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Researching a Local Heroin Market as a Complex Adaptive System

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Abstract This project applies agent-based modeling (ABM) techniques to better understand the operation, organization, and structure of a local heroin market. The simulation detailed was developed using data from an 18-month ethnographic case study. The original research, collected in Denver, CO during the 1990s, represents the historic account of users and dealers who operated in the Larimer area heroin market. Working together, the authors studied the behaviors of customers, private dealers, street-sellers, brokers, and the police, reflecting the core elements pertaining to how the market operated. After evaluating the logical consistency between the data and agent behaviors, simulations scaled-up interactions to observe their aggregated outcomes. While the concept and findings from this study remain experimental, these methods represent a novel way in which to understand illicit drug markets and the dynamic adaptations and outcomes they generate. Extensions of this research perspective, as well as its strengths and limitations, are discussed.

Keywords Illegal drug markets · Ethnographic research · Complex adaptive systems · Applied social simulation modeling

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Introduction

This paper describes an experimental study using agent-based modeling (ABM) techniques to computationally reproduce and investigate the operation of a local heroin market in Denver, CO, circa 1992–1996. The objective of the illicit drug market simulation (IDMS) project was to computationally simulate what occurred in Denver's Larimer area open-air heroin market, using ethnographic data. Simulation experiments evaluate and extend our understanding of two research questions: (1) How important was the role of "brokers," heroin users who facilitated transactions between customers and dealers,[1] to the market's overall operation? (2) To what extent did police activity influence the market and its eventual transformation?

It is important to note, the model described in this manuscript is not intended as a forecasting tool. Rather, it was created as an exploratory laboratory to expand ethnographic findings, and to identify essential parameters to the market's operation and transformation. In developing an ABM logically consistent with ethnographic research, the IDMS project was a proof of concept study. Few examples of this type of synthesis exist (Agar 2001, 2005), but applying this approach in prospective research could make it easier to interpret conventional market outcomes, as well as expand research on local illicit drug market operations in novel ways.

This paper highlights utilizing ABM as a research tool to exploit the unique strengths of ethnography. Namely, ethnographic research occurs within the participant's natural

[1] The term "copping" is an indigenous term often used in the literature to describe when one user buys drugs for another. The author uses "broker" and "brokering" to better specify these activities. These more widely known terms also show their crucial role to the market's operation and adaptation.

environment. This way, researchers cannot help but address social and environmental interactions. The ethnographer must confront, and attempt to explain, nuance and change. The challenge of the IDMS project involved reformulating findings of an ethnography using ABM. Could we reproduce the essential behaviors of market participants within an ABM to reflect (and quantify) what was discovered in the ethnography? What would "scaling-up" results demonstrate, and what could we learn from this new data?

Future applications of the hybrid methodology described in this paper are numerous and could make substantial contributions to research in new drug prevention and treatment interventions and in impact evaluations of drug policies. Community outreach, needle-exchange, treatment programs, and other services aimed at reducing the negative health consequences of drug use could be designed, integrated, and tested using such simulation techniques. Additionally, taking advantage of geographic information systems (GIS) and other geographical data sources, future ABMs of drug markets could observe illicit drug activity in real time. However, to apply ABMs to inform policy, researchers must be cautious. Unlike Systems Dynamics and other more mature simulation and modeling techniques (Forrester 1994; Homer and Hirsch 2006; Mabry et al. 2008), guidelines for integrating data into ABMs and procedures for validating such models need further development. In fact, theoretically oriented ABMs do not require data to be useful. Because of ABM's micro-simulation characteristics, they provide a unique opportunity to examine rare and "unusual" scenarios. Statistical and system dynamics models focus on describing the means, but ABMs allow researchers to examine trajectories strongly deviating from the mean trend and find out why such factors occur. For research on illegal drug markets, this paper hopes to advance methods for designing ABMs using ethnographic data, better integrating behaviors within their local environments.

Perspectives on Heroin Markets

The global economy for heroin is comprised of countless numbers of heterogeneous agents who produce, distribute, sell, and consume the drug (Eck and Gersh 2000). As with other drugs not produced in the US, it is recognized that the heroin economy has a hierarchical structure, with profits and resources coalescing exponentially at its highest levels (Curtis and Wendel 2000). At the top of this structure sit large-scale, well organized, well financed, and politically entrenched international cartels.

Understanding heroin markets in local communities indirectly involves what cartels do. In Denver, the market was connected to a global enterprise. Heroin sellers who were researched on the streets of Denver for this project sold heroin for Mexican Drug Trafficking Organizations (DTOs). Sellers went to the market, worked shifts, and received pay on commission based on their sales. The traffickers recruited sellers from villages in Central America, arranged for their transportation, and provided them with housing. Expenses incurred, in turn, justified the seller's servitude. The Mexican DTO's controlled heroin distribution in Denver.

This perspective highlights the top–down structure in illicit drug markets, implying what happens locally is directed by forces acting higher up the economic hierarchy. The arrangement is "supply-centric." It emphasized how producers influence the behavior of distributors. Distributors then influence the behaviors of dealers. Dealers then influence the behaviors of customers. In this "command economy" system, higher echelons are presumed to control subordinates, promoting the ideology that interventions should be targeted upward. This, after all, is where dynamics are set in motion. This top–down approach is commensurate with a "supply-reduction" policy, and is often used to justify the "war on drugs." However, coordination and independence coexist in illicit drug markets, and this admixture confounds such simplification (Johnson 2003).

A "Bottom–Up" Perspective on Heroin Markets

Considering the economic structure, hierarchy, and vertical integration of heroin distribution, changes in organization can reverberate "downward," influencing subordinate operations and end-users, i.e. customers. However, a significant portion of activity in local drug markets occurs outside such "organized" frameworks. People and groups are often operationally independent from, or in direct competition with, one another (Bourgois 1997). For example, a distributor interacts with a dealer to provide the dealer with heroin; however, the distributor and the dealer are independent businesspeople. In other words, it is up to the dealer to make sales, enforce rules, and manage transactions with customers, and the distributor has to manage suppliers bringing them product. As a result, based on the primary author's ethnographic research, we could not understand Denver's open-air heroin market only by understanding the activities of the DTO that supplied the heroin. Appearances suggested a functional monopoly. However, this façade only partially explained how heroin was sold.

Like most street-based markets, the Larimer area was not Denver's only venue for heroin sales. A considerable number of independent (i.e., private) dealers sold heroin from their homes. Our ethnographic case study examined one such organization. Like street-based sellers, the dealers researched purchased the half-ounce supply of heroin for

$750 from a supplier affiliated with a Mexican DTO. They were then free to sell it with no operational support, guidance, or oversight from the DTO.

Illicit drug markets involve hundreds, if not thousands, of loosely affiliated organizations, gangs, groups, and individuals, all in business to make profits. How the actions of these heterogeneous agents are coordinated, or synchronized, is important. This statement does not diminish the importance of the global or organized nature of the drug economy. Nonetheless, many sales operations are only loosely, if at all, affiliated with larger groups and operate almost entirely outside any control. In the primary author's ethnography, an important observation was how little influence the dealer's supplier had on day-to-day operations. Maintaining autonomy, the dealer was only dependent on his supplier for material, i.e., heroin. Similar to the organization of a large intelligence agency, or terrorist network, operational activity in illicit drug markets is compartmentalized.

