Borders as Membranes: Metaphors and Models for Improved Policy in Border Regions

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Abstract

Political borders are controversial and contested spaces. In an attempt to better understand movement along and through political borders, we applied the metaphor of a membrane to look at how people, ideas, and things "move" through a border. More specifically, we employed this metaphor in a system dynamics framework to construct a computer model to assess legal and illegal migration on the US-Mexico border. Results from both quantitative and qualitative data searches were used to modify a 1977 border model to demonstrate the dynamic nature of illegal migration. Model runs reveal that current US-policies based on neo-classic economic theory have proven ineffective in curbing illegal migration, and that proposed enforcement policies are also likely to be ineffective. The modeling supports views expressed in the current literature suggesting that demographic and economic changes within Mexico are likely to slow illegal migration by 2060 with no special interventions made by either government.

Introduction

Throughout history humans have dedicated intense energy to identifying, expanding, and protecting borders — those places that delineate where one territory ends and another begins. While a border is how we define the political boundary between two countries, the word also has more conceptual definitions including to "extend along the edge of" or to "almost be", such as *to border on madness* (Neufeldt 1988). The similarities between a conceptual border and a physical border are numerous and political borders are unique subjects for studying these similarities. This project (Malczynski 2005) approaches a political border conceptually as a membrane with gradient and permeability characteristics that affect the dynamics of who crosses a border and why. The research team applied the membrane metaphor within a system dynamics framework. As efforts throughout the world to draw and/or enforce existing boundaries between political entities remain conflicted and controversial, it is relevant to develop tools to try to better understand the dynamics in a border region and to better understand what we mean when we say a border exists. Using a system dynamics model to apply the metaphor of a membrane with concentration gradients on either side is one approach for looking at how people, ideas, and things move through a border. Borders and their concomitant tension are a global issue, but in the interest of time and resources, this project focused on the political boundary between the United States and Mexico. Further, this project looked more specifically at a sister city locale in Columbus, New Mexico and Palomas, Chihuahua. Because both the concept of a border is large and the variables at play on a physical border are numerous, the research team narrowed their focus to looking at people crossing the political border, both legally and illegally.

The timing for this effort is propitious as President Bush is emphasizing immigration as a key policy issue for his second term and has made strong statements in State of the Union addresses about immigration reform (Bush 2005; Fix et al. 2005; Storrs 2005; Bush 2004). News stories from Idaho to New Hampshire to New Mexico reveal mounting pressure for local, state, and federal agencies to address Mexican migration (Carrier 2005; Egan 2005; Gorman 2005; Marks 2005). Immigrant benefits, work visas, and border patrols are topics debated in the halls of Congress as well as in city halls. The US government is running advertisements in Mexico discouraging illegal crossing attempts (Fox News 2005). The governors of Arizona and New Mexico have declared “states of emergency” to address increasingly negative conditions along their borders (Blumenthal 2005).

Relevant data shed some light on the increasing attention to these issues. Since the 1970 census, there has been a 13-fold increase in the number of people living in the US who were born in Mexico and currently about 9% of the Mexican population resides in the US (Passel 2005). Estimates suggest that by 2050 there will be 22 million Mexicans in the US (Passel 2005). Historically, immigrants settled into the border states or in large cities with existing immigrant populations (e.g. Chicago). This has changed, with unauthorized immigrants becoming more geographically dispersed. In fact, North Carolina is classified as a “major destination” and states as diverse as Georgia and Washington are seeing increased immigration (Passel 2005). Since 1995 unauthorized immigration has outpaced legal entries and about 85% of immigrants from Mexico enter the US unauthorized. Many of these individuals eventually obtain legal status (Passel 2005).

The terrorist attacks in 2001 have had a significant impact on how the US perceives and protects its borders. Both the US and Mexico governments want to avoid adversely affecting the billions of dollars in trade between the two countries each year. Both, however, have taken measures designed to reduce potential terrorist attacks and this has affected border crossing dynamics (Smith 2005).

Researchers well understand the complexity inherent in studying border regions. There are cultural, economic, historical and political variables intertwined with immigration and this complicates our ability to comprehend drivers and incentives for migration. As Fix et al. (2005) note, “Immigration issues are complex, with wide ranging consequences that span individual rights, the rule of law, the way our cities and labor markets operate, American competitiveness, national security, and the unique character of the United States in the world. Immigration issues are also controversial and little consensus exists on key policy questions. Part of the explanation for this controversy and political division owes to the fact that immigration policy debates are often poorly informed, polarized and narrow."

This project was designed to help broaden the debate and thus reduce the level of polarization. There is evidence that traditional beliefs about what drives migration may be flawed and subsequently policies designed to manage migration have perhaps not been as effective as they might be (see Reyes and Mameesh 2002; Zahniser 1999; Massey and Espinosa 1997). System dynamics modeling is an appropriate tool for highlighting where assumed relationships among variables may be erroneous. Using system dynamics enables people to "see" the complexity and the relationships among the diverse and often un-quantified variables. Ultimately, such models can be useful in better understanding border dynamics and designing improved policies for addressing border control and immigration.

This project is not the first to apply a system dynamics modeling approach to explore the US-Mexico border. Several simple system dynamics models of trans-border human migration have been created as tools for teaching fundamental systems thinking concepts (see Charles & Kolvoord, undated; isee Systems, undated). More complicated models include that of Dabiri and Low (1977) and Peach (2005). This project relied on the Dabiri and Low (1977) work to create the illegal migration model reported here. The research team also reviewed the demographic model that the Border + 20 (B+20) team of the Southwest Consortium of Environmental Policy and Research (SCERP) developed as a module within their system dynamics model of human-environment interactions in the Paso del Norte trans-border region (Peach 2005; Sadalla 2005).

This report documents the year-long effort focused on understanding the dynamics in the US-Mexico border region and the process for developing system dynamics models using the membrane metaphor as a unique way of looking at border dynamics.

Border as Membrane: Applying Metaphor

Philosophers and scholars from time immemorial have used and debated metaphor as a tool and a way of seeing the world. Robert Frost is attributed with writing that, "All thinking is metaphorical" and this project has been an attempt to treat a political border metaphorically as a membrane in order to think about the border from a different perspective. Ramsey (1972) noted that metaphors are "tangential meetings of two diverse contexts" and that the meeting often generates insight and inspiration.

The language of science is metaphorical because metaphors help us understand what is often complex and/or incompletely defined (see Brown 2003; Dunbar 1995; Kuhn 1979). We are a visual species, yet many phenomena are not truly visible and are often not completely understood, so we describe them using a metaphor for something we can see and do understand. Metaphor is not simply a literary device; its choice frames and shapes how we think and subsequently what we learn about a process or system. For example the success of applying the metaphor of earth as machine significantly influenced the development of western science (see Brown 2003; Hesse 1972).

Brown (2003) provides the following ideas related to using metaphor:

- Metaphors can be thought of as mappings from a source domain of literal, everyday experience to a target domain, with the aim of enlarging and enhancing understanding of that target domain. We

use understandings from the domain of direct physical and social experiences to structure our understanding of a more abstract domain.
- A given metaphor highlights certain features of the source domain and hides others, depending on the intent of the author. Often, however, some of the hidden elements are implied by the author or are inferred by the recipient, depending on context. It is just these implications that make metaphor a powerfully creative force in scientific reasoning.
- Although metaphors invite comparisons of two disparate things, the more interesting metaphors do more than this. They stimulate creation of similarities between the source and target domains, such that the target domain is seen in an entirely new light.
- Metaphors in science serve an explanatory role and are a stimulus to new experiments. They may be very simple and evocative initially, then grow more detailed as research findings support or disconfirm inferences drawn from the initial metaphor.
- Models, which are extended metaphors, give rise to metaphorical entailments, which influence the ways in which the model is understood and applied. Models commonly form the basis for theory formation.

