believed to have been present in the region at the time of initial settlement, the point of departure for an analysis of change through time in which we trace the cumulative effects of agricultural exploitation on these vegetation communities.

Maps were generated to model the effects of human settlement expansion together with increased agricultural exploitation of the region through time. For example, in the Cualanlan phase a limited area of 1,117 ha or 1.17% of the regional biodiversity in the region was affected by agricultural activities of the villages established between 700-300 BC. The urban center of Teotihuacan, although founded around 100 BC, experienced significant demographic and spatial expansion during the Classic period, dominating the region between AD 150-600/650. Assuming agricultural productivity sufficient to fulfill the needs of the estimated population, biodiversity in at least 19,509 ha (20.47%) was affected (Figure 2a). The demise of the Teotihuacan state was followed by a considerable decline in regional population. Finally, during the Late Aztec occupation up until the Spanish Conquest (AD 1350-1520), an area of at least 31,358 ha (32.91%) was exploited for agricultural activities, thus increasing the impact on regional biodiversity (Figure 2b). In Table 2, the proportion of each vegetation type affected by settlement and agricultural production is summarized. The legacies of prior impacts were cumulative through time as new settlement systems and cultural traditions replaced earlier manifestations. While we would have expected a much more extensive regional impact, especially considering the demands of hierarchically structured state systems during both the Classic period and the Late Aztec occupation, the results presented here indicate gradual impact over several millennia.

<table>
<thead>
<tr>
<th>VEGETATION TYPE</th>
<th>Total Area (ha)</th>
<th>CUANALAN PHASE 650-300 BC</th>
<th>CLASSIC PERIOD AD 150-600/650</th>
<th>LATE AZTEC PERIOD AD 1350-1520</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lakeshore/Aquatic plant</td>
<td>2,667.54</td>
<td>0.00%</td>
<td>0.05%</td>
<td>0.90%</td>
</tr>
<tr>
<td>Grassland</td>
<td>21,161.43</td>
<td>1.30%</td>
<td>24.73%</td>
<td>37.28%</td>
</tr>
<tr>
<td>Xerophytic shrub</td>
<td>26,232.67</td>
<td>0.52%</td>
<td>30.14%</td>
<td>44.29%</td>
</tr>
<tr>
<td>Oak shrub</td>
<td>25,564.84</td>
<td>1.39%</td>
<td>13.18%</td>
<td>23.34%</td>
</tr>
<tr>
<td>Mixed Conifer/Oak forest</td>
<td>19,668.79</td>
<td>1.05%</td>
<td>6.27%</td>
<td>13.74%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>95,295.28</td>
<td>1.17%</td>
<td>20.47%</td>
<td>32.91%</td>
</tr>
</tbody>
</table>

Table 2. Proportion of each vegetation type affected by human agricultural activities, implying impact through time on the biodiversity of the Teotihuacan Valley.
Although, it has not yet been possible to evaluate the effects of the Spanish Conquest from this perspective, historical documents point to the extreme transformation of the biodiversity of the Teotihuacan region, and the entire Basin of Mexico as well, as a result of the introduction of European agricultural techniques and domestic animals, disease, and intensified exploitation of the remaining forests.

Several limitations to this approach should be mentioned. We did not consider sites related to salt production and quarrying activities, or ceremonial centers, because it is unlikely that permanent resident populations occupied them. In any case, population estimates are generally not available for these site types (Gorenflo and Sanders 2007). Areas of settlement coverage and/or population estimates could not be assigned to some sites, often covered by modern construction, and these locations are not considered in our analysis.

Our intention is to examine how estimates of productivity can be used to assess the area potentially affected by human activities to evaluate landscape modification rather than focus on the carrying capacity of the region. The effects of specific topographic features, (gullies, rock outcrops, extreme slope or other surface characteristics) that would limit agricultural production in the region were not considered in the definition of buffers, due to the limitations of the Geographical Information System (ArcGIS).

While paleoethnobotanical evidence from archaeological excavations in the Teotihuacan Valley indicates that many other plant resources were used, available evidence at present is insufficient to quantify the extent to which they were consumed. Consequently, we propose broad conservative estimates based on part of the area affected by subsistence activities. Finally, although it is highly likely that a significant proportion of surplus agricultural produce as well as other resources were channeled as tribute to local and state level authorities, there is no basis on which to develop an estimate. Consequently, we have not incorporated possible surplus production in the calculations, beyond employing a generous per capita maize requirement. In conclusion, the area impacted by prehispanic subsistence activities and consequences for regional biodiversity were undoubtedly more extensive than what we have been able to model here based on available archaeological settlement pattern data.