Top–down management influences local markets, but this momentum also works in reverse. Local market dynamics often shape (or reshape) the larger economy of an illicit drug. Local markets respond and adapt to what local dealers do, to local demand, and to changes that happen locally. Unlike organizational directives that "trickle down," this type of endogenous bottom–up activity evolves in seemingly spontaneous ways, making it exceedingly challenging to understand or anticipate. This mixture of organization and independence promotes nonlinearity and results in complexity (Caulkins and Reuter 2006; Hough and Natarajan 2000). Crack cocaine and methamphetamine use are two modern examples of trends that emerged in this manner.

Cocaine cartels did not invent crack. An anonymous group of entrepreneurial mid-level drug dealers invented crack to increase profits from the product they were selling locally. This innovation completely reorganized cocaine sales, along with HIV and other associated health risks (Singer 2006). Outlaw motorcycle gangs were the first to use, produce and distribute methamphetamines. However, based on a steady increase in popularity (i.e., local demand), large-scale Mexican DTOs began producing, importing, and selling methamphetamines.

The history of crack and methamphetamines is a dramatic example of the power of local market dynamics. In both instances, local demand set in motion macro-scale restructuring. Simply stated, in many instances, what happens in drug economies emerges from low-level interactions and feedback, reconstituting the nature, function, and structure of the larger system.

A first step in realizing the potential of this local dynamic perspective was to use this "bottom–up" approach to understand Denver's heroin market, the conceptual objective of the IDMS project.

The methods of this project involve the descriptive findings from the background ethnography. This data is then contextualized through an understanding of complex adaptive systems, and how such systems are researched. Once the data and conceptual framework are outlined, details are provided on the model building processes we used and how data were extracted from the ethnography to inform ABM development. Finally, the model, initial conditions, and experimental results are discussed.

Methods

It is important to recognize that ethnographic research describing local factors associated with the operation and adaptation of local illicit drug markets is not new. Since the 1960s, researchers have described the roles (Adler 1985; Agar 1973; Johnson et al. 1985; Preble and Casey 1969; Reuter et al. 1990) and interactive factors (Agar et al. 1998; Bourgois 1997; Caulkins 1997; Hamid 1991a, b; Johnson et al. 2000; Koester 1994) that shape behavior in drug markets. However, no one has explored how these micro-interactions scale-up to produce macro-level patterns, or how such interactions constitute the larger system. This project integrates ABM to address this specific limitation.

In the mid-1990s, one of us (LH) conducted ethnographic research in an open-air drug market in Denver, CO through a number of research projects funded by the National Institutes of Health, National Institute on Drug Abuse. This work, summarized in the ethnography *Junkie Business: the Evolution and Operation of a Heroin Dealing Network* (Hoffer 2006), describes how two homeless heroin users developed and managed a full-time business selling heroin.

The data for the ABM presented here were extracted from *Junkie Business*. The portion of the ethnography re-analyzed relates to the operation of the Larimer area open-air heroin market, from which the dealers' business emerged. During the ethnography, a natural experiment occurred in which the police, in combined effort with other city groups and organizations, effectively "closed" the Larimer area drug market. To understand the market's operation before, during, and after this intervention, the authors present it as a complex adaptive system (CAS) (Holland 1995, 1998; Waldrop 1992). Before addressing what affected this perspective, we present details of the case.

Denver's Heroin Market, Circa 1990–1993

The operation of the Larimer area heroin market involved three primary groups of actors: immigrant sellers, local junkie brokers, and customers. Before 1993, this market operated in a state of "dynamic stability," with agents mutually benefiting from their relationships with the other agents. The Larimer market was an "open-air" drug market, meaning customers did not need an introduction to purchase drugs and could walk or drive into the area and buy heroin from one of two sources: directly from a seller or indirectly through a local junkie broker. Even though most people who concerned themselves with these matters (e.g., the police, social service and health care providers) knew drugs were sold openly in Larimer, the area was also home to Denver's homeless and transient populations. The considerable number of people on the street disguised these activities. Private heroin dealers, who were not part of this Larimer "scene," also had an integral role in the market's operation and eventual transformation. We will discuss these dealers in greater detail later.

The most visible heroin sellers in Larimer came from Central America. They did not use heroin. Mexican mafia organizations recruited sellers and exploited them as labor. These organizations controlled the city's heroin supply. Typically, sellers stayed "in business" for short-term profits and for a limited time. Working as part of an organized syndicate, sellers made money based on a daily sales commission. Immigrant sellers dominated the market, but they had unsophisticated sales strategies; they stood on the street and asked people who passed by if they wanted to buy drugs. Based on these public and primitive methods, sellers often made themselves targets of arrest by the police.[2]

Beyond selling heroin, sellers had little involvement or interest in the lives of customers, or in developing relationships with them. Few sellers spoke English beyond the minimum needed to sell heroin or other drugs. This was a closed community. Most sellers did not use drugs and looked down on, depersonalized, and mistreated customers, viewing them as an economic means to an end. As a result, sellers often cheated customers by ripping them off to make a little extra money. Anyone could buy heroin from a seller in Larimer, and if a customer had no other options or desired a quick, no-nonsense, anonymous sale, they went to a seller. But Larimer had another popular option for heroin sales.

Among the homeless loitering in the streets of Larimer existed a relatively small but active group of local junkies.[3] As heroin users who lived on the streets, junkies knew the detailed infrastructure of the market. They knew who the sellers were, where to find them, and when sellers were on the streets. If a customer wanted to purchase heroin using a broker, transactions were indirect. Customers would give their money to the broker, the broker would purchase heroin from a seller, and then the broker would return to the customer with the heroin purchased. Brokers required "payment" for their services and, because customers and junkies were heroin users, customers often paid junkies by injecting drugs together. In other words, junkie brokers would receive a small portion of the liquefied drug from a customer during the process of injecting (Koester and Hoffer 1994). This tax, referred to locally as a "kick-down," was how the local junkies maintained their addictions (Koester 1994). Brokers knew customers and had no language or other cultural barriers interacting with them. Before living on the streets, brokers were ordinary customers. In moving to the streets they did not sever relations with their peers. In fact, as brokers, they could improve these relations by acting as third parties.

Brokers stood less of a chance of immigrant sellers cheating them because the drug market was their "home." Sellers understood that brokers could bring them business or, if mistreated, steer customers away from them and damage their reputations.

Ironically, despite the fact that brokers could easily cheat customers, they were less likely than sellers to do so. Local junkie brokers were a relatively small and highly connected group of users. They all knew and relied on one another to meet their basic needs, both for heroin but also for more instrumental resources like food and shelter. Although this group had no formal leadership, they occupied a small geographical area, and communication traveled rapidly within the group. If a junkie consistently cheated a customer, their fellow junkies suffered because next time the customer came to purchase heroin they would be less likely to use a fellow broker to purchase drugs. As a result, the group enforced fairness. Customers also avoided cheating a junkie. If they did so, it jeopardized their chance of using another junkie next time they came to Larimer. The most important benefit to customers in using a broker was safety.

Using a broker effectively insulated both sellers and customers from arrest because the broker made the heroin transaction. Although such instances were rare, brokers arrested typically did not carry large enough quantities of drugs[4] or money to receive long, if any, jail time. Arresting

[2] It should be noted that arrest tactics had little long-term success in disrupting market activities, because after sellers were arrested they were deported. Once back in Mexico, or their home country, they would make the trip back to Denver and resume their job selling heroin.

[3] The authors do not use the term "junkie" in a derogatory way. Rather this was the term the group self-reported.

[4] Because brokers used drugs immediately after obtaining them in transactions, they rarely possessed drugs. If they were caught with drugs it was usually an amount intended for personal consumption, not distribution.

brokers also had no long-term influence on the market because police only removed indirect participants in the distribution process. Police rarely arrested brokers;[5] by spending all day on the streets, brokers became familiar with police tactics and they knew who the real sellers were. Customers coming to the area quickly learned who the brokers were. As a result, police had a difficult time infiltrating the system by posing as either customers soliciting sales from brokers, or as brokers soliciting sales from sellers.