This project began with considering a membrane, characterized by gradients and permeabilities as a way to think about dynamic relationships at international political borders. In proposing this effort, the principal investigator prepared the following abstract:

> Understanding and managing border dynamics is critical to U.S. regional and international security. *Border dynamics* include legal and illegal immigration and the exchange of raw materials, manufactured goods, water, pollution, disease, and drugs across international borders. These exchanges affect the physical security of the U.S and are moderated by cross-border gradients and permeabilities. *Border gradients* characterize the difference in concentrations of goods, jobs, wealth, etc., across a border. *Border permeability* refers to the ease with which goods, people, wealth, etc., move across the border. Physical and geographic barriers, security regulations, immigration policies, etc. control permeability. Together gradients and permeability control border dynamics and physical security. For example, a gradient in wealth across an international border may create higher concentrations of laborers on one side, and higher concentrations of jobs on the other. Permeability controls the rate at which laborers can cross the border. Better understanding of interactions among permeability and gradients across multiple interacting systems (i.e., immigration, goods, drugs, etc.) can lead to better border control and less border conflict.

Throughout the project, the team repeatedly returned to the metaphor and progressed through levels of “literalness” in thinking about borders as membranes. The following provides a narrative of this metaphor in its various incarnations.

The semi-permeable membrane has often been used as a metaphor to represent the interface between a wide range of adjacent entities such as business organizations (Gander et al. 2005) and nations (Slatta 1997). In biological and industrial applications, membranes permit selective transfer of different molecules or ions between two regions. Similarly, international borders permit selective transfer of different types of people (citizens, visa-holders, illegal migrants) between two countries. It is this similarity in selectively limiting movement across an interface that makes the membrane metaphor useful in explaining, and modeling, movement of people between countries. In biology, the cell membrane is a physical barrier between two fluids, one inside and one outside the cell. A national border is a physical and imaginary boundary between two cultures, two countries, or between other political entities.

Applying the membrane metaphor requires some care when moving beyond the analogy of the border as a membrane to consider the factors that cause people (e.g. workers, tourists, shoppers) to cross a border in response to the analogs of concentration gradients that cause chemical species to move through a membrane. The gradient that drives diffusion transport is expressed in terms of the concentration of the chemical species that moves down the concentration gradient. For the diffusion analogy to exactly match the border crossing process, we require a direct analog to the concentration gradient. Although we have considered several possibilities we have yet to identify an exact match. For example, if the number of unemployed Mexicans willing to take low paying jobs in the US is analogous to concentration, then having a greater number of such people in Mexico would cause a diffusive type flow from Mexico to the US until the number of formerly unemployed Mexicans residing in the US equals the number of currently unemployed Mexicans in Mexico. This view of the system does not make sense, however, because the movement of unemployed Mexicans is largely in response to job availability in the US rather than the different numbers of unemployed people in each country. Although very useful as a general analogy, difficulties in finding an exact analog in the diffusion process led us to consider more complex metaphors where people moving across the border are being carried in a flow that is, in turn, caused by a gradient related to the number of available jobs and the number of unemployed people on each side of the border.

From a high-level perspective people move across border in response to a gradient that reflects the various factors that affect their personal decision-making. At this level, Fick's First Law of diffusion provides a way to more carefully review the applicability of the membrane metaphor. Fick's Law states:

$$J_A = -D(dC_A/dX)$$

where D is the diffusion coefficient (Length^2/Time)
J_A is the flux of molecule type A across the interface (moles/L^2/T)
C_A is the number of moles of the molecule of interest (moles)
X is membrane thickness (L)

where the dimensions of each parameter are given in terms of length (L), time (T) and moles. In this case, the rate of transfer across the interface is controlled by the diffusion coefficient of the molecule within the membrane D, the membrane thickness X, and the gradient in concentration of the molecule across the membrane (dC_A/dX).

Under Fick's First Law a potential gradient (e.g., chemical concentration gradient or fluid pressure gradient) causes the specified constituent (e.g., specific molecule or specified fluid) to move down gradient (from high to low potential) through a region (e.g., a membrane) that restricts free movement. For example, applying Fick's First Law to the movement of unemployed workers between countries leads to the idea that unemployed workers move across a border from the region with a greater number of unemployed workers to the region with fewer unemployed workers. The passive diffusion model represented by Fick's First Law predicts that molecule concentrations (numbers of unemployed workers) on each side of the membrane (Figure 1) will eventually equalize (Figure 2) as long as molecules (unemployed workers) are neither added to, nor subtracted from, the two-region system. In Figure 1 the upstream volume has high concentration before the process begins while the downstream volume has low concentration. After a time controlled by the diffusion rate of the diffusing species, both volumes ultimately contain an equal concentration of the species. In Figure 2 note that concentrations in both volumes equilibrate at a normalized concentration of 0.5 because the volumes are equal in size and mass is neither added nor subtracted during this process of passive diffusion. This equalization behavior is unlikely to occur in the US-Mexico system because, in the absence of job creation in Mexico or massive unemployment in the US, population growth in Mexico will provide a continuing supply of unemployed workers. This observation, however, does not negate the applicability of the Fickian diffusion model.

Applying Fick’s Law also requires that the unemployed Mexican workers would only return to Mexico when there is a higher ‘concentration’ (greater number) of unemployed workers in the US than there is in Mexico. Although likely true in an aggregate sense, more factors affect the two-way movement of unemployed workers (and other people) across a border than just the number of unemployed workers on each side of the border. Jobs must also be available in sufficient numbers to induce the workers to make the step of dealing with the various factors that promote, or inhibit, their crossing the border. The decision to cross the border is also affected by the strength of social networks that extend between countries and provide support for those considering crossing, non-economic (social unrest) factors in the home country, and perceptions of the risks associated with illegal crossing (see Zahniser 1999; Massey and Espinosa 1997). Although the net effect of these factors can be embodied in a ‘potential’ that causes unemployed Mexican workers to travel to the US, the detailed 2-way movement of people in various categories (unemployed workers, tourists, shoppers, etc.) across a border is poorly represented by Fick’s First Law.

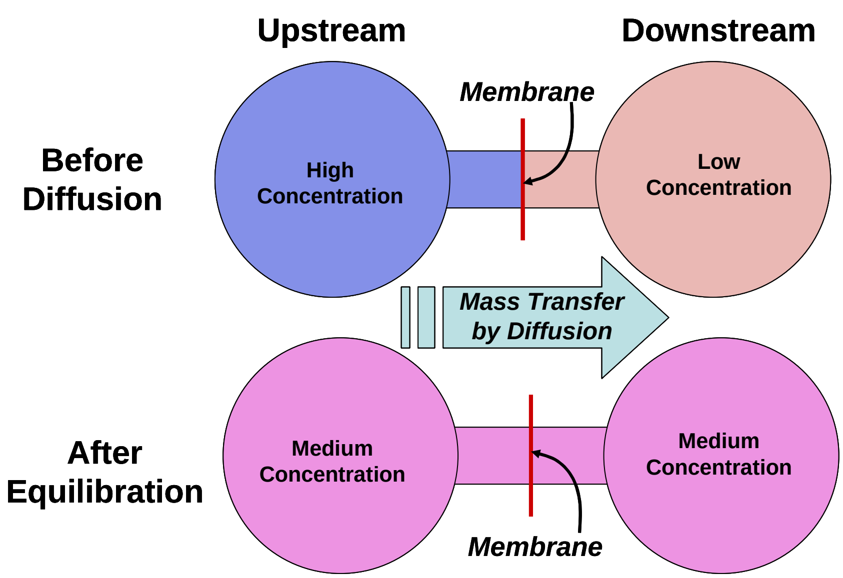

Figure 1. Schematic of the diffusion process that transports mass (molecules or ions) between two closed volumes separated by a semi-permeable membrane.

