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Dynamics of Human-Environment Interactions in the U.S.-Mexican Border Region

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Abstract

The Border Plus Twenty Years (B+20) Project makes possible the exploration of the consequences of alternative "what-if" scenarios in the U.S.-Mexican border region. The project team developed a computer-based modeling framework for supporting interdisciplinary, bilateral decision-making in the region. The goal of the B+20 team is to provide a modeling framework for decision-making that will increase the likelihood of improved transborder cooperation and help lead to a sustainable future for those living along the U.S.-Mexican border.

The modeling framework provides a series of "micro-borderlands" where alternative policy options can be explored, via the computer-based model, by framing a series of hypotheses or questions and then using the model to quantitatively compare the consequences of the various alternatives. This process provides a valuable framework for the bilateral discussions needed among stakeholders and decision-makers planning the future of the border.

Water availability and quality, air quality, human health, and ecosystem health are key elements of the border's human-environment system that suffer as a consequence of high population growth rates and rapidly expanding urban areas. The dynamics of these human-environment interactions can be explored using systems thinking and system dynamics modeling approaches that quantitatively capture simplified versions of these complex interrelationships.

An important advantage of system dynamics modeling approaches is that the "stories" built into the resulting models can be traced by users lacking advanced mathematical or modeling skills. The use of object-oriented, commercially available system dynamics software enables models to be constructed by linking stocks and flows in a structure that reflects a holistic understanding of the system.

Over the past 30 years, many models have been created to study single-city, regional, single-nation, and multi-national issues that involve population growth, economic development, and the environment. Quantitative models of human-environment dynamics in binational borders, however, are lacking.

Dinámicas de Interacciones Humano-Ambientales en la Frontera México-Estados Unidos

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Resumen

El Proyecto Frontera Más Veinte Años (F+20) hace posible explorar consecuencias de escenarios alternativos de "que si" en la región fronteriza de México-Estados Unidos. El grupo del proyecto desarrolló un esquema de trabajo de modelado basado en programas com-

putacionales para apoyar la toma de decisiones interdisciplinarias y bilaterales en la región. El objetivo del grupo F+20 es proporcionar un modelo de esquema de trabajo para la toma de decisiones que incremente la probabilidad de mejorar la cooperación transfronteriza y que ayude a llegar a un futuro sustentable para quienes viven a lo largo de la frontera México-Estados Unidos.

El modelo del esquema de trabajo provee una serie de "micro-límites fronterizos" en los que se pueden explorar opciones de políticas alternativas, vía el modelo armando una serie de hipótesis o preguntas y usando el modelo para comparar cuantitativamente las consecuencias de las diversas alternativas. Este proceso proporciona un esquema valuable para las discusiones bilaterales requeridas entre las personas interesadas y los tomadores de decisiones que planean el futuro de la frontera.

La calidad y disponibilidad del agua, la calidad del aire, la salud humana, y la salud del ecosistema son elementos claves del sistema humano-ambiental de la frontera que sufre como consecuencia del gran crecimiento de la población y del rápido crecimiento de las áreas urbanas.

Las dinámicas de estas interacciones humano-ambientales pueden ser exploradas usando sistemas de pensamiento y enfoques de modelado de sistemas de dinámicas que capturen cuantitativamente versiones simplificadas de estas complejas interrelaciones.

Una ventaja importante del enfoque de modelado de sistema de dinámicas es que las "historias" construidas hacia los modelos resultados pueden ser rastreadas a través de usuarios sin habilidades matemáticas o de modelado. El uso de programas de sistema de dinámicas comercialmente disponibles y orientadas al objeto, permite la construcción de modelos al unir las reservas y su tránsito en una estructura que refleje un entendimiento holístico del sistema.

Durante el transcurso de los pasados 30 años, muchos modelos han sido creados para estudiar factores municipales, regionales, nacionales y multinacionales, que involucran el crecimiento de la población, el desarrollo económico, y el medio ambiente. Sin embargo, los modelos cuantitativos de dinámicas humano-ambientales en las fronteras binacionales carecen de estos modelos.