3. Discussion: Implications for Modern Societies

Deforestation of surrounding slopes and the development of intensive agroecological systems, based largely on maize cultivation on the piedmont and alluvial plain, are believed to have reduced the biodiversity of the region by modifying habitats of primary vegetation and associated animal taxa. However, following the Spanish conquest, large-scale alterations of the hydrological system, sheet and gully erosion on slopes, stream incision and flooding of the alluvial plains also took place. Some of these events may have begun on a much smaller scale following population decrease and abandonment of settlements after the demise of Teotihuacan in the seventh century. However, later landscape impacts frequently obscure the evidence for earlier processes.

The consequences of impact are visible today on the landscape of the Teotihuacan Valley. Approximately five decades ago, a few remnants of the primary vegetation types characteristic of the region were reported, showing considerable change between the end of the prehispanic period, suggested by our earlier maps, and modern times. Incorporating the period between AD 1520 (the beginning of the colonial period) and 1964, (a relatively recent vegetation survey carried out in the region), approximately 85% of the original biodiversity of the study area has been modified.
Dense urban societies impact the landscape significantly, and represent a challenge to their hinterlands because spatial organization within an urban zone often limits the production of food, which in turn generates emergent environmental problems based on resource availability. Services become the focus of resident populations, providing resources and fulfilling other types of non-subsistence needs. Although communication infrastructure is required to obtain resources, this same infrastructure increases the attraction of the urban area, thus stimulating greater population size/density and the consequent need for still more food resources and services, which reduce subsistence productivity without favoring improved biodiversity.

Few if any landscapes exist today that have not been directly or indirectly shaped by human impact. However, it is necessary to consider the limits within which the landscape can maintain resilience – and the consequences for past human populations as well as those in the present and future. Even considering methodological limitations, our research based on archaeological settlement distributions over a period of approximately 2,500 years in the Teotihuacan Valley suggests that the impact of human activities together with the possibility of some recuperation of vegetation through succession, related to variable periods of abandonment associated with cultural changes in the region, was significantly less when compared with the five centuries following the Spanish conquest.

Human-induced changes in biodiversity are mainly driven by: 1) land-cover changes, 2) land-use intensity, 3) fragmentation, 4) climate change, 5) atmospheric nitrogen deposition and 6) infrastructure development, according to recent studies at a global scale (Alkemade et al. 2009). All of these factors are relevant at a regional level in the Basin of Mexico. Archaeological, historical and modern indicators for several of these drivers are evident in the Teotihuacan Valley specifically. Current trends in anthropological approaches to the study of human resilience in response to risks generally focus on potential adaptation in past and present situations. Insofar as biodiversity is concerned, emphasis is usually placed on how humans have co-evolved with plant and animal resources, indicated by the richness and diversity of so-called traditional ecological knowledge. In spite of the importance of the resilience of human societies may be, the implicit anthropocentric focus of this kind of perspective risks ignoring the latitude and precariousness of biodiversity and landscape resilience. We are not suggesting by any means that the landscape determines the parameters of human adaptation, but rather that human neglect of the landscape’s limits amplifies the threat of disasters and enhances vulnerability, affecting humans as well as other components of the ecosystems involved. Unfortunately, the impacts of biodiversity loss at different scales often appear to be unperceived by human actors.

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Notes
1 The figure of 200 kg per year is based on an average between Charlton’s (1970) figure of 234 kg per person per year and Sanders (1976) and Sanders et al.’s (1979) figure of 160 kg.
Bibliography

Adriano Morán, C.C. and E. McClung de Tapia  

Alkemade, R., M. van Oorschot, L. Miles, C. Nelleman, M. Bakkenes and B. ten Brink  

Caballero, M.E., B. Ortega, S. Lozano, J. Urrutia and J.L. Macías  

Castilla Hernández, M. and D. Tejero-Díez  
1987 Flora y vegetación del Cerro Gordo (San Juan Teotihuacan) y regiones aledañas, Valle de México, México, *Biótica* 12:231-255.

Charlton, T. H.  

Charlton, T.H.  

Evans, S.T.  

Gorenflo, L.J. and N.D. Gale  

Gorenflo, L.J. and W.T. Sanders  
2007 *Archaeological Settlement Pattern Data from the Cuautitlan, Temascalapa, and Teotihuacan Regions, Mexico*. Occasional Papers in Anthropology No. 30, Department of Anthropology, the Pennsylvania State University, University Park, Pennsylvania.

Lorenzo, J.L.  

Lozano-García, M.S. and B. Ortega-Guerrero  

McClung de Tapia, E. and C.C. Adriano Morán  

Nichols, D.L.  

Nichols, D.L., M. Spence and M. Borland  

Rzedowski, J., G. Guzmán, C. Hernández and R. Muñiz  

Rzedowski, J.  

Sanders, W.T., J.R. Parsons and R.S. Santley  