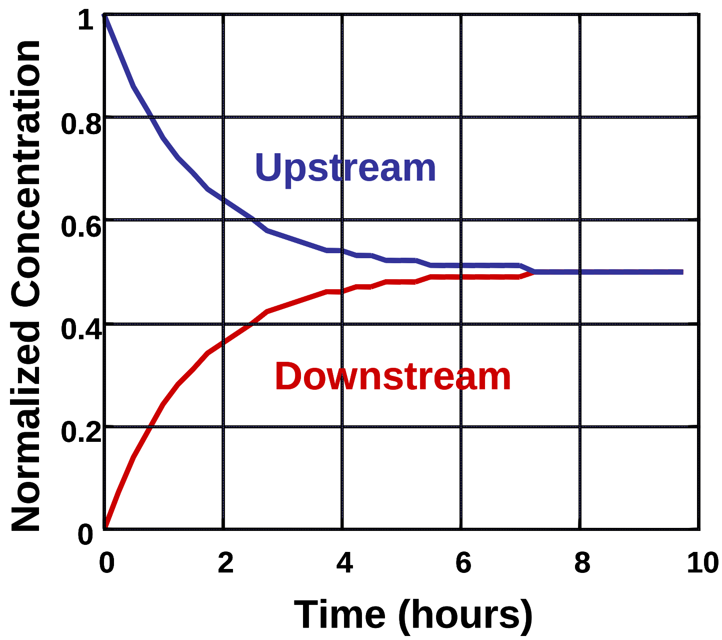

Figure 2. Growth in concentration (normalized to range from 0 to 1) of a hypothetical molecule in a downstream volume as molecules are transferred through a membrane from an initially higher concentration upstream volume.

The process of membrane filtration used in industrial processes provides a more appropriate metaphor for the forces driving movement of people across an international border. Here, a fluid pressure gradient generated using external energy drives a carrier fluid (e.g., water) through the holes in the membrane. Any molecules or suspended solids small enough to pass through the holes are transferred across the interface by the fluid. Molecules, or solid particles, too large to pass through the holes remain on the up-gradient side of the membrane. Although both filtration and diffusion processes require a gradient to cause flow across a membrane, two very different gradient types are needed. In the diffusion case, the gradient is defined in terms of the constituent traveling through the membrane. In the filtration case, the gradient causes the fluid flow that, in turn, carries the constituent through the membrane.

Given the imperfect analogy provided by the diffusion process, we looked more closely at the membrane filtration process. This metaphor represents more clearly the way that illegal migrants without proper documentation are turned away by immigration officials at national borders while legal migrants are allowed to cross. In this case, the legal migrants correspond to the smallest particles that can pass through a membrane. The factors cause people to want to travel between nations correspond to the pressure gradient that drives the carrier fluid through the membrane while filtering out particles larger than a desired size (illegal migrants). Factors that can pull people to a destination across a national border include: tourism, business, attractive jobs, family visits, shopping, access to personal services, and education. Factors in the home country that can enhance the pull by the destination country include: social strife, poverty, lack of jobs, family breakup, and unhealthy conditions.

Many, but not all, of these factors also motivate illegal migrants to cross at locations other than official border crossings (and, to a lesser degree, at official border crossings). Consider a membrane with two hole sizes; small holes represent ports of entry that permit legal migrants to cross while larger holes represent the border between official crossing points where illegal migrants attempt to cross. As border security is tightened, illegal migration is reduced in the same way that the larger hole size might be reduced in a new batch of membranes. The movement of legal migrants through the official border crossings, however, is little affected by increased border security; except when some trips are eliminated because delays at the border become intolerable. Only a portion of the illegal migrants making the attempt successfully reach their destination after crossing the border. Thus, it seems reasonable to assume that the wide variability in factors that inhibit the success of individual illegal migrants (e.g., poor health, lack of funds, apprehension by border guards, dangerous environmental conditions, and risk aversion) is mimicked by a range of suspended particle sizes that might be carried to a membrane in a carrier fluid. Only a portion of the suspended particles will pass through the largest hole size of the membrane; the rest will remain on the up-gradient side of the membrane.

Adopting the membrane filtration metaphor indicates that reducing the flow of people across an international border would require one or more of the following:

1) reduce the overall motivation to cross the border (reduce the fluid flow rate by reducing the fluid pressure gradient)
2) reduce the number of people willing to act on that motivation to cross the border (reduce the number of particles in the fluid stream)
3) increase border security to reduce the number of people able to cross the border (reduce the size of the membrane holes)

One approach to reducing the number of people crossing an international border would involve reducing the underlying factors that attract people to cross the border by improving social, economic, public health and educational conditions in the country of origin and restricting access to jobs in the destination country. It is likely that declining birth rates accompanying the improved living conditions would lead to slower growth in the numbers of people that might become motivated to migrate. In fact, Dowd (2005) has predicted that changing demographic patterns in Mexico will result in fewer unauthorized migrants entering the US. This approach is similar to reducing the pressure gradient driving flow of the transporting fluid while also decreasing the number of particles flowing in the upstream region (points (1) and (2) above). Another approach is to increase border security and divert illegal migrants into increasingly dangerous border territory. Knowledge of the increased risk of apprehension, or death, may dissuade some migrants from attempting to cross. Some of those that remain highly motivated to cross the border, however, will contribute to the migrant apprehension and death rate statistics. This approach is similar to reducing the size of the membrane holes to reduce the number of particles passing through the membrane (point (3) above).

With the previous discussion in mind, a simpler approach to the metaphor was identified that may be more accessible to those unfamiliar with the dynamics of flows across semi-permeable membranes. Brown (2003) outlines how the biological processes of flow across a semi-permeable membrane can be explained using flows through a channel as a metaphor. Thus, rather than using the membrane metaphor for the details of border crossing dynamics, we can revert to the channel metaphor that is conceptually more accessible to the average person. In taking this tack we return to the higher-level view where a gradient in 'something' either directly (diffusion analogy) or indirectly (membrane filtration analogy) causes people to cross international borders.

A channel is a narrow waterway connecting two water bodies. Ships move in one direction or another through the channel under their own power, depending upon the various factors that dictate the ultimate destination of the ship. By analogy, people crossing the border travel along the roads, air routes, railroads and trails that provide legal and illegal routes (channels) for crossing the border in ways that depend upon the factors that motivate them to travel. New border crossings (analogous to increasing the number of channels) can be constructed to enable more efficient movement between nations. Laws, regulations, border entry characteristics and border climate/terrain exert constraints on people wanting to enter a nation (analogous to constraints imposed by channel width, depth, locks or gates). Just as ships travel between water bodies under their own power in response to economic, and other factors, people travel across borders between adjacent nations after weighing economic, social and logistical factors/risks. The factors involved in decision-making lead to a ‘potential’ gradient that induces unemployed workers to cross the border. However, the ‘potential’ is only partly related to the number (concentration) of unemployed workers in each country.