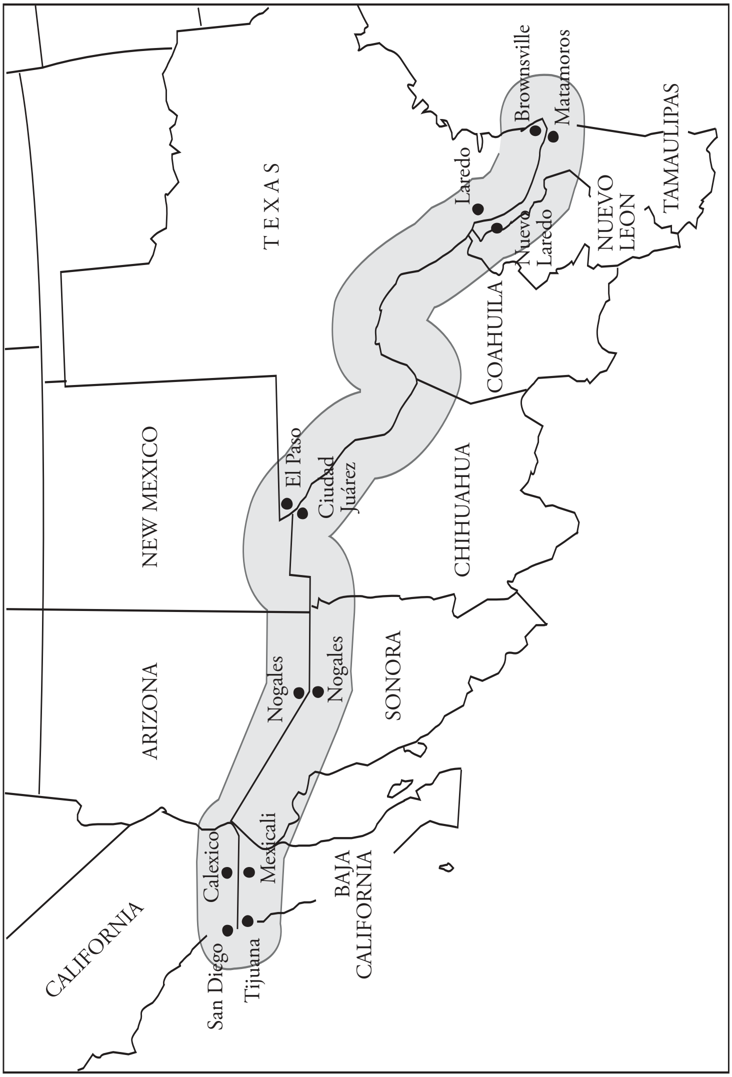
Introduction

How will human and ecological conditions look on the U.S.-Mexican border 10 years, 20 years, and 30 years in the future? Will quality of life improve if current policies and practices are continued, or are changes needed to improve border conditions? In pondering the future of the border region, would it help to explore alternative futures by playing "what if" games that test possible outcomes of proposed strategies? The Border Plus Twenty Years (B+20) Project is designed to provide such an environment for enabling the exploration of the consequences of alternative "what if" scenarios in the U.S.-Mexican border region.

The B+20 Project team developed a modeling framework for supporting interdisciplinary, bilateral decision-making in the U.S.-Mexican border region, which measures 3,200 kilometers (km) in length and 200 km in width (Figure 1). The principal goal for this effort is derived from the vision statement generated at the first Border Institute convened by the Southwest Consortium for Environmental Research and Policy (SCERP) (1999): To aid border decision-makers in finding ways to maintain a satisfactory quality of life for all residents and a healthy, sustainable natural environment. To this end, the B+20 Project is tasked with providing a framework for exploring future conditions for a series of alternative 20-year futures—hence the "20" in the project name "Border+20." As recommended by Kinsley, Lovins, and Spalding (2002), the team uses a systems thinking approach to map key elements of the border human-environment system and build system dynamics models that quantitatively represent complex links, flows, and feedbacks between and within system elements.

The goal of the B+20 team is to provide a modeling framework for decision-making that will increase the likelihood of improved transborder cooperation and help lead to a sustainable future for those living along the U.S.-Mexican border. The modeling framework provides a series of "micro-borderlands" where alternative policy options can be explored by framing a series of hypotheses or questions, then using the model to quantitatively compare the consequences of the various alternatives. Possible questions of interest to border stakeholders and decision-makers include the following:

Figure 1. The U.S.-Mexican Border Region



Source: U.S.-Mexico Chamber of Commerce

1. How should limited financial resources be expended in attempting to maintain and improve quality of life on the U.S.-Mexican border? For example, can stringent water conservation and recycling efforts postpone capital investments in central water treatment plants to release the funds needed to ensure that all households are connected to a potable water supply? Or, would the available funds perhaps have maximum beneficial impact on quality of life in the border's twin cities if they are instead used to pay for the technological or transportation infrastructure improvements needed to reduce air pollutant emissions?
2. If funds available to a twin city for infrastructure development could be spent anywhere without their use being restricted to one side of the border or the other, how might the funds be used to maximum advantage? For example, how might taxes collected from Mexican shoppers in U.S. retail stores be redirected to improve conditions in the Mexican communities where shoppers live?
3. Options for increasing border urban water supplies include transferring water currently used by border agriculturalists to border urban centers. What economic consequences might result in cases where agricultural operations underpin the local economy? How should uncertainties about water availability in future climate regimes, combined with transborder differences in institutions that control water rights, be accounted for when designing and implementing future policies for water transfers?
4. Border twin cities typically share common airsheds and similar air quality. Given a common interest in improving air quality, what mix of emission reduction policies might be implemented on each side of the border to obtain the best air quality outcomes? For example, what are the relative merits of reducing emissions from brick kilns through technological improvement, paving unpaved roads to reduce particulate emissions, reducing border wait times through changes in U.S. border security procedures, or reducing the age of the vehicle fleet through vehicle purchase incentive plans?

Well-defined answers to the above questions are unlikely to be found because uncertainty about the future abounds, data are sparse, and relationships between human health and environmental conditions are difficult to identify, much less quantify. Yet, the process of building model structures that represent the factors involved, combined with the ability to quantitatively compare the implications of alternative policy options, provides a valuable framework for the bilateral discussions needed among stakeholders and decision-makers planning the future of the border.

Transborder Issues and Challenges in the U.S.-Mexican Border Region

The 3,200 km U.S.-Mexican border spans the North American continent with 14 principal twin-city communities distributed along it. The total population in the U.S. border region is 6.3 million; the highest county population—2.8 million—is in the west coast county of San Diego, Calif. A total of 5.6 million people live in the Mexican border region; the highest *municipio* (the Mexican equivalent of a U.S. county) population is in Tijuana, B.C., San Diego's twin city, which has 1.3 million people. The rapid population growth the border is currently experiencing leads to projected 2020 populations of 8.7 million and 10.0 million in the U.S. and Mexican border regions, respectively (Peach and Williams 2004). Thus, the current total border population of approximately 11.9 million people is likely to increase by more than 60% to 18.7 million in 2020.

Most population growth will occur in the existing transborder twin cities where intense interaction between human activity and the environment is concentrated. At the same time, long, desolate stretches of desert between the principal twin cities are essentially unpopulated, leading to significant difficulties in restricting the illegal flows of people and drugs from Mexico to the United States. The tremendous rate of population growth in the border region is derived from moderate natural population increase, combined with people migrating to work in the economically attractive border region (Peach and Williams 2000).

