Green Niche Market Development

A Model With Heterogeneous Agents

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Supplementary material is available on the *JIE* Web site

Summary

This article introduces a multiagent simulation framework for investigating the emergence of niche markets for environmentally innovative products. It clarifies how consumer preferences, business strategy, and government policy interact during market development. The framework allows investigation of the effects of uncertainty and agents' corresponding coping strategies. We describe the model, illustrate how it works when applied to the case of hybrid cars, and analyze results spanning several policy cases and a range of scenarios that make different assumptions about the heterogeneity of agents. Heterogeneity within each agent class strongly influences aggregate outcomes. Innovative firms can create green products in response to or in anticipation of government regulation, but true green niche markets do not emerge unless there are also green consumers. Niche markets do not go mainstream unless scale economies drive costs down to parity with conventional products. Preferred environmental innovation policies change with heterogeneity assumptions.

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Introduction

Many of us hope that humanity will innovate its way out of current environmental dilemmas. This optimistic view of technology and markets has been serially framed as ecological modernization (Huber 1982), industrial ecology (Frosch and Gallopolos 1989), eco-innovation (Fussler and James 1996), and eco-imagination (GE 2005). Businesses have encouraged this focus on innovation, and governments have adopted a range of innovation-oriented environmental policies.

Consumer behavior has also gained attention as a key driver of environmental problems. At the macro level, changes in the structure of consumption are known to contribute to systematic changes in environmental impacts (Grossman and Kruger 1995). At the micro level, individual product and service choices are known to yield a variety of environmentally significant aggregate outcomes (Hertwich 2005). Moral leaders have encouraged a rethinking of consumer values, but businesses and governments have focused more narrowly on providing consumer information. "Green" consumerism is an emerging force for environmental improvement.

Recent efforts to set priorities for environmental product policy represent a valuable practical step toward better decisions given inadequate knowledge (Tukker 2006). Missing, however, has been much systematic investigation of the interactions among business strategy, consumer behavior, and government policy in establishing green products in the marketplace. Introductory economics courses teach each of these three topics separately in the context of static analysis, but rarely does anyone explore the dynamics, even though scholars recognize the importance of their interactions (Jarvenpaa and Tiller 1999; Sen and Bhattacharya 2001; Rugg et al. 2002; Villas-Boas and Zhao 2005), especially in the product innovation context (Voss et al. 2006). This article targets that gap.

The three forces—producer innovations, green consumerism, and government policies—together offer great hope that society's environmental and economic objectives are reconcilable. Regulatory agencies have a keen interest in fostering the emergence of markets for products that have a smaller environmental impact than existing market alternatives. Yet the individual decisions that govern the emergence of markets for these green products are rife with imperfect information: Governments must formulate regulations despite having incomplete environmental knowledge, firms must sell products in an evolving and uncertain regulatory environment, and busy consumers must make choices without all of the relevant environmental facts at hand.

Viable markets for green products often depend on the early support of green consumers, who constitute an enthusiastic minority among a broader, heterogeneous population of consumers. Green consumers are willing to pay a premium to become early adopters of environmentally preferable products. The trajectory of green product sales is likely to be sensitive to the number of early adopters, the prices they are willing to pay, and the rate at which new product information diffuses through the marketplace.

This article presents a multiagent simulation framework for investigating the emergence of niche markets for environmentally innovative products under conditions of uncertainty. We use a limited definition of uncertainty that includes local ignorance (requiring search efforts), stochastic uncertainty (requiring estimation of expected values), and structural uncertainty (requiring research and adaptation; Morgan and Henrion 1990; Stirling 2003).

The central hypothesis to be tested is whether, under conditions of uncertainty and bounded rationality, the emergence of green product markets depends on the existence of heterogeneous producers and consumers. Secondarily, does heterogeneity affect preferred public policies?

This article applies the simulation framework, which we have named EcoNiche, to the case of hybrid cars, such as the Toyota Prius, emerging as a green niche market in the automotive sector. This application illustrates how the model works and provides an empirical anchor for interpreting and discussing the results.