Over time, interactions between sellers, brokers, and customers developed into an arrangement of mutual dependence and cooperation. Customers who did not wish to pay the heroin tax could purchase heroin directly from a seller, a quick and anonymous transaction some customers preferred. Immigrant sellers clearly benefited from direct transactions with customers. Sellers also benefited from brokers bringing them business, as an enterprising broker could bring them a considerable number of customers. Sellers could also access customers through brokers who might otherwise be cautious of going directly to a seller. Because many customers did not trust sellers, they could use a broker, thereby decreasing their chance of being arrested and getting ripped off, both important considerations. Finally, brokers benefited from their unique position in the market and in developing good reputations with both customers and sellers. Brokers also clearly benefited from open communications and maintaining strong ties with other brokers.

It is important to acknowledge that the relationships described had no basis in mutual trust, communal feelings, or empathy, although some relations in time became personal. Interactions that occurred between sellers, brokers, and customers were fundamentally pragmatic and motivated by individual economic self-interest. Over time, intra-group norms emerged, as did punishment for non-compliance (i.e., a local junkie who consistently ripped off customers would eventually be socially ostracized by other junkies). Nonetheless, all the players in the market operated in autonomous ways, motivated independently. The symbiotic connection was a byproduct of mutual economic self-preservation, not affinity.

Secondly, the authors' research delineates brokers and customers as distinct social groups, but this distinction was somewhat artificial. Customers commonly recognize brokering as a strategy to reduce the cost of their own drug use. Brokers in Larimer were distinct only because: (1) their primary access to the drug came from brokering, (2) they spent most of their time with other homeless heroin users who engaged in similar activities, and (3) they spent most of their time in the Larimer area. But this "community" had porous boundaries, meaning that if a heroin user with a home decided to broker heroin sales to reduce the cost of addiction, they were welcome to do so. Junkies with homes maintained their membership in the community of brokers in several ways. These junkies used heroin with others in the networks through which the brokers survived and also participated in the informal exchange relationships that made up broker networks.

Police saw "Mexicans" (i.e., the immigrant sellers who operated on the streets) as the only relevant group associated with the distribution of heroin (and other illegal drugs) in the city, but this inaccuracy had important consequences. The organization of the Larimer area heroin market, and subsequent homeostatic relations between actors, was not a function of central organization. This observation was critical in casting the Larimer market in terms of a complex adaptive system. In other words, elements imposed by both the vertical integration of the Mexican DTOs and conventional forces of supply and demand contributed to how the market operated, and yet neither exclusively justified the markets sustainability or stability. Juxtaposing formal and mechanistic understandings of market behaviors, activities in the Larimer market were organic, meaning they were self-organizing, self-correcting and solidified through the social ties of the actors.

Closing the Market

In 1993, Larimer abruptly changed. As a continuation of urban renewal efforts already flourishing in lower downtown, the city decided to build Coors Field, home of the Colorado Rockies major league baseball team, on the border of the Larimer area drug market. As one of the few areas of undervalued and undeveloped real-estate adjacent to the downtown business district, Larimer was ideal for redevelopment. With popular support for the new stadium from the city, state and region, the homeless (and drug market) did not stand a chance. It is important to recognize that the Larimer area has no official residents. Other than the homeless, no one lived in this area of town. As a result, the media largely ignored its transformation. Within just a few years (1993–1995), the Larimer area was "cleaned-up" and transformed, at least superficially.

During this time frame, through the uncoordinated yet dedicated efforts of a number of different groups (i.e., the police, parks and recreation department, and homeless shelters), the numbers of street-people were drastically diminished in Larimer, permanently. Without the homeless, only immigrant sellers and brokers remained on the streets, primarily because neither had resources to go elsewhere. As a result, police efforts started to have more impact on open-air sales.

Immigrant sellers responded in two ways. First, they varied their locations on the streets. In other words, instead

[5] The police rarely arrested brokers because they did not meet the profile of drug dealers in the area.

of standing on the same corner every day they moved locations to make it more difficult for the police to find them. Second, some immigrants left the area altogether. Some went to other areas of the city where their presence on the streets was less noticeable while others migrated to more private venues, switching to a beeper system to fill orders and make sales.

Unlike immigrant sellers who were required to change their tactics, brokers did not have to significantly alter their activities. In other words, customers still came to Larimer to purchase heroin and were still able to find brokers. Brokers maintained contacts with immigrant sellers during this time, although these connections were more difficult to maintain as the immigrants moved and/or relocated. However, during this interim period brokers had another ready access point to fill orders for heroin. As former customers, in their interaction with current customers and through communication networks with other brokers, many brokers had and maintained contacts with private dealers who resided outside the Larimer area.

In general, private dealers were a valuable resource because they usually made better deals and sold higher potency heroin than could be purchased on the streets. Residing in neighborhoods unassociated with open-air drug sales, most private dealers' businesses were invisible to the police. In fact, occasionally brokers used private dealers instead of immigrant sellers when brokering sales even before Larimer was under pressure. However, most brokers did not take full advantage of such opportunities for one important reason: it jeopardized their continued livelihood. If either a customer or private dealer became aware that a broker was making consistent sales for a customer, it was in the interest of both the customer and dealer to, in effect, cut out the middleman, i.e., the broker. Inevitably, brokered sales using private dealers would ultimately result in the broker losing the customer to the dealer. Nonetheless, as Larimer was under pressure this was an important short-term strategy brokers employed to fill customer orders. This option for brokers was a vital component to the heroin market's successful and largely uneventful transition during the Larimer area clean-up effort. Once brokers reestablished connections with immigrant sellers, and things settled down in the area, business returned to normal, although the area was forever changed after the clean-up. Without the cover of large populations of homeless, after 1995 sellers and brokers needed to be more cautious.

Paradoxically, in a review of the available drug trend indicator data for Colorado, the transformation of the Larimer market did not register via traditional economic indicators. In other words, based on the primary author's research with customers and dealers in the market at the time, heroin price, purity, and sales unit sizes remained constant. With more brokers operating during the clean-up and changing a "kick down," one could argue that the "cost" of heroin increased slightly for customers over this time period. However, the aggregated effect of this change was negligible because the market's adaptation was so rapid.

Drug Markets as Complex Adaptive Systems (CAS)

This paper suggests Larimer and other local illicit drug markets operate as self-organizing *complex adaptive systems* (CAS). As a science, Complexity theory is concerned with understanding precisely these systems through answering the fundamental question, "How could the decentralized local interactions of heterogeneous autonomous agents generate the given regularity [in the system]?" (Epstein 2006: 5). This shift in perspective has important implications for how markets are researched, as well as the analytic tools required to understand them.

A self-organizing CAS is a type of social system directed by the micro-level individual interactive behaviors of "actors" occurring within a dynamic environment (Conte and Gilbert 1995; Conte et al. 1997; Doran and Gilbert 1994; Epstein and Axtell 1996; Gilbert and Conte 1995; Gilbert and Toritzsch 1999; Holland 1995, 1998; Marney and Tarbert 2000; Sawyer 2003; Schelling 1978; Waldrop 1992). Interactions between actors, or actors and the environment, are non-linear and non-reducible via aggregation (Agar 1999). The environment is proactive in a CAS, both shaping and being shaped by how agents behave. The self-organizing property of a CAS acknowledges that there is no centralized pre-existing infrastructure or organizational framework that directs it. Rather, outcomes are endogenous and based exclusively upon the system's internal momentum. Borrowing from Non-linear Dynamics and Complexity theory, a CAS is "emergent," operating solely from its members interacting with the environment (Epstein 2006).