The channel metaphor is readily applied to the movement of particles through a semi-permeable membrane where some particles are carried by a flow of water across the membrane while others are filtered out to remain on the upstream side of the membrane. In this case, ships moving in the channel by drifting in the water flow, or traveling under their own power, are analogous to the particles carried through the membrane pores by the flowing water; or to ions driven by electrical gradients. Similarly, the channel metaphor can be applied to describe a variety of cross-border flows from one country to the other with adjustments made to match the metaphor to each type of flow. Types of flows to consider might include, but is not restricted to: (1) unemployed workers moving to find jobs, (2) people returning home after working in another country, and (3) tourists and shoppers making short visits.

The description of the process that the research team applied to utilizing the membrane metaphor to model border dynamics well demonstrates philosopher Max Black’s (1962) critical discussion of using metaphor in a comparative sense. He states, “Metaphorical statement is not a substitute for a formal comparison or any other kind of literal statement, but has its own distinctive capacities and achievements” (p. 37). While it may be *possible* to find analogs for the gradient requirements in Fick’s Law (or other physical characterization of a membrane) the benefit in terms of more clearly elucidating border dynamics is likely negligible. Black goes on to state that, “It would be more illuminating in some of these cases to say that the metaphor creates similarity than to say that it formulates some similarity antecedently existing” (p. 37). Kuhn (1979) contributes the idea that, “However metaphor functions, it neither presupposes nor supplies a list of the respects in which the subjects juxtaposed by metaphor are similar” (p. 409). The power in metaphor is not found in its ability to “fit” literally the source of the metaphor (in this case a mathematical formula such as Fick’s Law), but to provide a more generalized image that can help people better understand some process or system (in this case seeing the border as a channel).

System Dynamics Modeling

Like the power in a good metaphor, system dynamics modeling provides a means for re-viewing a complex system and “seeing” in potentially new ways. Also like a metaphor, model structure—variables selected, data utilized—all frame and shape the outcome from the model. System dynamics utilizes a stock and flow metaphor to help visualize the interaction among variables in a complex system.

In Industrial Dynamics[1], Jay Forrester (1961) presents a type of model structure that is “amenable to the objectives and principles outlined.” He indicates that a model should have the following characteristics:

- Be able to describe any statement of cause-effect relationships that we may wish to include.

[1] Now commonly termed system dynamics.

- Be simple in mathematical nature.
- Be closely synonymous in nomenclature to industrial, economic and social terminology.
- Be extendable to large numbers of variables (thousands) without exceeding the practical limits of digital computers, and
- Be able to handle "continuous" interactions in the sense that any artificial discontinuities introduced by solution-time intervals will not affect the results. It should, however, be able to generate discontinuous changes in decisions when these are needed.

He concludes that those requirements can be met by "an alternating structure of reservoirs or levels interconnected by controlled flows." These are made operational by stocks, flow rates, decision functions and information channels, the building blocks of a system dynamics model. Forrester's proposal has often been metaphorically described as "bathtub dynamics." Stocks are the bathtubs themselves, decision functions are the automated or humanly controlled valves on the flows to and from bathtubs, and the information channels serve as pipes between stocks. It is a small and enlightening step from stocks and flows to membranes and borders as shown in Table 1.

Source Domain		Target Domain		New Domain		System Dynamics Domain
Channel		*Cells*		*Border*		*Stocks and Flows*
Narrow passage between two larger bodies of water	Maps to →	Rapid transfer of ions between inside and outside of cell	Maps to →	Movement of persons across a point of entry	Maps to ←	Information channel between stocks
Channel walls may be constructed	Maps to →	Formed from substance embedded in cell wall	Maps to →	Formed by paths, roadways	Maps to ←	Decision function and existence of flow
Channel width and depth constrain sizes of vessels that may pass	Maps to →	Selective for ionic size or charge	Maps to →	Physical characteristics of port of entry permit different kinds of traffic	Maps to ←	Decision function resulting in controlled flow rates
Channel may have locks or gates	Maps to →	Ion passage can be blocked by chemical agents	Maps to →	Laws or regulations	Maps to ←	Decision function resulting in controlled flow rate

Table 1. Knowledge representation scheme mapping the properties of channels in the macroscopic domain onto biological channels and biological channels on to a port of entry between two countries. The concepts are further annotated by a comparison to Forrester's modeling paradigm. Adapted and enhanced from Brown (2003) Figure 2.2

The applicability of the stock and flow or system dynamics paradigm is powerful in helping to explain relationships among numerous variables. Sterman (2000) states, "Stocks and flows are familiar to all of us" and this makes them useful in model building. Sterman (2000) cautions, however, that it is imperative to understand the distinctions between stocks and flows. He notes that, “Failure to understand the difference between stocks and flows often leads to underestimation of time delays, a short-term focus, and policy resistance.”

The non-trivial aspect of the modeling is to ask the right questions in order to map the correct real world objects to the system dynamics metaphor. A typical attempt to model a problem using the system dynamics approach starts with listing variables of interest, creating reference modes or time graphs, building causal loop diagrams, developing dynamic hypothesis and then, if required, building a computer model (Sterman 2000).

In developing causal loops and models, the team utilized information, data and models from other sources. Early in the project, the team reviewed the model developed by SCERP’s B+20 group and used that model to think about the legal migration component of the project (Sadalla 2005). Much of this work was examined via the insight gained from our membrane metaphor, especially as developed into the generic membrane model (Figure 4). The team also used information provided by Zahniser (1999) to populate a system dynamics model in Powersim Studio 2005. This model includes variables about demographic characteristics of people who choose to migrate to the US, why they migrate, and what prompts them to return to Mexico. Finally, this project relied heavily on a model developed by Dabiri and Low in 1977 as a modeling assignment at the MIT Sloan School of Management.

Model Construction

The system dynamics paradigm was applied to border issues as early as 1977. However, if we include Forrester's urban dynamics work (1969), especially his attraction theory of migration, we can go back to the late 1960s. Criticism of Forrester’s work included the belief that simple gravity models could adequately describe migration and that Forrester’s formulation was incorrect. However, Laird (1971) showed that gravity models only work over short periods of time, from one to five years. “The standard gravity formulation does not include variables which describe factors creating differential attractiveness or the factors which change the attractiveness differential between starting and ending points” (Laird 1971).

Employing the membrane/channel metaphor, the team developed a causal loop diagram and a generic membrane transfer process model (Figures 3 and 4). Our generic membrane model alludes to the multi-dimensioned measure of attractiveness in the arrows that indicate that ‘An entire model may determine this stock’s value.’

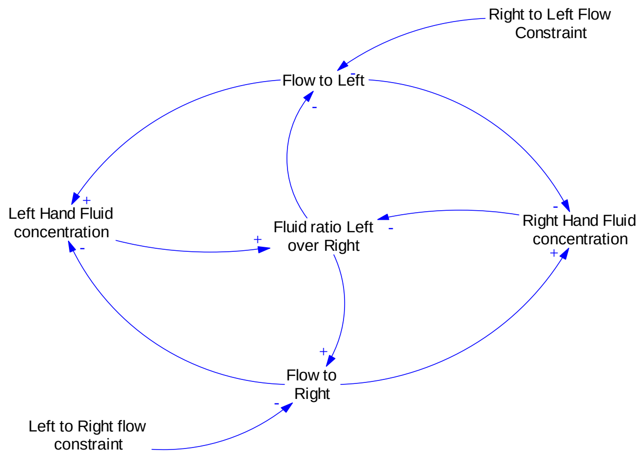

Figure 3. Causal loop diagram for a generic membrane transfer process.