Method

Available methods for studying the dynamics of regulated, emerging markets each have weaknesses. Case studies can provide detailed narratives of what happened to a particular

product or firm but seek only to explain historical events and do not offer explicit, formal models. Econometric models can provide a firm empirical grounding and an explicit formality but are limited to the study of phenomena for which abundant time-series data exist. System dynamics modeling allows much freedom to set parameter values and explore structural relationships among variables, but it is poorly suited to cases with heterogeneous actors with evolving relationships, and validation is difficult. Agent-based modeling (ABM), the method used here, is a computer simulation technique in which systemic actors are represented by software objects that are allowed to interact and even evolve. The result is a bottom-up view of a complex system, such as a firm or a market. The intellectual origins of multiagent simulation lie in artificial intelligence, cellular automata, game theory, system dynamics, and differential equations. This method is valuable because it allows a natural focus on agency questions, heterogeneous actors, interactions in networks, and the emergence of structure, and because it supports easy strategy and policy experimentation (Axtell et al. 2001). Validation of these models can be a challenge, however.

As always when one is building models, we have striven to keep this one "as simple as possible, but no simpler" (Einstein 1934, 165). The framework we present here employs formal models of consumer, producer, and government interactions and decision making to enable the simulation and analysis of niche markets under alternative policy regimes. Of course, in real markets these processes are more complex and varied. Our formal models reflect levels of abstraction and detail that spotlight certain aspects of the real-world processes that we have found crucial to creating realistic simulations; other real-world details are modeled less closely and left to future work.

We begin with a high-level overview of our simulation framework, including brief, nonmathematical descriptions of how we model the market, environmental knowledge, producers, consumers, and the regulatory agency. Full details are presented in the Supplementary Material on the Web.

The first important aspect of our model is that imperfect information is pervasive. Consumers, firms, and a governmental regulatory agency all make their individual decisions under various forms of uncertainty. For example, to model the environmental impact of market evolution, we associate the production and consumption of products with environmental consequences or footprints. Consumers, firms, and the regulatory agency all lack certainty about these product footprints and must make their decisions at each step despite their local ignorance of environmental consequences, stochastic uncertainty around footprint estimates, and structural uncertainty about future conditions. Furthermore, firms lack certainty about current and future demand for potential products and about the regulatory environment they may face in the future. Consumers lack certainty about all the products that are available and what the environmental consequences of their purchases are.

The second important feature is that actors can take specific actions to reduce their uncertainty to try to achieve more favorable outcomes. We provide a mechanism by which the government and individual firms can carry out research on particular products to reduce their stochastic environmental uncertainty and structural market uncertainty. The better understanding of product footprints that results from this research diffuses out through the consumer population over time. Consumers can act to reduce their local ignorance by seeking guidance from other consumers, from producers, or from the regulatory agency directly.

A third important feature of our model is heterogeneity of actors. We distinguish several types of consumers according to how environmental factors enter into their preferences and how much money they can afford to spend on a new product. Producers also come in several types, which are distinguished by their particular profit-maximizing strategies. Finally, alternative regulatory regimes are characterized by the different policies they pursue in the face of such a heterogeneous marketplace.

It is important to note that in this model the strategies of the agents are set exogenously and do not adapt or evolve, so that what does evolve is the knowledge base for making decisions. Agents interact with one another during the processes of learning about, buying, and selling cars.

The model represents the marketplace as a random network within which consumers and producers search and act, within limits and with information provided by government. We represent the natural environment as a researchable space of sources and sinks. The following sections provide further details on consumers, producers, and government.

Consumers

A vast empirical literature characterizes consumer behavior as heuristic rather than strictly rational, with individuals varying in their preferences, search effort, and brand loyalty, among other characteristics (Wang and Lee 2006). In our model, consumers are heterogeneous in terms of their product knowledge, green preferences, position in the network, and search strategy and effort. A consumer's product inquiry is "Please tell me everything you know about products in this market." Consumers respond fully and truthfully to inquiries from other consumers. Firms also respond truthfully, but they only pass on information about their own products. Consumers use the latest information they have available to update their knowledge. Governments can help by broadcasting fresh knowledge. Consumers rank the product options known to them and then buy the highest ranked product they can afford.