As with natural ecosystems, not all interactions between agents in a CAS are meaningful. Some activity has little or no affect relative to the dynamics of the system or its output. Other times, small changes to the system result in major repercussions. A related feature of a CAS is that it is dynamic, meaning constantly active. Similar to when an ecosystem is described as "in balance," "stable," or "in equilibrium," such states are not necessarily fixed or perdurable.

Finally, based on its lineage from Complexity theory, a CAS borrows elements from Chaos theory (Sawyer 2003, 2006). However, this does not imply disorganization. On the contrary, it suggests spontaneous organization (Waldrop 1992). As a result, within the context of local heroin markets, hierarchy and formal structure can be incorporated to varying degrees within a CAS. As a caveat, this is now one of many features contributing to the systems

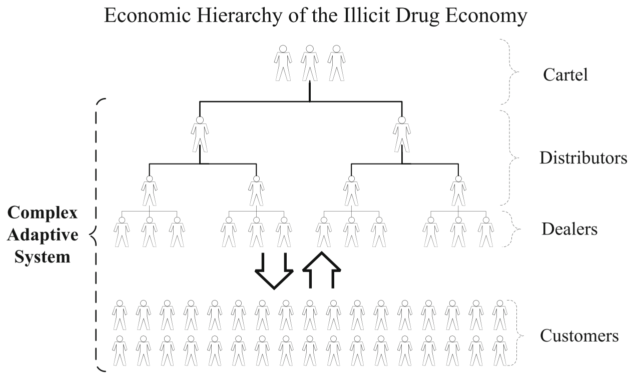

Fig. 1 The generic structure of an illicit drug economy noting that below the organized framework of a cartel such economies function like a complex adaptive system

overall operation. Conventional market assumptions of linearity and rationality are relaxed. Using a CAS model, the realities of a local drug market are decoupled from a priori economic assumptions, allowing more equitable inclusion of behaviors, factors, and contextualized interactions (see Fig. 1). Recognizing this flexibility, research on emergence using ABM is rapidly becoming a scientific field unto itself (Bankes 2002; Bonabeau 2002; Carley 2002; Conte 2002; Holland 1998; Waldrop 1992; Wolfram 1986). Research in public health is also beginning to adopt these tools to inform our understanding of interventions and their unintended consequences (Green 2006; Leischow and Milstein 2006; Lempert 2002; Levy et al. 2006; McLeroy 2006; McManus 2002; Sterman 2006).

Modeling a CAS

To evaluate a CAS, researchers simulate its operation through time. This requires the researchers to construct the system using the available data. In this project an agent-based (a.k.a multi-agent) modeling (ABM) approach was used. Agents are virtual objects reflecting specific states and behaving according to pre-specified rules. Technically, an agent is a computer program (Gilbert 2007). In this project agents were developed to represent actors in the Larimer heroin market. For example, “customer” agents (see below) were designed to represent heroin users. Customers existed in satiated, craving, or withdrawal states and could use, search for, and purchase heroin. Transitions in states and behaviors were patterned, i.e., programmed, by converting ethnographic narratives into decision trees and computer algorithms.

Ethnographic data were well suited to ABM programming because it focused on the micro-interactive behaviors of dealers, customers, and other groups operating within the market. This level of granularity was important because it included individual decisions, heuristics, behaviors, and memory, as well as changes in decisions based on interactions. In ABM research it is important to emphasize that the agent is programmed with the rules that generate its behavior when the simulation is run. Outcome data express the aggregated behaviors of agents. The environment in which agents are placed is also programmed. Ultimately, “The aim of agent design is to create programs which interact ‘intelligently’ with their environment” (Gilbert and Toritzsch 1999, p. 158). In this way, ABMs build the system from the ground up and system outcomes are ultimately the product of agents.

Although we selected ABM to maximize the utility of our ethnographic data, it is important to recognize other simulation techniques have a longer tradition of use in social science applications. For example, system dynamics (SD) is a particularly powerful modeling tool that relies on conceptualizing an entire system, incorporating stocks and flows of system variables, and understanding system feedback loops. However, a fundamental weakness in using SD for modeling local drug markets is that it relies on aggregate data of the total system. Because heroin users and dealers are hidden populations, valid data concerning stocks and flows of local illicit drug markets simply do not exist. Proxy data such as treatment entry statistics, drug price, or emergency department mentions are difficult to trust and challenging to interpret in this context. The only previous attempt to use SD modeling of a heroin market (Levin et al. 1975) was highly criticized for these reasons. On the other hand, methods such as process modeling allow detailed description at an individual level, but the interactions and adaptive consequences of interactions are beyond the assumptions identified in the process models. In such simulations agents do not adjust, adapt, or upgrade behaviors based on either previous information or specific situations presented in their environment.

It is important to acknowledge any advantage in flexibility ABMs hold over other modeling methods disappear if links between the data and agent development cannot be audited. A critical benefit using ethnographic data to program ABMs relates to the depth and nuance the data provides in this endeavor. ABMs essentially rely on programming social processes and then using such processes to generate behavior, and output.

> Complex models require numbers. But it is not so much a question of how to measure phenomena; instead, it is a question of how to express qualities learned through anthropological research, using functions instead of words as the language for that expression. (Agar 2001, p. 364)

Here the benefit and descriptive power of ethnography can be fully exploited. For example, in many drug use studies, including those of illicit drug markets, a common and important measure is "frequency of drug use." Traditional survey research methods collect frequency of use data in preset formats, (e.g., daily, weekly, monthly, lifetime). Heroin use by agents in our model was determined very differently and by incorporating a more extensive set of elements, including: (1) the drug's pharmacokinetics and pharmacodynamics (i.e., creating a dynamic level of "heroin" in an agents system); (2) an agent's drug "habit" (i.e., specifying a targeted amount of heroin the agent wanted to use); (3) defining the availability of the drug and (4) including the means to purchase it. If an agent obtained excess funds, it could purchase and use increased amounts of heroin, thereby increasing its drug habit and potentially using more frequently. This, in turn, could lead the agent to exhaust its funds and enter a withdrawal state. A desperate need for money could also potentially lead the agent to crime.

This, and other chains of consequences, are not obvious and are difficult to identify, represent, or model from survey research (Byrne 1998; Goldspink 2002). Converting decisions and behaviors identified ethnographically into dynamic probabilities allowed the authors to intuitively reproduce and explore causal paths. Unlike static models, ABMs allow agents to modify decisions and behavior based on past experience and/or new information. For instance, each customer agent had an individualized list of drug dealers and/or market locations to purchase heroin. These lists were continuously updated by information collected by the agent. If transactions with particular dealers end up being unsuccessful, that dealer was moved down an agent's list and the probability of using them diminished.

Procedures

Inherently transdisciplinary in nature, computational modeling requires close collaboration. The research team, which included a social scientist, computer programmer/statistician, and mathematician, jointly evaluated all agent schematics, model parameters, and logic to insure fidelity and de-bug computer code. However, as with all computational modeling projects the IDMS project bears the signature of the methodology used to inform the model. How the ethnographic data was extracted and utilized was critical.

In some instances, narrative and descriptive accounts directly informed programming the application. When possible, behaviors, how activities were organized, decision-making processes, interactive activity, and relations between agents were programmed as described by participants. For example, private dealers described the process of using brokers to gain introductions to customers. Behaviors were also programmed based on participant observation. For example, witnessing street sellers being relatively immobile when selling drugs and other observations of the actors within their environment made critical contributions to the validity of the data (see Hoffer 2006) and model.