Geographic conditions vary substantially along the border. High, north-south-oriented mountain ranges in the western border region separate border communities located at elevations ranging from sea level (at both coastal and inland communities) to 1,234 meters (m). In the east, community elevations are generally less than 300 m above sea level. The border region has semi-arid to arid desert climates. Precipitation ranges from less than 10 centimeters (cm) per year in some inland communities to 70 cm per year on the east coast. With the exception of the west coast communities of San Diego and Tijuana, annual average maximum temperatures are about 29°C and average minimum temperatures measure nearly 16°C. Cooler temperatures on the west coast yield an annual average maximum of 21°C and an average minimum of 14°C in San Diego and Tijuana. The specter of future natural and anthropogenic climate variability suggests that declining precipitation rates and increasing temperatures may cause additional stress on border water supplies, energy sources, natural resources, and ecosystems. Yet, knowledge of future climatic conditions is highly uncertain, thus decision-making must account for how a range of possible climates in the future might affect human-environment dynamics on the border.

Economic growth stimulated by border attributes, such as attractive differences in wages and enforcement of environmental laws, has been substantial since the 1940s (Peach and Williams 2000). In 1994, implementing the North American Free Trade Agreement (NAFTA) between Canada, the United States, and Mexico further stimulated economic growth. Unfortunately, the conditions that stimulate economic growth at the border have yielded low per capita incomes and high unemployment rates when compared to elsewhere in the United States. Although per capita incomes in the Mexican border communities are much greater than elsewhere in Mexico, Mexican border minimum wages are approximately 10% of their U.S. twin-city counterparts (Peach and Williams 2000). High rates of economic and population growth coupled with low incomes has meant that many environmental problems have developed in the U.S.-Mexican border region because public financial resources cannot meet rapidly expanding infrastructure needs. The current U.S. economic recession, combined with increasing attractiveness of low wages in countries such as China, raises concerns that the border's economic expansion of past decades may slow while the border population continues to grow. Economic stagnation in the border region would exacerbate current environmental problems and deteriorating human quality of life because access to the funding needed for infrastructure development will be further eroded.

Water availability and quality, air quality, human health, and ecosystem health are key elements of the border's human-environment system that suffer as a consequence of high population growth rates and rapidly expanding urban areas. In the arid climate of the border region there is increasing competition for the scarce water resources needed for human consumption, agricultural production, industrial activity, and ecosystem health. Average per capita water use in the U.S. border region (615 liters per capita per day) is approximately 41% greater than that of the Mexican border region (435 liters per capita per day) (Westerhoff 2000). Because water use is correlated with standard of living, efforts to improve the quality of life in the border region could lead to an increase in average per capita rates of water use, unless counteracting measures such as efficient water conservation and recycling are introduced. Bilateral planning for efficient water use and system-wide wastewater treatment is required if twin cities are to develop a sustainable water supply future while also reducing the prevalence of water-borne disease. Ultimately, border population growth and its consequences will be concentrated in and around twin cities. Thus, it is important to develop a systemic understanding of urban ecosystems in general (Nilon, et al. 2003) and border urban ecosystems in particular.

Non-enforcement of environmental regulations, or inadequate regulations, in some Mexican border communities allows excessive air pollution, which in turn causes the air quality in some twin cities to exceed U.S. national standards, despite relatively low emissions from the U.S. side. Imaginative approaches are needed to develop cost-effective reductions in the binational air emissions that affect quality of life and human health on both sides of the border. Natural ecosystems in the border's desert environments have been severely punished by human activity. Yet in many cases, well-managed desert ecosystems can provide cost-effective solutions to water supply challenges encountered in human communities (Committee on Sustainable Water Supplies for the Middle East 1999). For example, water supply development has eliminated many natural riparian areas that at one time provided natural water treatment in addition to habitat for indigenous flora and fauna. Artificial wetlands recently constructed in eastern California's Imperial Valley region help remove the suspended solids introduced to surface water by the irrigation runoff associated with agricultural activity. A systems thinking and modeling approach will assist decision-makers in evaluating the relative merits of various options proposed to mitigate the degradation of natural systems on the border and improve the quality of life for people living in the U.S.-Mexican border region.

Modeling the Dynamics of Human-Environment Interactions

The dynamics of human-environment interactions at the U.S.-Mexican border can be explored using systems thinking and system dynamics modeling approaches that quantitatively capture simplified versions of the aforementioned complex interrelationships. Although all models are, by definition, simplifications of real systems, the process of developing and applying simplified quantitative models of complex systems yields two key benefits:

- The process of building a quantitative model requires that all system components and their links be formally evaluated for their role and function in the system (this is not often accomplished with qualitative, descriptive models)
- A quantitative model provides a coherent framework for comparing the outcomes of alternative future scenarios proposed for the system (without computed outcomes, clear comparisons cannot be made)

An important advantage of system dynamics modeling approaches is that the "stories" built into the resulting models can be traced by users lacking advanced mathematical or modeling skills. Thus, even though the mathematical and numerical underpinnings cannot be fully explored by all users, the fundamental assumptions made to represent the model system can be readily reviewed and understood by all users.