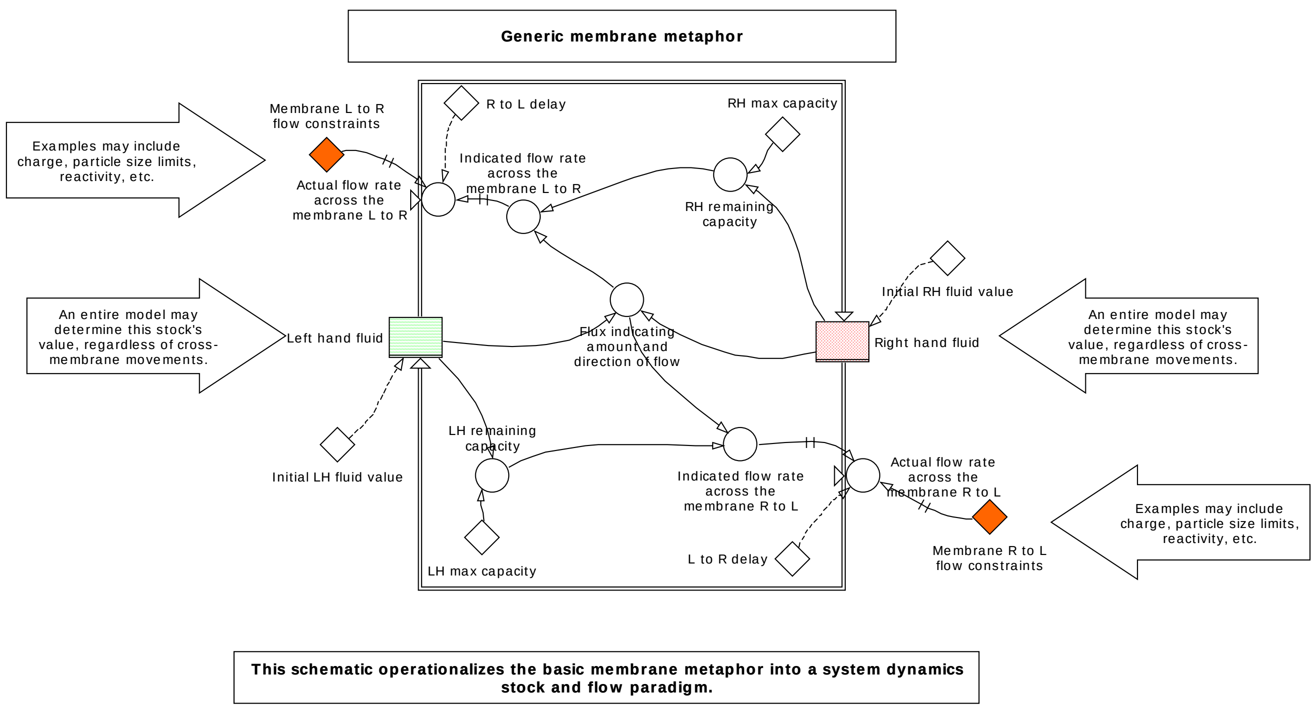

Figure 4. Generic membrane metaphor as a Powersim Studio model

Illegal Migration Model

The sense from the focus groups and interviews concerning unauthorized entry corresponds to what we found in published reports concerning illegal migration research and to model results. Despite the tightening controls on the US side and sharply increased budgets dedicated to halting the flow, illegal crossing attempts continue apace. Estimates suggest that there may be as many as 10 million unauthorized persons in the US. This is an increase from estimates ranging from 7 million to 8.4 million in 2000. The majority of these individuals are Mexicans (Passel 2005; Cornelius 2005). Apprehension levels have increased and crossers do report that they believe crossing has gotten more difficult. The evidence, however, does not indicate that this new reality is leading to a decrease in crossing attempts. Newspaper accounts and survey research feature individuals who have crossed as many as 20 times and have been caught many times, but say they will continue to cross to earn money (Associated Press 2005, Carrier 2005, Cornelius 2005; Hoffman 2004). Several hundred deaths are attributed each year to attempts at unauthorized border crossing (Cornelius 2005). Cornelius (2005) concludes that, “Enhanced border enforcement has no statistically significant effect on intention to migrate” and that “only ‘demand-reduction’ (= fewer jobs) on the U.S. side is likely to be an effective deterrent.”

Fix et al. (2005) draw a similar conclusion stating that, “Strengthened border enforcement has not been equal to the task of curbing unauthorized immigration. Although getting into the country has become increasingly difficult and dangerous, once here, jobs are plentiful and there is little likelihood that prohibitions on hiring unauthorized workers will be enforced with great enough vigor to change behavior. Our enforcement policies, then, essentially invite people to take great personal risk to defeat border controls in return for the payoff of ready access to the labor market. As long as this situation persists, border enforcement will be unable to override the economic laws of supply and demand that fuel unauthorized immigration.”

In 1997 Massey and Espinosa concluded that policy efforts geared toward discouraging and decreasing illegal migration may actually have exacerbated the problem. They found that contrary to many of the neoclassical economic-based rationales for illegal migration, more powerful drivers were access to social and human capital. Therefore, economic-based policy initiatives have not only failed to stem the flow of undocumented workers, but in some cases have contributed to increasing the flow.

As far as we can determine, the first complex efforts to use system dynamics for cross border migration modeling is Dabiri and Low's 1977 MIT modeling assignment specific to illegal Mexican migration into the United States. The original model was written in DYNAMO and was converted to Powersim Studio 2005 as a part of this project. We have also reverse engineered a simplified causal loop diagram from the original DYNAMO model (Figure 5). The model works at a national level and focuses on issues including economic aid to the Mexican government for labor-intensive industries, introducing added control at the border to reduce the flow of illegal Mexicans across the U.S./Mexico border, allowing temporary-worker migration visas to reduce the institutional barriers for Mexican workers in the U.S., and programs to address the birth rate in rural Mexico.

The model develops five main levels to address illegal migration from Mexico to the U.S., and the subsequent drivers of these levels. The levels include the number of U.S. businesses hiring illegal migrants, the illegal migrant population in the U.S., the population of rural Mexico, the potential migrant population in Mexico, and the number of business hiring rural Mexicans. The central thesis of the model is to examine how the business climate in rural Mexico affects the drive for illegal migrants to seek work in the United States. Population growth, local and national economic conditions, political border rigidity (difficulty of crossing) and a multitude of other variables drive the model’s insights for illegal Mexican migration.