There are several types of consumers in the model, distinguishable by their answers to two questions.

- Does a consumer have green preferences? (no, yes within limits)
- How large is the consumer's budget? (poor, medium, rich)

Producers

In the model, we characterize firms as either *conventional* or *innovative*, depending on their product selection and research strategies. At a high level, conventional firms do not take the risk of offering innovative products or bear the costs of research, preferring instead to maximize short-term profits with an established product. Innovative firms take a greater risk and bear the costs of research but have the potential to establish a new market and reap the associated gains.

Otherwise, the two types of firms have much in common. All firms identify candidate price points using accurate knowledge of the population of consumers, including precise knowledge about consumer budgets. All firms select the price point and product that maximize their expected profits (subject to the firm-type-specific constraints on product type described above). Both types of firm are willing to sustain losses if no profitable product is available. (In such cases, firms select the product that minimizes their expected losses. This is typical at the beginning of the simulation, when production experience is low.) A firm considers both production costs and expected regulatory costs or limits when choosing to make a product; thus, it complies with the law and maximizes profits within the law.

Government

This model includes a broad suite of exogenously specified policy options: perform research, disseminate research results in either a limited or an aggressive manner, tax or ban undesirable environmental outcomes (those with large environmental footprints), and tax or ban undesirable technologies (noxious or inferior production ingredients). Several of these policy options may be combined into policy strategies.

The model characterizes the state of government at any time by vectors of knowledge about environmental footprints of products, research experience, research costs, and (exogenous) policy strategy. Government research costs are subject to a learning curve, so that cumulative experience reduces unit costs. Each policy strategy has associated governmental implementation costs, market costs, and environmental benefits.

Complete Model

Figure 1 provides an intuitive and generic illustration of the complete model of emergence of a niche market for a green product without governmental intervention. Figure 1a sets the stage for a potential niche market. With current technology, a green product could be manufactured and sold to green consumers, but a cheaper