A systems approach is valuable for exploring various aspects of U.S.-Mexican border issues. For example, it is frequently noted that infrastructure development in the water, sewer, housing, and transportation sectors of the U.S.-Mexican border region is proceeding too slowly to keep pace with the rapid population growth. Yet, it is not clear where limited funding currently available for infrastructure development should be spent to obtain the greatest quality of life benefits for the binational community. Suggestions made for improving quality of life at the border include paving unpaved roads, connecting houses to water supplies and sewers, increasing sewage treatment capacity and the level of treatment, reducing brick kiln emissions, reducing border wait times, conserving and recycling water, eliminating aged personal and commercial vehicles from the border fleet, and modifying housing development practices. Implementing one or more of these strategies creates cost and quality of life implications that can ripple throughout the community to create both intended and unintended consequences. The systems thinking approach provides a conceptual framework for defining how a system dynamics model should be structured. The resulting models enable users from a range of backgrounds to anticipate the possible nature and magnitude of the alternative outcomes, discover unanticipated consequences, and assess which options might create the greatest benefit for the least cost.

Systems Thinking and System Dynamics Modeling

Systems thinking approaches enable the integration of scientific principles with the environmental and sociological impacts of technology and policy. Deaton and Winebrake (2000) outline six characteristics of systems thinking:

1. Systems thinking begins with a global description and moves toward the specific. This is the opposite of traditional reductionist thinking where a researcher would first focus on unraveling the detailed aspects of small components of a system before attempting to resolve how the larger system operates as an aggregate combination of the smaller components. On the U.S.-Mexican border, the national-level transborder exchanges

and interactions must be addressed before drilling down to look in closer detail at how individual urban border communities operate. At the local scale, the interaction within transborder twin cities across a range of interrelated factors—including population, economy, land use, transportation, housing, water supply and quality, air quality, and quality of life—must be accounted for, rather than focusing on only one factor or one part of the twin city.

2. Systems thinking focuses on dynamic processes. The behavior of the system reflects ongoing change in the underlying processes that drive system evolution. For example, changing rates of migration to the border from elsewhere in Mexico reflect changing local economic conditions in both the migrants' hometowns and in the border cities that, in turn, reflect the dynamic evolution of the interrelated U.S. and Mexican national economies.
3. Systems thinking seeks a closed-loop explanation of how things work. The boundaries of a system should be defined so that the key behaviors of the system are defined by processes that operate within the boundaries. Some external factors are often required to fully describe the operation of a system. However, those factors should be few and exert only a small impact on the behaviors of greatest interest. For example, although the mechanics of national-level demographics of the United States and Mexico must be considered in a border system, the mechanics of global population growth can likely be ignored.
4. Systems thinking identifies feedback loops. A feedback loop represents a closed-loop circle of cause and effect whereby changes in one part of the system cause effects in other parts of the system that then act to update and change conditions in the original part of the system where the change was initiated. For example, a rapidly growing population might cause increased air pollutant emissions that ultimately lead to increased death rates and a slowing of population growth. This is a counteracting, or negative, feedback loop. Meanwhile, road building associated with urban population growth causes the urban area to expand at an ever-growing

rate as construction of new road systems intended to reduce traffic congestion enables commuters to travel progressively greater distances between work and home while promoting increased traffic congestion. This is a reinforcing, or positive, feedback loop.

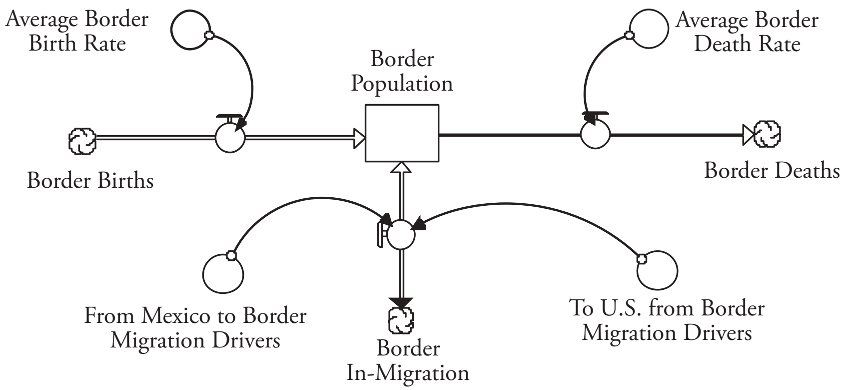
5. Systems thinking looks for checks, balances, and the potential for runaway processes. Factors that control competing processes can help either stabilize or destabilize a system. For example, improving health conditions in a community can lead to both increased birth rates and reduced death rates that destabilize a community by producing increased rates of net population growth. A systems thinker would search for ways to improve health conditions while also searching for a mechanism to maintain birth rates at current or reduced levels.
6. Systems thinking focuses on causal relationships. Thus, the systems thinker searches to define cause-effect relationships rather than relying on apparent correlations where there is no direct relationship between cause and effect.

A systems thinking approach is used to develop system dynamics models by telling the stories that explain the system behaviors of principal interest to decision-makers and stakeholders, then converting the stories into their mathematical equivalent as supported by on-the-ground data. Several aspects of the U.S.-Mexican border's story are outlined above. The stories are represented in model structures using the small suite of graphical icons commonly found in system dynamics modeling software. For example, the population of a border community can be viewed as a stock, or reservoir, of people that increases, decreases, or stabilizes depending upon a variety of interacting factors. Migration of people to or from the population stock can be viewed as flows of people per unit of time. Births and deaths can be viewed as flows of people into or out of the population stock. Flows of people can also increase, decrease, or stabilize depending upon a variety of interacting factors. Migration of people to the Mexican border region reflects both push and pull forces that cause people to leave their homes elsewhere in Mexico in search of a better economic future. Thus, economic activity induced at the border through trade with the United States draws people to the border, while political unrest and the absence of economic opportunity induce people to leave their homes elsewhere in Mexico.