Ethnographic data was also extracted after it had been processed analytically. Such findings are not accessible using other methods. For example, the explanatory frameworks detailed in *Junkie Business* required considerable fieldwork, bringing together multiple instances and examples of behaviors. This process involved interpreting relationships embedded in the market such as the "street-brokers" role. Brokers were defined as a social group by interviewing, observing, and carefully investigating a broad range of issues, i.e., *thick description* (Geertz 1973). These findings produced a composite representation that was accessible to programming. In other words, the ethnography allowed the behaviors of brokers to be mapped by their interactions and the environment.

Agent probabilities were translated into model parameters. This translation was a two-step process: First, data were structured to identify the parameters necessary for the model. Second, calibration of parameters was conducted to match known marginal values. We monitored global characteristics such as means, standard deviations and shapes of histograms for several variables over the lengths of the simulations to make sure that they were within the reasonable range. In this way, we balanced simplicity (i.e., refraining from introducing unnecessary noise) and realism (i.e., ensuring that the collective behavior of all agents reproduces believable results). Some parameters varied by agent while others were fixed for entire agent groups. For some parameters, values were unknown and could only be estimated from the data (see "Limitations"). For example, the probability that a customer knew a private dealer was estimated from the data, while the threshold for entering a "desperate" state was calibrated to produce the observable rates of drug arrests and treatment admission. Using this hybrid combination of ethnography and ABM prospectively, researchers could accurately guide and target research questions to better calculate these estimates.

The Market Model

The IDMS project incorporates six different agent types. Constructed to reproduce the operation of the market, the behaviors focus on heroin sales and consumption. *Customers*, *brokers*, *sellers*, and *private dealers* are the most behaviorally complex agents. These agents can learn about market, change their level of addiction based on heroin use, choose transaction partners, and modify their activities based on past experiences. *Police* and *homeless* agents are less complex. These agents are used more as proxies for market conditions and are “reflexive” in design. Agent behaviors are outlined below:

1. *Customers*: Customers are the model’s most complex agents. All customer agents purchase, use and have addictions to heroin. Each agent incorporated pharmacodynamic characteristics that allowed their addiction to grow or diminish based on their use. All customers have an inventory of heroin that diminishes when they use. To use heroin, customers must purchase specific amounts of the drug based on its full retail price (e.g., a gram for $130). Retail drug prices were extracted from the ethnographic data. Customers attempt to use the amount of heroin that most closely matches their addiction level, i.e., their targeted use amount. In purchasing drugs, customer agents can *purchase* their targeted amount or as much as possible. Customers receive an income replenished weekly, bi-weekly, or monthly. They can also receive money randomly. Customers keep track of the agents (sellers and brokers) they purchase drugs from and update lists of where to go to purchase based on previous successful or unsuccessful sales.
2. *Brokers*: Like customer agents, broker agents also use heroin. They interact with customers by transporting money to sellers and returning to customer agents with heroin. Brokers do not have incomes, nor do they purchase heroin with their own money. They only receive heroin through a tax on the drug they purchase for customers. Once they receive heroin from customers they use it.
3. *Sellers*: Seller agents do not use heroin. Each has a given inventory of heroin to sell. For all transactions, sellers charge and receive the full retail price for the drug. Sellers stop selling when they are out of drug or when their shift ends, whichever occurs first. If sellers are arrested they are sent to jail and removed from the market. The length of time a seller is removed is linearly correlated to the amount of heroin they are arrested possessing.
4. *Private Dealers*: Private dealer agents also sell heroin in standard units and for the full retail price like sellers. However, a private dealer operates outside the open-air (public) market environment. Private dealer agents only sell heroin to customers, or brokers, they know. A broker is the only agent that can introduce a customer agent and a private dealer.
5. *The Police*: Police agents patrol the market, randomly inspecting and subsequently arresting agents who posses heroin. Police “busts” are represent by short-term increases in the numbers of police agents patrolling the area, and by altering their inspection and arrest rates.
6. *The Homeless*: Homeless agents take no active role in the market or its transactions. Rather, homeless agents provide “noise” in the market by populating it. Police treat homeless agents as if they were sellers, brokers, or customers.

All agents interact on a grid in space designated public or private. In public space, representing the Larimer open-air drug market, all agents freely moved and interacted within this space. Agents were only able to “see” other agents in public space. Customer and private dealer agents resided in private space. When customers wanted to purchase heroin they either traveled into the public space (i.e., open-air market) or directly to a private dealer known to them. Private dealers only resided in the simulation’s private space.

Initial Conditions

Unlike theoretical ABM, the IDMS had basic estimates to set initial conditions. For example, the area of the simulation represented a square geographic area that was a half-mile by half-mile in size. To determine the number of customers to populate the model, the authors worked from estimates of brokers and street-sellers. These groups were smaller and easier to estimate from the ethnography. The model was then calibrated with different numbers of customers and ratios of failed and successful deals were evaluated. The final version of the model included 345 agents: $n = 200$ customers, $n = 25$ private dealers, $n = 20$ street dealers, and $n = 100$ homeless agents. The number of street brokers was varied from zero to 50 (see below). The public area of the model was also “patrolled” by one police officer. This agent moved around the market, inspected agents randomly within a 100 ft. radius, and removed agents who were found with heroin in their possession. The number of police agents was varied for experiments (see below). Police agents removed other agents for a time according to the amount of heroin found in the agent’s possession, i.e., the more heroin, the more time. After serving the “jail term,” agents returned to the market.

Results

Outcomes in ABM research represent the aggregated output of agent behaviors. Because the researcher controls the environment, ABMs allow a researcher to set up virtual experiments, such as comparing two scenarios with different numbers of agents or different behavioral parameters. To extend the ethnography, model experiments concentrated on two research questions: (1) quantifying the role of the broker relative to the market's output, measured by drug-related revenue; and (2) determining the influence police "busts" had on the market's long-term function, market dynamics and agent behaviors. Experiments were descriptive and not intended to formally test specific hypotheses.

Because the behavior of agents is independent, each simulation run generates unique outcomes. To identify trends, each 12-month scenario was replicated 50 times. Data shown at daily time-steps represents average values for agents. All graphs start at day 100 because the first 3 months of each simulation represented a transient state occurring prior to the quasi-equilibrium that emerged.

Figure 2 shows the number of daily customer transactions by seller in the absence of street brokers. In addition to noting the number of transactions the number of heroin units sold is also indicated. Differences between the number of transaction and number of units sold slightly increases over time, indicating a change in customers' purchase amounts while their drug habits are maintained. Sales involving private dealers are low because the primary way in which customers learned of private dealer locations was through the activity of brokers.

The second figure shows daily customer transactions by seller when brokers are present in the market, Fig. 3 includes 25 street brokers and Fig. 4 includes 50. Street brokers change market dynamics by increasing the total amount of drugs sold and enhancing the role of the private dealers. After approximately 90 days, private dealer sales overtake market sales from street dealers, ultimately reducing the number of sales by street dealers' by almost half. These results are dramatized when 50 street brokers are in the market. This illustrates the convenience of knowing a private dealer in making the drug more accessible. Interestingly, the brokers inclusion in the market results in more transactions; however, doubling the number of brokers does not markedly increase transaction totals. Overall, when the number of street brokers is very high we observe the brokers make more transactions than street dealers. This does not mean that the role of the street dealers is drastically decreased. The brokers still use street dealers as a source of drug supply.