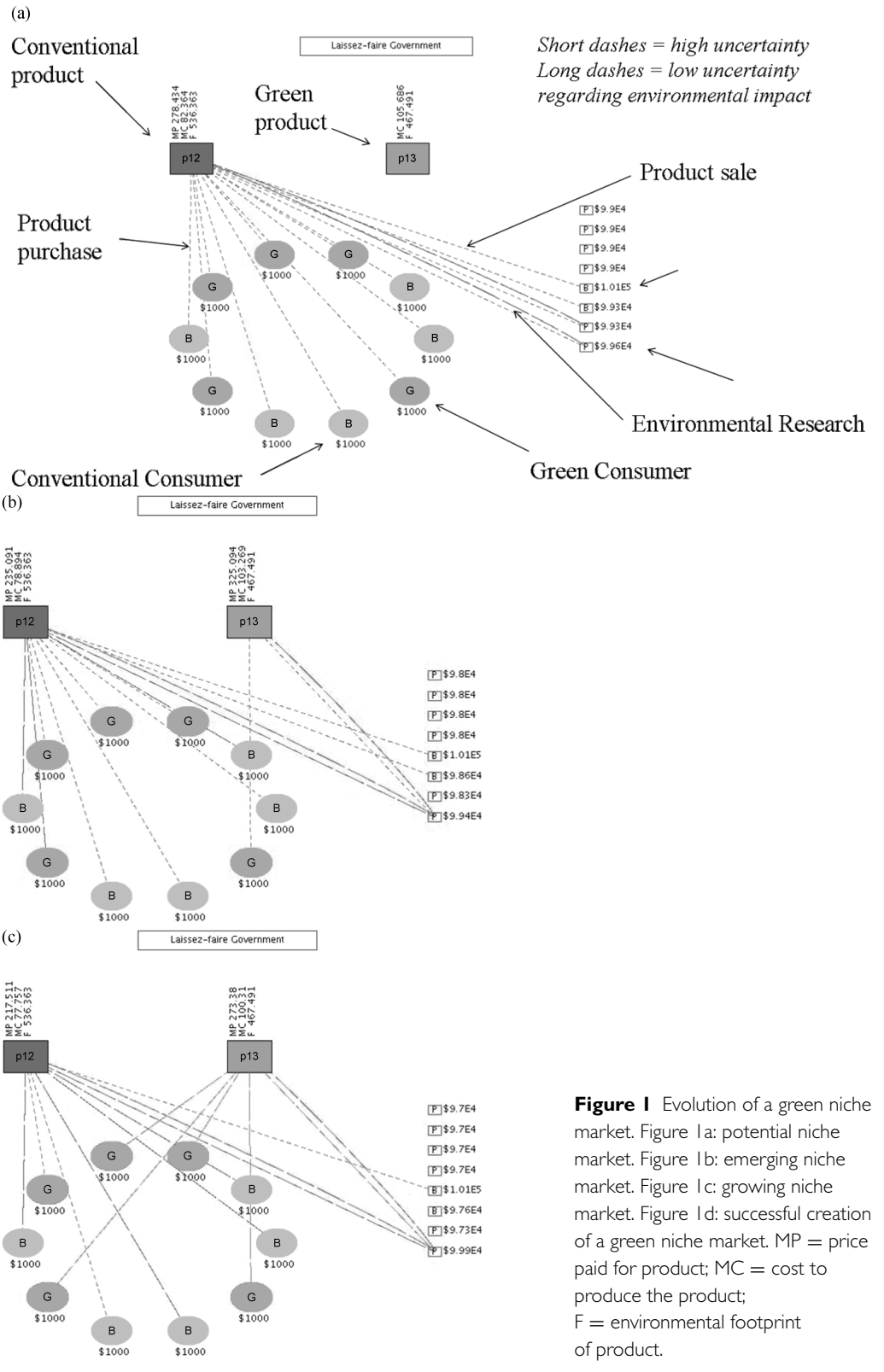

Figure 1 Evolution of a green niche market. Figure 1a: potential niche market. Figure 1b: emerging niche market. Figure 1c: growing niche market. Figure 1d: successful creation of a green niche market. MP = price paid for product; MC = cost to produce the product; F = environmental footprint of product.

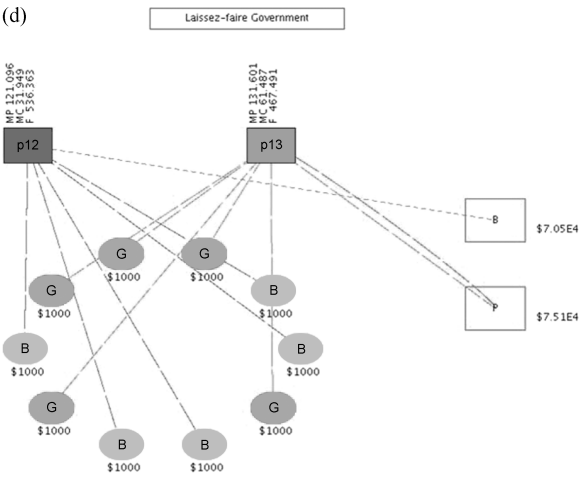

Figure 1 Continued.

conventional product dominates because poor information leaves the two products environmentally indistinguishable. Two innovative firms begin to research the environmental performance of the conventional product. Figure 1b shows an emerging niche market. Innovative firms reveal better information about the conventional product to consumers who ask. A first green consumer encounters this new information and decides to buy the alternative green product. Less knowledgeable green consumers continue to buy the conventional product. Figure 1c shows a growing niche market. More green consumers choose the green product as better environmental information permeates the social network. Conventional consumers ignore environmental factors and continue to buy the cheaper, conventional product. Finally, figure 1d shows the successful creation of a green niche market. Eventually, all green consumers become aware of and choose the green product.