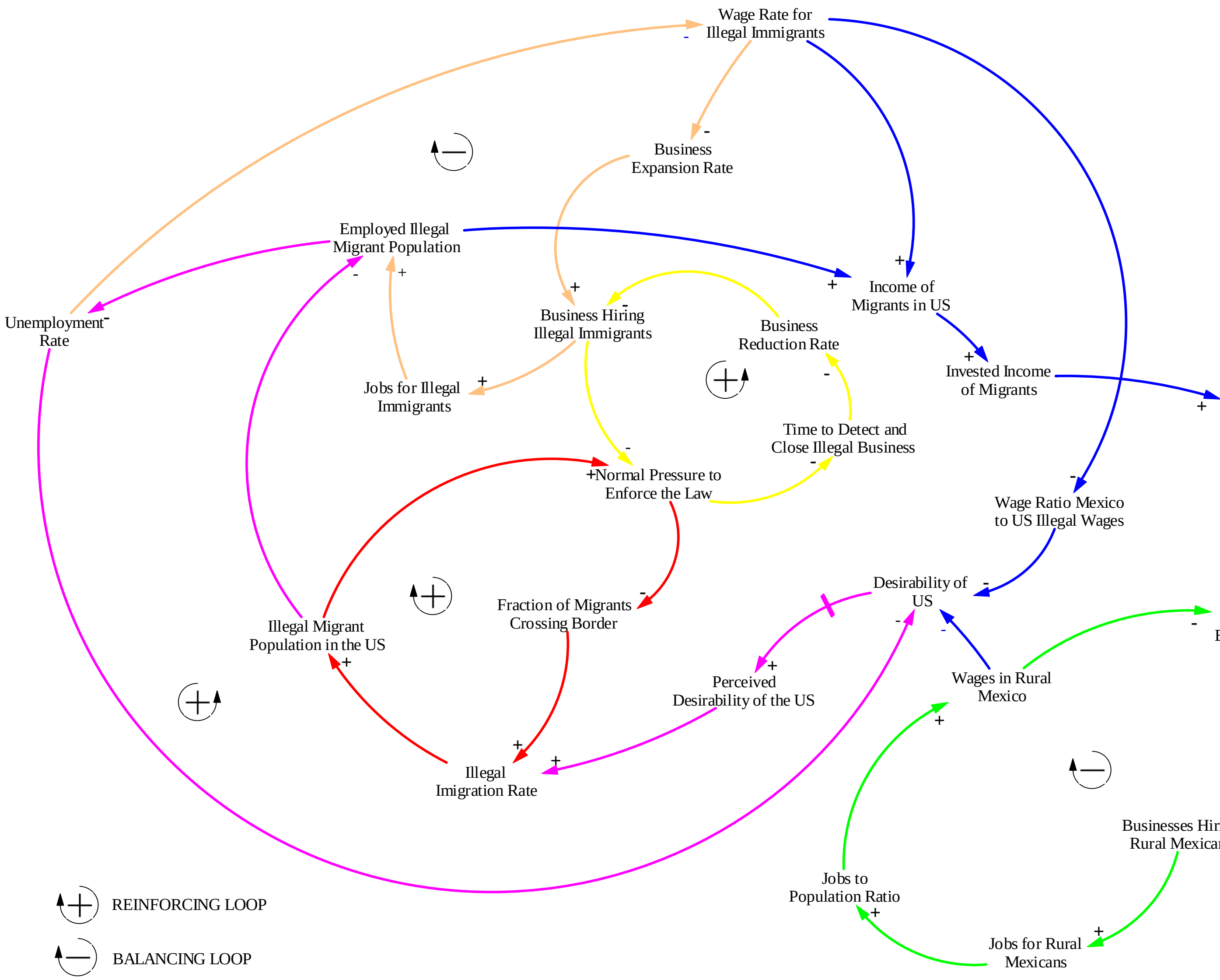

Figure 5. A simplified causal loop diagram created based on the Dabiri and Low system dynamics model of illegal migration.

Dabiri (1977) and Dabiri and Low's (1977) main findings included an ever-growing population of potential illegal migrant labor from Mexico to the U.S. (from 500,000 in 1960 to an expected 2.5 million by 1995, to a stabilizing 3.5 million by 2050), an increasing number of U.S. businesses that hire illegal Mexican migrants (4.5 thousand U.S. businesses in 1960 to an expected 40 thousand by 1995). A few of the key drivers for this change include increasingly "inadequate wages in rural Mexico," and a high birth rate in rural Mexico that adds to the potential pool of illegal Mexicans seeking work in the U.S. (Dabiri 1977, pp. 25). Additionally, as the illegal Mexican population increases (by way of the model's calculations) the pressure on border patrol increases – leading to questions regarding border security resources necessary to address the growth in potential attempted illegal border crossings. As the illegal migrant population fills the demand for illegal labor in the U.S., along with border control measures, the desirability of Mexicans to illegally cross the border may decrease until an equilibrium of sorts develops that, "is characterized by high wages in the U.S. and in Mexico, low desirability of U.S.

for potential migrants, low domestic law enforcement pressures, and a high presence of illegal Mexican migrants in this country" (Dabiri 1997, pp. 33).

Finally, the model tests policies that address tighter border control, increasing economic aid to Mexico, instituting a system of temporary worker visas, and how family planning could achieve a reduced birth rate in rural Mexico. The model finds no discernable impact to increasing border efficiency; rather, reinforcing the border control may only postpone an illegal migration problem. Providing aid to Mexico could increase the local and national conditions to a point where the perceived benefit of migrating to the U.S. illegally diminishes to an extent (e.g., reducing the desirability to migrate), thereby reducing the potential population of illegal Mexicans in the U.S. Establishing a temporary worker visa program leads to a higher total illegal Mexican population in the U.S. This is due to the fact that illegal migration does not change after the legal visa program develops (up to 5 million illegal migrants in the U.S. and stabilizing at 4 million vs. 3.5 million under the base case assumption). Finally, addressing rural birth rates in Mexico would eventually lead to a smaller illegal migrant population in the U.S. using the model's assumed decline in the birth rate from 3% in the base case in 1980 to 1.5% by the year 2000. Illegal migrant population would reach a peak of 4 million by 2010, and decline to 1 million by 2060.

Comparing Dabiri's Model DYNAMO output to Powersim Studio 2005 output

In order to gain a rapid understanding of the dynamics of illegal Mexican migration, this research team attempted to duplicate the results of Dabiri's DYNAMO model by converting that model to Powersim Studio 2005. DYNAMO was the original digital computer software that permitted the modeling of system dynamics problems. Although DYNAMO is still available, its use has been superseded by other system dynamics modeling software. Studio has a graphical interactive development environment (IDE), which greatly eases the programming of models.

The Powersim Studio model of illegal migration developed in this project has at its core the generic membrane metaphor shown as a causal loop diagram in Figure 6 and as a Powersim Studio model in Appendix A. Two central stocks represent the cumulative outcome of movement of chemical species (illegal migrants to the US from Mexico) from one side of the membrane (US-Mexico border) to the other: (1) 'left hand fluid' or 'illegal migrant population in the US - IMPUS', and (2) 'right hand fluid' or 'potential migrant population in Mexico - PMPM'. The stocks are connected by flows ('actual flow rate across the membrane', or 'immigration rate - IMR' and 'emigration rate - EMR') that represent the flux of chemical species (migrants) across the membrane (US-Mexico border). The model of illegal migration differs from that of the generic membrane metaphor in two principal ways. First, the stock of potential migrant population in Mexico is affected by two additional flows: gains through a growing population ('new additions to the potential migrant population') and losses through disinterest on the part of prospective migrants ('permanent departures from the potential migrant pool'). Second, the flows between stocks at the core of the model of illegal migration are influenced by a variety of factors and relationships captured in the much larger model that reflect the complexity of border crossing dynamics. Flows between stocks in the generic membrane metaphor model comprise very simple relationships. We find that starting with the metaphor and building the simple generic model were valuable preliminary steps to getting the team more deeply involved and knowledgeable while modifying and exercising the illegal migration model of Dabiri and Low (1977).