Other stocks and flows can be identified in the evolving border story. Growth in the population "stock" is accompanied by growth in the stocks of urban land area, road lane miles, vehicle miles traveled, households, personal vehicles, commercial vehicles, sewage treatment plants, maquiladoras, water treatment plants, and air pollution sources. Accumulations in and dissipations from each stock are controlled by the material "flows" of people, money, vehicles, water, and goods that are affected by changing dynamics in economic activity, birth/death/migration rates, urban development patterns, infrastructure development, tax structures, border security, and climate.

The use of object-oriented, commercially available system dynamics software (such as STELLA®, Powersim®, and Vensim®) enables models to be constructed by linking stocks and flows in a structure that reflects a holistic understanding of the system. This is best performed in a group model-building activity so that people with different backgrounds can contribute the varied perspective and understanding required to make appropriate links both within and between disparate model elements. A sample model structure for a simple border population model is shown in Figure 2. Stocks are represented as rectangular icons and flows are represented by water tap icons. The cloud-like icon at the end of the water tap represents the exogenous source, or sink, of flowing material (e.g., people) that need not be explicitly accounted for in the model. Information indicating the magnitude of the flows and computed results of system evolution are represented as circular converters. A variety of simple-to-complex relationships can be represented by equations contained within the converter icons. Soft information based on qualitative understanding of the system, or possible impacts of policy interventions, can be included in the model structure using graphical relationships that represent how experts in that disciplinary area think the specific system element might operate. The arrow-shaped information connectors transfer computed information from one icon to another.

Figure 2. A Simple System Model Structure for Tracking the Evolution of Demographic Change in the U.S.-Mexican Border Region

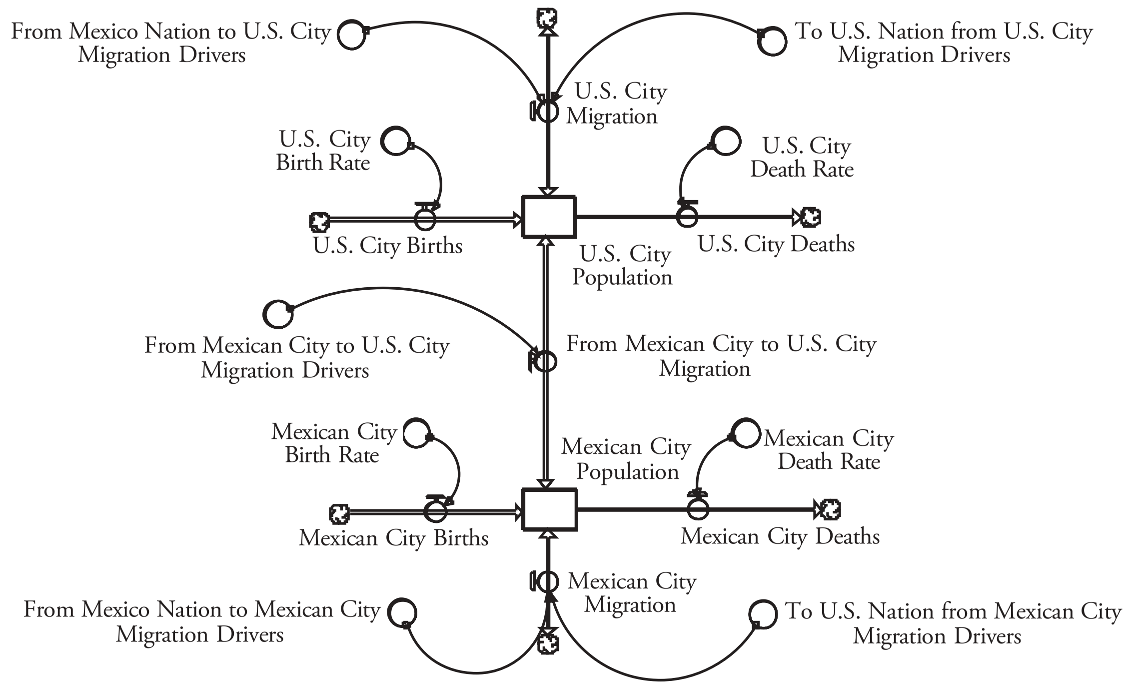


Note: The stock of Border Population is affected by flows of people into (Border Births, Border In-Migration) and out of (Border Deaths) the population stock. Model structure created using STELLA®.
Source: Authors

In Figure 2, the number of people in the stock of Border Population is affected by migration flows, deaths, and births. An exogenous source of babies generated according to the Average Border Birth Rate leads to the flow of newborns into the population stock. An exogenous sink of decedents controlled by the Average Border Death Rate accommodates the flow of deceased from the population stock. Although not explicitly shown in Figure 2, both birth rates and death rates vary as a function of time due to changing demographic trends. For example, implementing policies that lead to improved health conditions might produce reduced death rates while improved educational attainment policies might produce reduced birth rates. The border migration drivers differ depending on whether one is considering the arrival of Mexican nationals from elsewhere in Mexico to the border or the departure of U.S. and Mexican nationals from the border to other locales in the United States. This differential perspective is required because the Mexican border region has greater economic opportunity than most other places in Mexico. In contrast, the U.S. border generally has less economic opportunity than most other places in the United States. Ultimately, migration drivers will vary through time as local economic conditions change in response to national-level economic changes in both the United States and Mexico. This aggregate view of the evolving border population is represented by using birth rates and death rates averaged for both U.S. and Mexican population cohorts. In addition, neither age nor gender differences are accounted for in this simple, aggregated model of the evolving border population. This issue will be revisited in a subsequent discussion of the population sectors incorporated into the B+20 model (Chapter II-3).