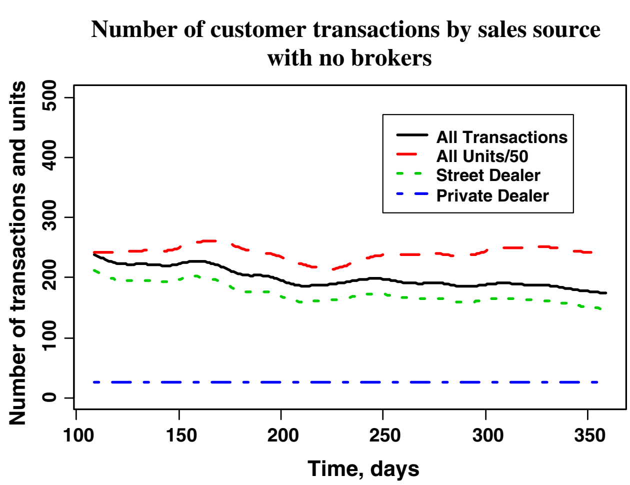

Fig. 2 Number of daily customer transactions by seller when no street brokers are present

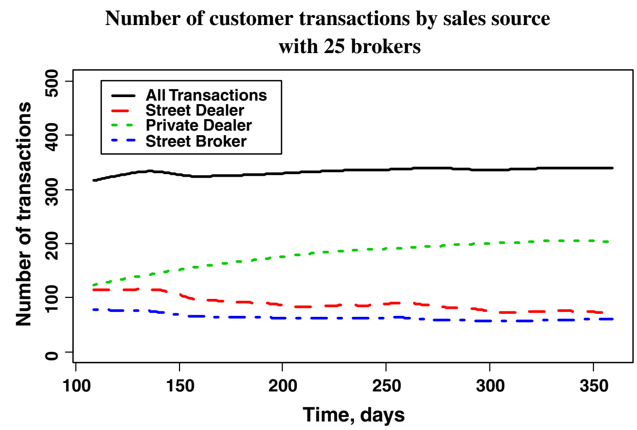

Fig. 3 Number of daily customer transactions by seller when 25 street brokers are present

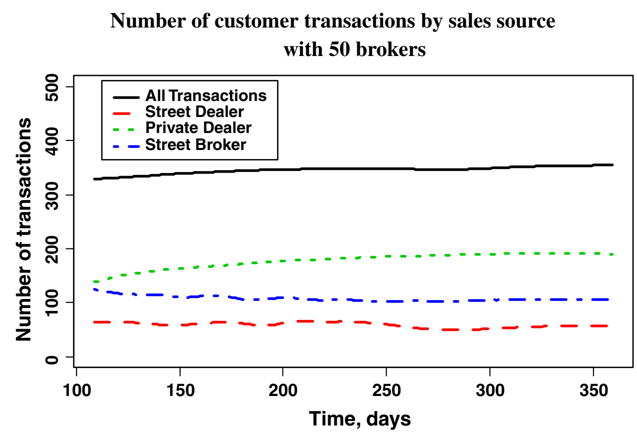

Fig. 4 Number of daily customer transactions by seller when 50 street brokers are present

Figures 5 and 6 involve evaluating the effect of a drug bust on market dynamics. On day 120 of the simulation we added 29 police agents into the market (n=30) for a 24-h period. For this experiment we included 50 street brokers.

In the short-term, the drug bust scenario had an effect on all market agents. Figure 5 notes a sharp reduction in street dealer sales at the time of the bust, i.e., as seller agents were arrested. However, simultaneous to this change, sales with private dealers increase. Although the bust results in a sharp short-term drop in total transactions in the market, brokers play a key role in mitigating effects. In Figure 6 we see during the bust, brokers transfer customer sales from street sellers to private dealers. In fact, a drug bust can

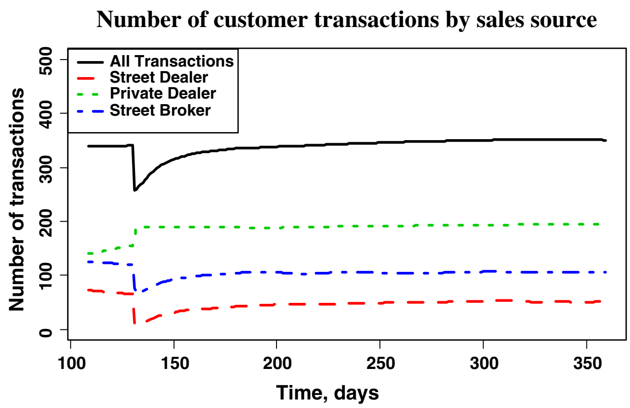

Fig. 5 Number of daily customer transactions by seller when 50 street brokers are present and a police bust occurs at day 120

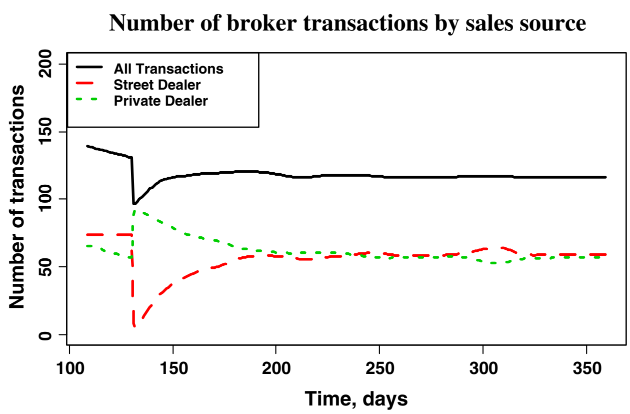

Fig. 6 Number of daily broker transactions by sales source

remove nearly all the street dealers with little long-term effect. During these timeframes the market relies on brokers transitioning customer sales to private dealers. After the incarceration of street dealers ends and they return to the market, they are unable to generate the same revenue as a large portion of their "business" has been taken over by private dealers.

Limitations

Like other modeling efforts, in ABM research the investigator is ultimately responsible for developing the model and model limitations often reflect what the modeler wants, or can, include. Limitations vary in concert with what features of social behavior the researcher decides to model (Gilbert and Toritzsch 1999). The objective of the IDMS project focused on reproducing the operation and history of a local heroin market informed by ethnographic data. Capturing the nuances associated with agent/environment interactions, the simulation involves a considerable amount of complex behavior. However, it is important to acknowledge how this "mirror to reality" is imperfect.

First, agents in this model only interact in limited ways. Customers do not communicate or cooperate with one another, nor do street sellers operate in coordinated ways, e.g. when sellers sell all the heroin they have, they do not go to fellow sellers and get more heroin. Although adding these interactions would have increased the simulation's realism, decisions and computational limitations constrain the behavioral repertoire of agents in ABM research.

In our simulation customers could not purchase heroin for less than full retail price, nor could they use credit to purchase heroin. The primary author's ethnography details that both these activities were important in reducing a customer's cost for drugs; both also involve dealers closely monitoring sales relationships and customer behavior. In other words, heuristics were available to program. However, incorporating algorithms to reflect elastic pricing and issuing credit would have exponentially complicated agent's simulated interactions and it was decided to include these behaviors in subsequent model extensions, or in a different model.

This simulation focuses on demand and not on supply. Mechanisms for supplying the market with heroin are not incorporated, i.e., when selling agents run out of inventory they are automatically re-supplied. This decision was data driven. Despite high levels of rapport with the heroin dealers in *Junkie Business*, the ethnographer was unable to interview members of the Mexican DTO supplying these dealers with heroin.

Unique features of the Larimer market are integrated in the model and potentially limit its generalizablity. For instance, variations in heroin quality (i.e., purity) are not included. At the time, most of the heroin in Denver was Mexican black tar, of low purity, and supplied from homogeneous sources. Customers had a general sense that heroin sold by private dealers was better in quality than heroin purchased on the street, but substantive reports of purity variations were rare. As a result, agents' assessments of the product are minimal and only indirectly affected decision-making.