Application to the Hybrid Car Niche Market

One of the most exciting cases of eco-innovation in recent years is the hybrid car, with the Toyota Prius being the exemplar. Hybrids can be dramatically more fuel-efficient than cars powered by conventional internal combustion engines. In 1997, while U.S. manufacturers were producing outsized sport utility vehicles and ignoring growing concerns about global warming and energy security, Toyota and Honda initiated boutique production of small, efficient hybrids. These hybrid cars cost more than conventional cars with similar features, yet certain customers were strongly attracted to them. Demand quickly outstripped supply. A decade later, that is still the case. Production of hybrids continues to increase, even as costs drop and profits rise (Taylor 2006). Toyota has now surpassed General Motors as the world's largest automobile producer (Naughton and Sloan 2007). Hybrids are not yet mainstream, but their niche is expanding, reaching 2.4% of U.S. light-duty vehicle sales as of this writing (Green Car Congress 2008). In U.S. markets, policies to encourage this eco-innovation include consumer tax credits and information on product performance.

What would have happened to this niche market under a different policy regime? What if consumers and producers had behaved differently? What will happen in coming years? The EcoNiche model provides a way to explore this space of "what-ifs." The next section summarizes results of a series of simulations. Key simplifying assumptions include that the automobile market has products that vary only along dimensions of price and environmental footprint, that the entire market is under one government's purview, and that the market is approximately the size of the U.S. market. Table 1 summarizes the free parameters available in the model as well as illustrative values used for the hybrid vehicle simulations.

Table 1 Summary of free (adjustable) parameters fixed across the *EcoNiche* model scenarios

Parameter	*Value*	*Source*
Number of simulated consumers	5,000	
Product purchase interval	Mean ≈ 8.5 years, distribution as per source	NHTS (2001)
Number of real-world U.S. consumers represented by each simulated consumer	979	Toyota Motor Corp. (2005)
Green consumer utility measure	U = 50,000 – price – 3.35· |mean (footprint)|	
Conventional consumer utility measure	U = 50,000 – price	
Poor/medium/rich consumer product budget	$18,750/$20,000/$25,000	U.S. Census (2008)
Number of firm inquiries before purchase	4	
Number of consumer inquiries before purchase	4	
All consumers inquire with regulatory agency before purchase	Yes	
% consumers who are green	10	Frankel (1998)
Number of connections to neighboring consumers per consumer	60	
Production ingredients	{base,cTech,hTech}[b]	
Hybrid car production ingredients	{base,hTech}	
Conventional car production ingredients	{base,cTech}	
Production ingredient base true footprint	2,921 gallons	NHTSA (2008)
Production ingredient cTech true footprint	0.0 gallons	
Production ingredient hTech true footprint	−792 gallons	NHTSA (2008)
Production ingredient base learning curve[a]	$\$^{X}_{base}(q) = 12{,}336 \times q^{-0.014}$	Dutton & Thomas (1984)
Production ingredient cTech learning curve[a]	$\$^{X}_{cTech}(q) = 640 \times q^{-0.014}$	Dutton & Thomas (1984)
Production ingredient hTech learning curve[a]	$\$^{X}_{hTech}(q) = 34{,}820{,}483 \times q^{-0.646}$aa	Dutton & Thomas (1984)
Agent initial (prior) knowledge of production ingredient footprints[a]	$N(\mu_f = 710, \sigma^2{}_f = 3{,}825{,}111)$	
Research learning curve initial costs	$N(\mu_f \approx 16{\cdot}10^6, \sigma_f \approx 1.6{\cdot}10^6)$	Toyota Motor Corp. (2005)
Research measurement variance	$\sigma^2{}_m = 47{,}934$	
Research learning curve progress rates	As per Dutton & Thomas (1984)	Dutton & Thomas (1984)
Government research budget per cycle	$64,466,500	USEPA (2006)
Number of cycles per firm (product, price) reassessment	1	
Maximum % change in a firm's price for a fixed product per reassessment	1	