A more evolved model structure is shown in Figure 3 to represent the fact that the B+20 team was interested in studying the population dynamics of individual border communities of El Paso, Tex.-Ciudad Juárez, Chih., San Diego-Tijuana, and Mexicali, B.C.-Calexico, Calif., where local conditions that affect quality of life can be explored. Although modeling the entire border may be valuable to explore certain broad-scale questions, such a model cannot help explore the questions that typically arise as people try to respond to the dynamics of change in the specific airshed and watershed of a border twin city. Thus, two parts of a twin city are represented in Figure 3—the U.S. city and the Mexican city. Although the basic structure is unchanged from the aggregate border population model of Figure 2, new structural elements are introduced to account for differences in birth and death rates in each city and to represent the various factors that cause people to migrate to and from the twin cities, either between the cites or to and from elsewhere in the United States and Mexico. The model structure shown in Figure 3 has a number of features in common with the local population sector of the Paso del Norte system model outlined in detail in Section II. Other sectors of the Paso del Norte model that affect, or are affected by, the population sector include national and local economies, land-use, transportation, water supply, water demand, air quality, national populations, and infrastructure development. The resulting Paso del Norte model is an integrated model of population growth, economic development, and environmental change that has attributes in common with other models developed to explore relationships at single-city, regional, single-nation, multi-

Figure 3. A More Complex System Model Structure



Note: This structure might be used to track the evolution of demographic change within twin cities at the U.S.-Mexican border. Model structure created using STELLA®.
Source: Authors

nation, and global scales. Previous integrated models, however, have not attempted to explicitly account for the human-environment dynamics of border twin cities.

If completed as functional system dynamics models, the icon structures shown in Figures 2 and 3 would lead to a system of non-linear, ordinary differential equations that are solved simultaneously using standard numerical methods. It is important to note that the object-oriented programming language used to create the icon structures shown in Figures 2 and 3 enables the stories of diverse stakeholders and decision-makers to be incorporated into a model without requiring a detailed understanding of the underlying mathematics and numerical techniques. The ability to readily confirm that the stakeholder's stories are incorporated in the model enhances the probability that the model results will be used in policymaking. It is critical, however, that at least one person in the model development team have this understanding in order to ensure that the final model structures produce reasonable computed results.

Models of Human-Environment Dynamics

Over the past 30 years, many models have been created to study single-city, regional, single-nation, and multi-national issues that involve population growth, economic development, and the environment. Quantitative models of human-environment dynamics in binational borders, however, are lacking. The B+20 project team has been building on the experience of previous modeling efforts to create a new suite of models specifically tuned to the interrelated social and environmental complexities found in the U.S.-Mexican border region. Several integrated models of population, development, and environment are briefly outlined to help explain the approach adopted by the B+20 project team. A subsequent section describes how the systems thinking and modeling approach underlying these models can be used to capture the interrelationships and complexities of human-environment dynamics in the U.S.-Mexican border region.

Sanderson (1994) and Lutz, et al. (2002a) provide useful summaries of several population, economy, and environment modeling studies. The most notable, or perhaps notorious, of these models is the World3 system dynamics model produced by Meadows, et al. (1972) for the Club of Rome. Developed to explore issues of global sustainability over a century, this system dynamics model contains separate sectors that represent global population, pollution, resources, agriculture, and capital. Meadows, et al. (1972) explored alternate futures under different conditions of total food supply, total resource base, and the ability of technology to improve production and efficiency. Computed outcomes based on business-as-usual scenarios typically show a collapse of global population and industrial capacity sometime within the 100-year projection time period because the population would grow beyond a level that could be sustained by projected food availability. Twenty years into the 100-year projection period, Meadows, et al. (1992) note that there is little evidence that the attitudes and policies needed to control growth and reduce the likelihood of a global collapse have been adopted. Key intervention strategies suggested by the World3 model would involve slowing growth and improving technology at rates not currently being attained. Unfortunately, at the global scale, many of the parameters needed to constrain the World3 model are unknown and unknowable (Sanderson 1994). Furthermore, the lack of specificity leads to overly general results that are difficult to interpret and incorporate in policy recommendations. Because changes in model parameters create a range of possible outcomes, the model user may create any desired outcome by changing pertinent parameters (Meadows, et al. 1992; Sanderson 1994). This non-specificity led to significant debate about the plausibility of the outcomes indicated by the World3 model. Although widely criticized, the World3 model provides valuable insight by graphically illustrating how the global system might operate under different future growth scenarios.

Location-specific models lead to less debate because the models are more closely tied to reality and are based on parameters specific to the modeled region. Because the results from such models are more credible and meaningful to stakeholders, they provide valuable support for policymaking. This is the intent in focusing the B+20 project team on border twin cities, rather than modeling pan-border processes. Sanderson (1994) and Lutz, et al. (2002a) outline several location-specific models developed to explore relationships and interactions between population, the economy, and the environment. Soon after the World3 model results were published (Meadows, et al. 1972), Picardi (1974) developed and applied a suite of models to study the effects of past and potential future policies on sustainable development in a portion of the Sahel in Niger, where the inhabitants depend on livestock for food and other purposes. The model provides valuable support for policymaking because the abrupt economic and environmental collapse experienced in the region during the early 1970s was mimicked by the overshoot and collapse behavior computed by the model. Explorations made with the model indicate that the collapse occurred through unsustainable use of common grazing land, rather than as a direct consequence of a severe drought, though the timing of the drought influenced the timing of the collapse. In addition, the model results show that interventions implemented to improve conditions ultimately worsened the effects of the drought. Finally, Picardi (1974) shows that progressive elimination of the interventions over several decades would produce better conditions than if the interventions were retained.