Finally, the available data often determines what is modeled. The IDMS project attempted to employ a data-driven protocol, grounding model components in the data. Nonetheless, it must be acknowledged that the original research was *not* originally collected for the purposes of constructing an ABM. Gaps in data were informed by a combination of literature review and consultation with subject matter experts. Such substitute techniques are clearly not ideal. An important secondary objective of this experimental project was to identify prospective research methods combining ethnography and ABM to minimize these limitations in future studies implementing this approach.

Discussion

Experimental results presented are the first in a series using this computational methodology to explore the dynamics of the Larimer area heroin market. Thus far, experiments confirm the importance of the role of the broker in the market, as well as the limited effectiveness of police busts on the marketplace. Combined, these findings suggest that brokers stabilize heroin sales when the police attempt to disrupt market activities by arresting street-based dealers.

One novel policy implication suggested by these results would be to specifically target brokers with interventions, removing them from the market. As brokers do not actually buy or sell significant amounts of heroin, arrest would likely not yield success. Our model already includes brokers being arrested. However, because these users tend to have highly variable heroin habits, limited economic resources, and are homeless and/or live transient lifestyles, maybe other interventions (and/or incentives) might work. Future experiments with our market simulation could identify a functional threshold of brokering activity. In other words, how much brokering (in the aggregate and as an average per broker) is required for the market to successfully adapt to police intervention? Sample size, specific outcome objectives, as well as inclusion/exclusion criteria could then be developed for an intervention. Next, using ABM the potential broker-targeted intervention could be prototyped and evaluated before being rolled-out into the field. After such an intervention is in operation, statistical and ethnographic data could feedback into the ABM to update behaviors, extrapolate potential unintended consequences, and project results. To date, this sort of real-time integrated relationship between data collection, intervention and ABM is yet to be realized. However, the capacity is in place to make it happen.

As a feasibility study, additional contributions the IDMS project makes relate to future research projects integrating ABM. In our project, programming agent specifications that incorporate environmental conditions provides researchers with a novel framework to identify and evaluate parameters essential to market performance. For example, in brokered sales the threshold of transactions occurring before private dealers sold directly to customers was critical. If this threshold were too high customers would be unable to connect with private dealers. Identifying parameters and how they contribute to the function of the system greatly enhances opportunities for future research. Because data collection and analyses are iterative, this type of feedback has particular utility in ethnographic research. In other words, an ethnographer could conduct preliminary analyses using ABM to guide follow-up interviewing and observation. An important next step in complex systems research will be to prospectively collect both the descriptive data required to identify parameters, as well as the systematic data necessary to set them.

Finally, because this project was specifically oriented to an ethnographic case study of a heroin market that operated in Denver, Colorado, 1992–1996, its generalizability needs to be considered. As a feasibility study of a hybrid methodology, this discussion is bifurcated by the product described, i.e., the market model, and the techniques used in its development, i.e., combining ethnography and ABM.

Although this was an ethnographic study of a local heroin market operating in a very specific place and time, the methodology this manuscript describes is entirely transportable. Independent of topic, in ethnographic studies that: (1) describe and situate social behaviors of participants within an environment, and (2) delineate change over time, opportunities exist to integrate ABM. This is because social processes, i.e., what ABMs model, are mandated in connecting these themes. Importantly, programming ABMs using data extracted from ethnography is not forsaking cultural complexity or the relevance of culture. Rather, as in the case presented here, the ethnographer is distilling interactions and/or belief systems that generated the observed outcome(s) of interest for quantification and more detailed analysis. As a potential procedure to observe quantitative output from qualitative inquiry, this method is particularly promising for ecologically oriented anthropologists.

For cultural anthropologists and other researchers using qualitative methods, the process of constructing ABMs from ethnographic data opens exciting new horizons. Specifically, it provides opportunities to quantify outcomes. During the process of building an ABM researchers can identify the data required to produce a verifiable model. Currently, quantitative aggregated data on behavior is only available via epidemiological surveys. Yet these methods alone cannot demonstrate how or why patterns in data occur. As in the IDMS project, ABMs offer a link between ethnographic details, i.e., an explanatory framework, and aggregated outcomes. While this new ethnographic tool needs further refinement to make such quantification commonplace, it offers a unique procedure for detailed investigation and experimentation.

The value of our market model to the field of illegal drug market research ultimately involves *creating a framework in which drug markets can be compared*. Reflecting one of the monumental challenges to this field, the generalizability of the Larimer market model to other illegal drug market contexts is impossible to fully determine. Currently, researchers who ethnographically characterize different drug markets, for different drugs, in different times, and using different theoretical perspectives, are highly challenged in comparative analysis (Curtis and Wendel 2000).

Clearly, drug markets in other geographic settings are unique from Denver. One immediate difference in the Larimer area was the absence of gang activity associated with heroin dealing. But customer, dealers, brokers, and the police exist in almost all local drug markets; in the cases of marijuana and methamphetamines, producers may also exist. In our model, most activities of and relationships between agents are generic. Customer agents representing heroin users have a drug addiction, inventory of drugs, supply of money to buy drug, and an understanding of where to go to connect with dealers or brokers. Broker agents simply mediate heroin sales between buyers and sellers for a tax. With rudimentary behaviors of customers and dealers programmed, organizational and interactive relationships among agents and between agents and the environment (i.e., what makes markets unique) can be compared and contrasted. Future iterations of this hybrid approach can also be designed to link simulation outcomes to community epidemiological indicator data such as drug arrests, treatment entry, and hospital admissions in an effort to track trends. Using ABM to provide a framework for comparing drug markets, dealer's behaviors, and outcomes could greatly enhance the application of data from ethnographic studies of illegal drug markets.

This paper presented an experimental research project that used detailed ethnographic data to simulate the dynamics of a local heroin market and enhance our understanding of this market. While research objectives presented in this manuscript clearly introduce new methodological and collaborative challenges, they exploit the benefits of using this ecological approach to model social systems, evaluate interventions, and project outcomes. As social and behavioral scientists continue to develop ways to express the importance of environmental factors on the behaviors of individuals, as well as how individuals modify their environment, our research supports these objectives through synthesizing ABM and ethnographic research.

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References

Adler, P. A. (1985). *Wheeling and dealing: An ethnography of an upper-level drug dealing and smuggling community*. New York: Columbia University Press.

Agar, M. (1973). *Ripping and running*. New York: Academic Press.

Agar, M. (1999). Complexity theory: An exploration and overview based on John Holland's work. *Field Methods, 11*(2), 99–120.

Agar, M. (2001). Another complex step: A model of heroin experimentation. *Field Methods, 3*(13), 353–369.

Agar, M. (2005). Agents in living color: Towards emic agent-based models. *Journal of Artificial Societies and Social Simulation, 8*(1). http://jasss.soc.surrey.ac.uk/8/1/4.html.

Agar, M., Bourgois, P., French, J., & Murdoch, O. (1998). Heroin addict habit size in three cities: Context and variation. *Journal of Drug Issues, 28*(4), 921–940.

Bankes, S. C. (2002). Agent-based modeling: A revolution? *Proceedings of the National Academy of Sciences of the United States of America, 99*, 7199–7200.

Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences of the United States of America, 99*, 7280–7287.

Bourgois, P. (1997). *In search of respect: Selling crack in El Barrio*. New York: Cambridge University Press.

Byrne, D. (1998). *Complexity theory and the social sciences*. London: Rutledge.