The equations that make up the original DYNAMO code take up approximately two pages of printed text. The model converted to Powersim Studio 2005 is composed of 76 variables, five of which are levels. The conversion process was relatively straightforward. Dabiri's (1977) suggested solution included a schematic of the model (similar to Appendix A) and an equation listing. There were some language syntax translation difficulties but we are confident that the Powersim Studio version calibrates to the DYNAMO model.

In order to increase our confidence in the calibration we present five sets of graphics, each includes a graph from Dabiri's memorandum and a similarly designed graph from the Powersim Studio 2005 model. Table 5 shows the five sets.

Dabiri's original graph	**Parameters changed in Powersim Studio**
Figure 14 Base Run	None
Figure 19 Border Control Policy	Decrease PNC50 Law Enforcement Pressure to Catch 50% at Border to 0.7 from 1 resulting in 66% success rate in crossing into the US.
Figure 20 Economic Aid to Mexico	Increasing FIGI Fractional Increase in Government Investment by 100% in 1980 to 2 billion USD.
Figure 21 Temporary Migrant Visa	Through the addition of several variables permitting 2 million migrants to enter the US with temporary visas.
Figure 22 Family Planning	Executing a 3% to 1.5% decline in NFBR Net Fractional Birth Rate in Mexico between 1980 and 2000.

Table 2: Comparing Dabiri (1977) to the Sandia Powersim Studio conversion

We have not attempted to duplicate the numerical output from both models, in part because we are not yet proficient in the current version of DYNAMO. We believe that the graphs (see Figures 5 an 6 for examples) show a very strong correspondence between the two model formulations. Of course this effort was undertaken due to our confidence that the Dabiri model is a useful representation of the causal issues concerning illegal Mexican migration to the US. After all, "All models are wrong, some are useful" (Box 1979).

The Dabiri model makes use of table functions. Table functions create an explicit relationship between two variables, typically in the form of a logistic or 'S' shaped curve. These functions are common when empirical data is unavailable. Many of the variables are constant, exogenously determined and useful as parameters to test model validity (See Sterman 2000 for a complete discussion of system dynamics model validity and verification). Ideally, a system dynamics model is causally closed, such that "…the closed boundary separates the dynamically significant inner workings of the system from the dynamically insignificant external environment" (Richardson 1991). There are upwards of 20 exogenous variables in the model that make excellent parameters to test policy changes. Recent work has indicated that one of Dabiri's exogenous variables may be causally closed. That variable is Average Duration of Stay (ADS) in the US. Work by Cornelius (2005) suggests that ADS may be dependent upon the effectiveness of border control. Average Duration of Stay is expected to increase with border control success.

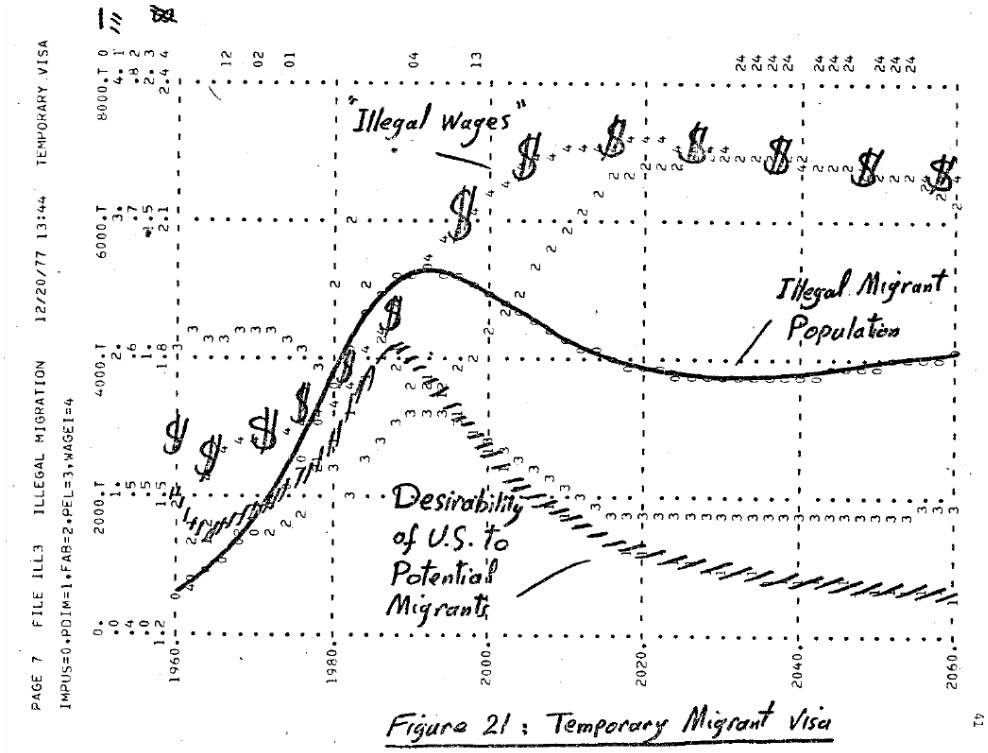

Figure 5. Dabiri Model Temporary Migrant Visa Scenario

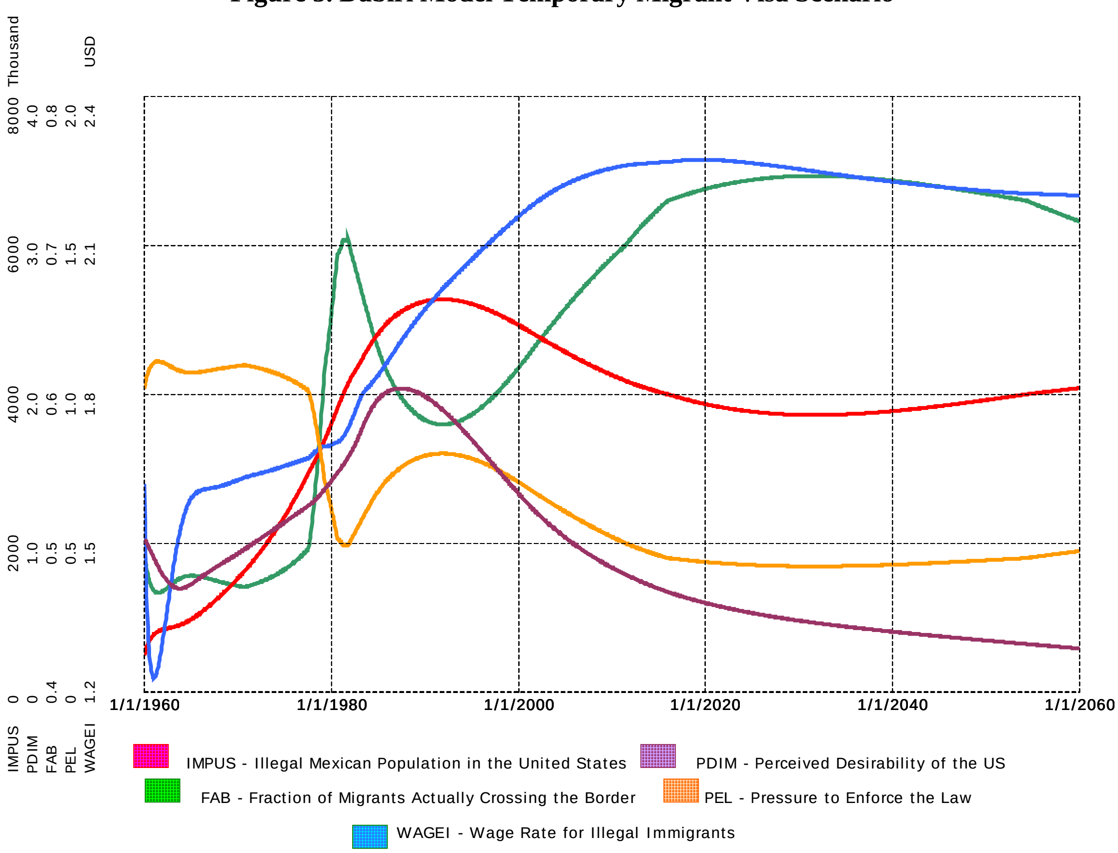

Figure6. Powersim Studio version of Temporary Migrant Visa. NOTE: MNMTV Maximum desired Number of Migrants with Temporary Visas set to 2,000,000