During the 1990s, the International Institute for Applied Systems Analysis (IIASA) completed a series of modeling case studies on Mauritius, Cape Verde, and the Yucatan peninsula, as well as in Botswana, Mozambique, and Namibia using variants of the Excel-based PEDA (Population, Environment, Development, Agriculture) model (Lutz, et al. 2002b). Although many site-specific aspects of the model studies differ, all include a population framework that distinguishes age, sex, and education while focusing on the interactions between changes in population size and distribution, natural resource degradation, agricultural production, and food security (Lutz and Scherbov 2000). The PEDA models have been used to explore well-defined questions of critical interest to stakeholders and decision-makers from each region. In each case, valuable insights were obtained that aid policymakers in planning for the future. These successes suggest that similar success can be obtained by exploring well-defined U.S.-Mexican border questions using appropriately crafted system dynamics models within a community engagement context.

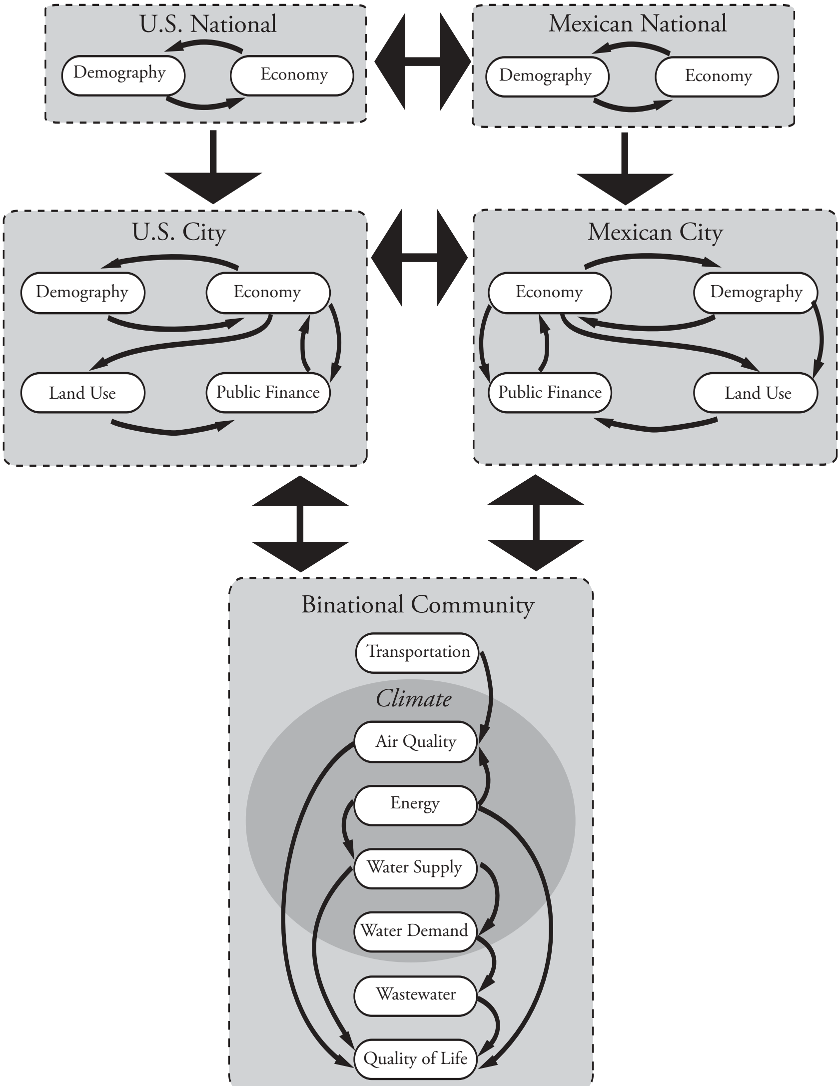
The Border+20 Project

A Systems View of the U.S.-Mexican Border

The principal elements of a binational, human-environment system model are shown in Figure 4. Changes in national populations and economies drive change in two twin cities that, in turn, interact through a common border community. Ultimately, local changes in both the economy and population are influenced by the way border inhabitants respond to concerns about human health and other aspects of quality of life that then reflect conditions evidenced at the national level. At the same time, quality of life is strongly influenced by the changes in transportation, energy, water supply, wastewater treatment, and air quality that are driven, in turn, by changes in population and economic activity. There are two parts to each model element—one on the U.S. side of the border and one on the Mexican side. The binational system model structure explicitly distinguishes between processes operating on each side of the border and the processes that cause the transfer of "stuff" across the border. An important contribution of the systems approach is it accounts for the links, feedbacks, and interactions across the border that are not always considered by decision-makers working independently on each side of the border.

"Stuff" flowing across the border and within the border community includes water (good and poor quality), air (polluted and otherwise), disease, money, products (food, agricultural, commercial, manufacturing, and entertainment, among others), waste products, social capital, services, electricity, fuels, vehicles, light, sound, ideas, community spirit, flora, and fauna. In many cases, human activity at the border restricts the flow of "stuff" across the border with the most active restrictions occurring at the ports of entry found in twin cities. Notable exceptions include the transborder movement of groundwater in binational aquifers, migration of air pollution in binational airsheds, and the movement of indigenous flora and fauna within and through regional ecosystems. The movement of other "stuff," however, is restricted by the physical, eco-

Figure 4. Overview of Human-Environment Links in a U.S.-Mexican Border System



Note: In the interest of clarity, the details of links between internal components of one sector and those of adjacent sectors (e.g., the influence of public finance on transportation, water supply, and wastewater treatment infrastructure) aggregate into the two-way arrows that link aggregate sectors of the system.
Source: Authors

nomic, legal, and spiritual presence of the border. Over time, climate and other characteristics of the border system evolve through both natural variability and the effects of man.