Continued

Table 1 Continued

Parameter	*Value*	*Source*
Number of innovative products offered by innovative/conventional firms	1/0	
Number of conventional products offered by innovative/conventional firms	0/1	
Firm research budget per cycle	$64,466,500	USEPA (2006)
Probability that a firm is innovative/conventional	27.3%/72.7%	
Firm initial budget	$21,500,000,000	Treece (1996)
Number of firms per simulation	11	Treece (1996)
Advertising cost per represented real-world consumer	$1.44	Social Marketing Institute (2007a)
% consumers affected by advertising	25	Social Marketing Institute (2007a)
Utility measure resulting from effective advertising	Green	
Length of advertising effect in cycles	1	
Information dissemination advertising budget	$10,000,000	Social Marketing Institute (2007b)
Aggressive information dissemination advertising budget	Unlimited	
Footprint threshold for tax policies	2,525 gallons	
Tax per excess gallon above threshold	$16.78/gallon	
Laissez-faire policy cost per active firm/represented consumer/product sold/other per cycle	$0/$0/$0/$0	
Tax policy cost per active firm/represented consumer/product sold/other per cycle	$0/$0/$52.40/$0	Costs in New Jersey
Ban policy cost per active firm/represented consumer/product sold/other per cycle	$0/$0/$50.00/$0	Costs in New Jersey
Information dissemination policy cost per active firm/represented consumer/product sold/other per cycle	$140,000/$0/$1/$680,000 + $10,000,000 for advertising	NHTSA (2006), Social Marketing Institute (2007b)
Aggressive information dissemination policy cost per active firm/represented consumer/product sold/other per cycle	$140,000/$0/$1/$680,000+ $7,048,800 for advertising	NHTSA (2006), Social Marketing Institute (2007a)

[a]For a full explanation of the mathematical formulas used and the corresponding variables, see this article's Supplementary Material on the Web.
[b]Firms produce automobiles using production recipes that include a base technology {base} plus one of two alternative technological ingredients, either conventional technology {cTech} or hybrid technology {hTech}. These technological ingredients have associated costs and environmental footprints.

Table 2 Summary of free (adjustable) parameters variable across the EcoNiche model scenarios

Parameter	*Scenario 0*	*Scenario 1*	*Scenario 2*	*Scenario 3*
Consumer type distribution	100% conventional	100% conventional	90% conventional/ 10% green	90% conventional/ 10% green
Consumer budget	100% medium	100% medium	100% medium	80% poor/ 20% rich
Firm type distribution	100% conventional	73% conventional/ 27% innovative	73% conventional/ 27% innovative	73% conventional/ 27% innovative

The following policies are modeled:

- Laissez-faire government: no governmental action.
- Research: Government performs research on the environmental performance of products in the marketplace and requires cars to have ecolabels.
- Information dissemination: Government shares the results of its environmental research but does not invest very much in that effort, limiting itself to creating a good consumer education Web site that reaches one in seven car buyers (see the Supplementary Material on the Web for explanation).
- Aggressive information dissemination: Government spends much more to spread the knowledge about its environmental research findings. This is equivalent to running advertisements as well as the consumer education Web site. The information reaches all car buyers.
- Outcome tax: Government imposes a substantial tax (about $16 per excess gallon of gasoline consumed by the car with respect to a market-specific threshold) designed to wipe out the cost advantage of the conventional car relative to the hybrid vehicle.
- Outcome ban: Government prohibits production of cars that perform substantially worse than the hybrid vehicle. The ban enters force as government research confirms the environmental performance of products in the marketplace.

Four Scenarios

How much does agent heterogeneity influence aggregate outcomes? Four scenarios allow us to explore the importance of assumptions about variation across producers and consumers. The scenarios, summarized in table 2, capture only a fraction of the possibilities built into the model, but they suffice to illustrate that heterogeneity is important. Key features of the scenarios follow:

- Scenario 0 assumes homogeneity, so that all firms are conventional firms and all consumers are conventional consumers.
- Scenario 1 includes both conventional and innovative firms but assumes that all consumers are conventional.
- Scenario 2 features both conventional and innovative firms and both conventional and green consumers.
- Scenario 3 has conventional and innovative firms, conventional and green consumers, and rich and poor consumers.