Discussion

Overall, the modeling exercise described above supports the idea that increasing controls on the border itself may not be the strongest measures for reducing illegal migration, contrary to most policy-level measures currently being taken. The modeling supports the idea that changing economic conditions on either side of the border may in fact be the strongest measures for changing the rates of illegal migration, and ultimately reducing the population of illegal immigrants in the U.S. This view is also widely reflected in the literature (Amador 2005; Angelucci 2005; Cornelius 2005; Dowd 2005; Fix et al. 2005; Zahniser 1999; Massey and Espinosa 1997).

Evidence for this view comes most clearly from the sensitivity analyses shown above. The variables that showed the greatest reduction in overall number of illegal immigrants to the U.S. with model runs beginning in 1960 and running with default values through 2060 were:

Time to detect and close illegal businesses
Normal pressure for law enforcement
Net fractional expansion of business in Mexico
Fraction of invested income in Mexico
Normal investment in labor intensive industry

It is worth noting that "Normal pressure for law enforcement" includes law enforcement pressure at the border as well as pressure on businesses hiring illegal immigrants. "Law enforcement pressure to catch 50% at border" does not make a big a difference in ultimate immigrant numbers, and it focuses on law enforcement pressure only at the border.

Similar results are found in the model runs that included a step change made away from default values, representing simulated policy changes, in 2010. Those most noteworthy are:

Net fractional expansion of business in Mexico
Fraction of Invested Income in Mexico
Normal investment in labor intensive industry

Model test results illustrate how different policies enacted in 2010 might lead to a wide range in projected illegal Mexican migrant population in the US (1 to 5 million). Although our updated results project a spread in possible illegal migrant population similar to that of Dabiri and Low (1977), our 2060 estimates are about 0.5 million larger. The patterns in future migrant population trends, however, are similar. Important lessons learned build on the conclusions of Dabiri and Low (1977) and include the following:

- we appear to be approaching a future of stable or declining illegal migrant population – particularly when compared to the pattern of the past 20 years
- increasing investment in Mexico through Mexican and US government actions, Mexico business expansion and investment of migrant remittance funds has the potential to help cut the future illegal migrant population to about half of the current population.
- it will be difficult, if not impossible, to eliminate the presence of illegal Mexican migrants in the US

- achieving a 50% decline in illegal migrant population requires that the pressure for border law enforcement be maintained at current or higher levels so that border security is not relaxed

- while attempts to reduce northward migrant flow by improving the ability to rapidly detect and close US businesses employing illegal migrants should be maintained, the necessary investment might be used to better advantage in rural Mexico

This project has successfully contributed to several knowledge bases. First, it provided lessons learned from working in a multidisciplinary team trying to develop an interdisciplinary tool while applying a metaphor to help explain complex phenomena. The research team faced difficulties that are common to integrated teams including communication and methodological issues. There were also some unique conditions, such as not having a client to frame project requirements and struggles employing a metaphor across disciplines. The team did, however, coalesce sufficiently to generate a model that is based on the metaphor and to prepare this paper, which both cross disciplinary boundaries.

The illegal migration model developed contributes to the growing body of work on using system dynamics models to help decipher complex systems and potentially contribute to improved policy-making. The model's output provides input to the cacophonous voices calling for various policy measures to address illegal migration. This effort also shows the value in building on existing models to save time and resources, as well as to strengthen the value of the new model. This project's model is based on work done by Dabiri and Low, whose results have well-matched illegal migration reality since 1977.

Dabiri and Low (1977) developed their system dynamics model to represent the process of illegal migration from Mexico to the United States by accounting for feedback and interactions within and between: (1) the US and Mexico economies, (2) US border security strategies, (3) US and Mexico investment policies in rural Mexico, and (4) population growth in Mexico. At that time, they estimated that illegal Mexican workers in the US numbered less than 1 million. Twenty-five years later, a number of writers estimate that illegal Mexican workers in the US number about 4 million; about half of the total illegal migrants in the US (see Leiken 2002). Interestingly, this is about the number of illegal Mexican workers Dabiri and Low (1977) estimated for the early 21st century (4 to 4.5 million) when applying their model across a range of policies and scenarios. Over subsequent decades (2010 to 2060) they project a range of possible outcomes from 0.5 to 3.5 million illegal Mexican workers in the US at 2060. Thus, the Dabiri and Low (1977) model appears to capture the now historic, steep increase in illegal migration between 1980 and 2000 and projects small to large declines in illegal migration over the coming decades. These projections are consistent with the expectation of the Mexican government, and others, who anticipate a significant decline in migration by 2015 in response to economic growth and declining birth rates in Mexico (Dowd 2005; Leiken 2002). If these projections are correct, then awareness of the fact that we have passed the period of steep growth in the illegal migrant population should help to identify preferred policy options for minimizing the flow of illegal Mexican migrants to the US in ways that improve economic conditions in rural Mexico. Accomplishing this goal will reduce criminal activity and migrant deaths in the borderland while enabling workers and their families to work locally towards improving conditions in their home communities; rather than by sending remittance checks.

Given the confidence we had in the model formulation and construction and regardless of the apparent success of their projections, we adopted the Dabiri and Low (1977) model to explore the possible outcomes of policies aimed at reducing illegal migration that might be enacted within the next decade. In doing so, we updated one aspect of their model by allowing for the possibility that illegal Mexican workers might stay longer than 1 year in the US. This change is important because border security has likely caused some migrants to postpone their return to Mexico due to concern that their chances of a subsequent return to the US might be reduced. Longer duration stays in the US lead to a net increase in the illegal migrant population because new migrants continue to arrive while previous migrants elect to stay.

In general, the results from this model reflect what the research team found in the literature concerning drivers and disincentives for illegal migration. Yet, the policies being promulgated do not reflect what appears to be growing consensus concerning immigration. There is little evidence that increasing border enforcement or increasing employer sanctions results in concomitant reduction in illegal migration and may well increase the resident illegal population as migrants remain in the US longer. Amnesty programs appear to increase illegal migration as the newly legal US residents provide the necessary social and human capital to encourage other illegal immigrants to enter the US. This project continues the body of work suggesting that perhaps the most effective approach to addressing illegal migration is to continue working to improve living conditions in Mexico and then to wait: as the birth rate in Mexico declines and economic conditions improve, the drivers to migrate will lessen.

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Appendix A: Diagram of the Powersim Studio Version of the Dabiri/Low Model