A thought experiment proposed by the B+20 project team asks: "How might the border human-environmental system change if all restrictions on transborder flows were removed?" Once this scenario is thoroughly mapped, it would be valuable to compare it to one where all flows that can be controlled are severely restricted. Several different outcomes could be envisioned for each scenario. It is hoped that such an exercise would help define a mix of bilateral policies that would lead to a sustainable future for border inhabitants. For example, removing all restrictions on human migration across the border might cause massive movement of Mexican citizens to the United States. Although one should expect an initial period of enhanced migration, people will only migrate across the border as long as conditions in the new location are clearly preferable to those in their home community. As people move from place to place, their behavior modifies the demographic and economic conditions at each location while consuming natural resources. At the same time, ties to one's home community are difficult to break—and perhaps even more difficult when it is easy to travel home frequently in the absence of border restrictions. In the absence of performing a quantitative, multifaceted calculation, however, it is difficult to guess the resulting demographic and economic conditions. At this stage in the B+20 project, however, the team is focused on more localized geographic targets with smaller-scale questions aimed at better informing decision-making in specific twin cities.

Two general options exist for developing system models of human-environment interactions on the U.S.-Mexican border:

- Contract with advanced modeling teams to adapt and combine existing system dynamics modules to fit the specifics of a border region
- Develop border-specific models and modules using commercial model-building software

Adopting the first option would cause the B+20 project team to act as an advisory group that could influence and inform, but not necessarily become proficient in, model development. The

Millennium Institute provides such a service with its Threshold 21 (T21) Integrated Computer Development Model. The Millennium Institute (2003) reports "...the T21 model enables integrated, comprehensive development and policy planning." In addition, "...T21 is transparent, collaborative, interconnected, valid and customizable with a core that can be applied to most countries and regions." The T21 model has been used to simulate alternate sustainable development futures at the single-nation scale in Bangladesh, China, Ghana, Guyana, Italy, Malawi, Somaliland, Tunisia, and the United States. A national water system model is also available. The Sustainable Development Research Initiative (SDRI) within the Institute for Resources, Environment and Sustainability provides similarly advanced modeling services with an emphasis on developing interactive gaming environments (QUEST™) for users to explore "what if" scenarios for the futures of a region. Gaming environments have been developed for the Georgia and Lower Fraser basins of British Columbia, Canada. Envision Sustainability Tools, Inc., has developed additional applications for regions in Mexico, Indonesia, Malaysia, Canada, New Zealand, and England. Although building models from scratch leaves the team unable to take direct advantage of the advanced T21 or QUEST™ modules that might be readily adapted for application in the border, border researchers are able to develop and hone their own system thinking and modeling skills. As a consequence, the B+20 project team has built an original model of human-environment interaction on the U.S.-Mexican border.

Several system dynamics model-building environments, including STELLA®, Vensim®, and Powersim®, are available and use a simple, visual programming language to create complex model structures. Although superficial aspects of these model-building programs differ, their fundamental properties are similar. The B+20 project team uses STELLA® in large part because several team members already had experience with the software. STELLA® software is best applied to aggregate views of the system of interest where modeling the detailed spatial patterns of change is not critical to developing the insight needed for policymaking. The B+20 models involve only a small number of aggregated spatial units—the two nations and three land-use types associated with each U.S. and Mexican twin city. As the need for spatial disaggregation is identified, the fundamental relationships and model structures developed with STELLA® can be transferred to other programming environments such as SIMILE (Muetzelfeldt and Taylor 2001; Simulistics 2003) or Spatial Modeling Environment (SME) (University of Maryland Institute for Ecological Economics 2003), which provide detailed representation of spatially explicit changes in a system dynamics modeling context. The user-friendly capabilities of SIMILE and SME have increased significantly over the past few years and continue to evolve in ways that suggest they will provide good options for the spatially explicit modeling that is impossible with STELLA® and similar software.

Interdisciplinarity, the B+20 Project Team, and Team Dynamics

In pursuing the goals of the B+20 project, it was necessary for SCERP to create a new interdisciplinary research team drawing on the resources of the various institutions involved in SCERP. The B+20 project team comprises researchers from U.S. and Mexican academic institutions that are members of the consortium. Disciplinary expertise represented by the team members included border studies, hydrology, air quality, energy supply and demand, water resources supply and demand, urban planning, psychology, economics, demography, sociology, ecology, earth science, human health, and communication. For many team members, this was their first broadly interdisciplinary research project. During the first years of the project, several team members became inactive while new researchers joined the team. At the same time, the remaining team members became increasingly able to work together.

Conclusion

The B+20 project team has developed operational system dynamics models for Paso del Norte and for the Salton Sea hydro-ecosystem using STELLA® software. Stakeholders have been engaged intermittently in discussions of the Paso del Norte model and stakeholder engagement will continue as the model becomes increasingly tuned to the specifics of the community and is disseminated for use. As the

Paso del Norte model became finalized, the B+20 project team shifted focus to the Mexicali-Imperial Valley community. Lessons learned when developing the Paso del Norte system model and the model structures created are transferable to the Mexicali-Imperial Valley community, with some modification. Although many fundamental aspects of the two border communities have similar model representations, such as national economy, local economy, population, land use, and air quality, differences between the two hydrologic systems requires markedly different hydrologic model structures. In Paso del Norte, key water features are the Rio Grande/Río Bravo and several groundwater aquifers. In the Mexicali-Imperial Valley, key water features include the Colorado River, Salton Sea, and several groundwater aquifers. Development of the Salton Sea hydro-ecosystem model has been proceeding in the background to provide the hydrologic and ecosystem modeling framework that must underlie integrated models of human-environment interaction in the Mexicali-Imperial Valley community.

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