Carley, K. M. (2002). Computational organization science: A new frontier. *Proceedings of the National Academy of Sciences of the United States of America, 99*, 7257–7262.

Caulkins, J. (1997). Modeling the domestic network for illicit drugs. *Management Science, 43*(10), 1364–1371.

Caulkins, J., & Reuter, P. (2006). Illicit drug markets and economic irregularities. *Socio-Economic Planning Sciences, 40*, 1–14.

Conte, R. (2002). Agent-based modeling for understanding social intelligence. *Proceedings of the National Academy of Sciences of the United States of America, 99*, 7189–7190.

Conte, C., & Gilbert, N. (1995). Introduction. In N. Gilbert & C. Conte (Eds.), *Artificial societies: The computer simulation of social life* (pp. 1–15). London: UCL Press.

Conte, C., Hegselmann, R., & Terna, P. (1997). *Simulating social phenomena*. Berlin: Springer–Verlag.

Curtis, R., & Wendel, T. (2000). Toward the development of a typology of illegal drug markets. In M. Natarajan & M. Hough (Eds.), *Illegal drug markets: From research to prevention policy* (pp. 121–152). Monsey, NY: Criminal Justice Press.

Doran, J. E., & Gilbert, N. (1994). *Simulating society: The computer simulation of social phenomena*. London: UCLA Press.

Eck, J. E., & Gersh, J. (2000). Drug trafficking as a cottage industry. In M. Natarajan & M. Hough (Eds.), *Illegal drug markets: From research to policy* (pp. 241–271). Monsey, NY: Criminal Justice Press.

Epstein, J. M. (2006). *Generative social science: Studies in agent-based computational modeling*. Princeton: Princeton University Press.

Epstein, J. M., & Axtell, R. (1996). *Growing artificial societies*. Cambridge: MIT Press.

Forrester, J. (1994). Policies, decisions, and information sources for modeling. In J. Morecroft & J. Sterman (Eds.), *Modeling for learning organizations* (pp. 51–84). Portland, OR: Productivity Press.

Geertz, C. (1973). *The interpretation of cultures*. New York: Basic Books.

Gilbert, N. (2007). *Agent-based models*. London: Sage Publications.

Gilbert, G. N., & Conte, R. (1995). *Artificial societies: The computer simulation of social life*. London: UCL Press.

Gilbert, N., & Toritzsch, K. G. (1999). *Simulation for the social scientist*. Philadelphia: Open University Press.

Goldspink, C. (2002). Methodological implications of complex systems Approaches to sociality: Simulation as a foundation for knowledge. *Journal of Artificial Societies and Social Simulation, 5*(1). http://jasss.soc.surrey.ac.uk/5/1/3.html.

Green, L. W. (2006). Public health asks of systems science: To advance our evidence-based practice, can you help us get more practice-based evidence? *American Journal of Public Health, 96*, 406–409.

Hamid, A. (1991a). From ganja to crack: Caribbean participation in the underground economy in Brooklyn, 1976–1986. Part 1. Establishment of the marijuana economy. *The International journal of the addictions, 26*(6), 615–628.

Hamid, A. (1991b). From ganja to crack: Caribbean participation in the underground economy in Brooklyn, 1976–1986. Part 2. Establishment of the cocaine (and crack) economy. *The International journal of the addictions, 26*(7), 729–738.

Hoffer, L. (2006). *Junkie business: The evolution and operation of a heroin dealing network*. Belmont, CA: Thompson Wadsworth.

Holland, J. H. (1995). *Hidden order: How adaptation builds complexity*. New York: Addison-Wesley.

Holland, J. H. (1998). *Emergence: From chaos to order*. Redwood City, CA: Addison-Wesley.

Homer, J. B., & Hirsch, G. B. (2006). System dynamics modeling for public health: Background and opportunities. *American Journal of Community Psychology, 96*(3), 452–458.

Hough, M., & Natarajan, M. (2000). Introduction: Illegal drug markets, research, and policy. In M. Hough & M. Natarajan (Eds.), *Illegal drug markets: From research to prevention policy* (pp. 1–17). Monsey, NY: Criminal Justice Press.

Johnson, B. D. (2003). Patterns of drug distribution: Implications and issues. *Substance Use and Misuse, 38*(11–13), 1789–1806.

Johnson, B. D., Dunlap, E., & Tourigny, S. (2000). Crack distribution and abuse in New York. In M. Natarajan & M. Hough (Eds.), *Illegal drug markets: From research to prevention policy* (pp. 19–57). Monsey, NY: Criminal Justice Press.

Johnson, B. D., Goldstein, P. J., Preble, E., Schmeidler, J., Lipton, D. S., Spunt, B., et al. (1985). *Taking care of business: The economics of crime by heroin abusers*. Lexington, MA: D.C. Heath and Company.

Koester, S. K. (1994). Copping, running, and paraphernalia laws: Contexual variables and needle risk behavior among injection drug users in Denver. *Human Organization, 53*(3), 287–295.

Koester, S. K., & Hoffer, L. (1994). Indirect sharing: Additional risks associated with drug injection. *Aids and Public Policy, 9*(6), 100–105.

Leischow, S. J., & Milstein, B. (2006). Systems thinking and modeling for public health practice. *American Journal of Public Health, 96*, 403–405.

Lempert, R. (2002). Agent-based modeling as organizational and public policy simulators. *Proceedings of the National Academy of Sciences of the United States of America, 99*, 7195–7196.

Levin, G., Gilbert, E. B., & Hirsch, G. B. (1975). *The persistent poppy: A computer-aided search for heroin policy*. Cambridge, MA: Ballinger Publishing Company.

Levy, D. T., Bauer, J. E., & Lee, H. (2006). Simulation modeling and tobacco control: Creating more robust public health policies. *American Journal of Public Health, 96*, 494–498.

Mabry, P., Olster, D., Morgan, G., & Abrams, D. (2008). Interdisciplinary and systems science to improve population health. *American Journal of Preventive Medicine, 35*(S2), S211–S224.

Marney, J. P., & Tarbert, H. F. E. (2000). Why do simulation? Towards a working epistemology for practitioners of the dark arts. *Journal of Artificial Societies and Social Simulation, 3*(4). http://www.soc.surrey.ac.uk/JASSS/3/4/4.html.

McLeroy, K. (2006). Thinking of systems. *American Journal of Public Health, 96*, 402.

McManus, R. (2002) A new kind of science: Wolfram goes from simple rules to complex forms. *NIH Record,* 1–4.

Preble, E., & Casey, J. (1969). Taking care of business: The heroin user's life on the street. *The International journal of the addictions, 4*(1), 1–24.

Reuter, P., MacCoun, R., & Murphy, P. (1990). *Money from crime: A study of the economics of drug dealing in Washington*. D.C. Santa Monica, CA: RAND-Drug Policy Research Center.

Sawyer, K. R. (2003). Artificial societies: Multiagent systems and the micro–macro link in sociological theory. *Sociological Methods and Research, 31*(3), 325–363.

Sawyer, K. R. (2006). *Social emergence: Societies as complex systems*. New York: Cambridge University Press.

Schelling, T. C. (1978). *Micromotives and macrobehavior*. New York: Norton.

Singer, M. (2006). *Something dangerous: Emergent and changing illicit drug use and community health*. Long Grove, IL: Waveland Press.

Sterman, J. D. (2006). Learning from evidence in a complex world. *American Journal of Public Health, 96*, 505–514.

Waldrop, M. M. (1992). *Complexity: The emerging science at the edge of order and chaos*. New York: Simon & Schuster.

Wolfram, S. (1986). *Theory and applications of cellular automata: Including selected papers, 1983–1986*. Singapore: World Scientific.