Scenario 0 approximates the simplistic view of markets underpinning much of traditional public policy analysis. Scenarios 1–3 add richness to the model and encourage users to consider different policy alternatives.

Results

The government—producer—consumer system is highly complex, and even this greatly simplified model demonstrates path-dependent behavior. Hence, it is necessary to perform multiple simulations and report results with confidence intervals. Each case is simulated 24 times over a 20-year horizon, and we report mean values and 95% confidence intervals. Table 3 shows how the hybrid vehicle market share in Year 20 varies across scenarios and policies. In the figures, vertical bars represent the confidence interval around

Table 3 Hybrid vehicle market share in Time Cycle 20 (Year 20) across the EcoNiche model scenarios and policies

	Scenario 0		*Scenario 1*		*Scenario 2*		*Scenario 3*	
Policy	*Mean*	*C.I.*	*Mean*	*C.I.*	*Mean*	*C.I.*	*Mean*	*C.I.*
LF (also BAN, TAX)	0	0	25	5	22	6	21	7
LFR	0	0	25	5	22	6	21	6
BANR	100	0	100	0	100	0	100	0
LFRI	0	0	29	5	26	6	5	3
LFRAI	0	0	44	5	48	6	19	9
BANRI	100	0	100	0	100	0	100	0
BANRAI	100	0	100	0	100	0	100	0
TAXR	0	0	25	5	22	6	21	7
TAXRI	0	0	29	5	27	6	23	7
TAXRAI	0	0	44	5	48	5	42	6

Note: Mean and 95% confidence interval (C.I.) are shown for 24 simulations of each case. Scenario 0 = conventional firms, conventional consumers. Scenario 1 = conventional and innovative firms, conventional consumers. Scenario 2 = conventional and innovative firms, conventional and green consumers. Scenario 3 = conventional and innovative firms, conventional and green consumers, and rich and poor consumers. LF = laissez-faire government; BAN = ban on conventional car production; TAX = tax on conventional cars; LFR = laissez-faire research; BANR = laissez-faire research plus ban; LFRI = laissez-faire research plus information dissemination; LFRAI = laissez-faire research plus aggressive information dissemination; BANRI = research, ban, and information dissemination; BANRAI = research, ban, and aggressive information dissemination; TAXR = research and tax; TAXRI = research, tax, and information dissemination; TAXRAI = research, tax, and aggressive information dissemination.

the plotted mean. All of the scenarios show how uncertainty and actions to address uncertainty affect outcomes.

Scenario 0 Results

A market made up of conventional firms and consumers behaves predictably. All 11 firms are conventional; hence, they offer only the conventional vehicle unless the government bans it, in which case they all offer only the hybrid vehicle. Information dissemination and taxes fail to change the market because firms are being conventional and consumers do not care. Research helps government distinguish between the conventional and hybrid vehicles' environmental performance, thus providing a basis for the regulation banning conventional vehicles (see figure 2). Aggregate vehicular pollution levels decrease when government bans conventional vehicles. With only the government taking action to reduce the uncertainty surrounding the environmental footprint of cars (by doing research), no firm gains a strategic environmental advantage, and all market actors move together in response to regulation. Under the assumptions of Scenario 0, no niche market ever emerges.

Scenario 1 Results

A market that includes innovative firms becomes more interesting. Figure 3 shows the effects of policies on market share growth for hybrid vehicles. As before, a ban on conventional cars is the most effective way to increase the market share of the hybrid vehicle. But now the benefits of other policies are also apparent. Combining research and aggressive information dissemination is especially effective, helping the hybrid vehicle attain a share of more than 40% of the market. Other policy combinations that include little or no information dissemination still push the hybrid vehicle market share over 25%.

The story here is that all of the innovative firms offer the hybrid vehicle to consumers, whereas the conventional firms continue to offer the conventional vehicle. Production costs of

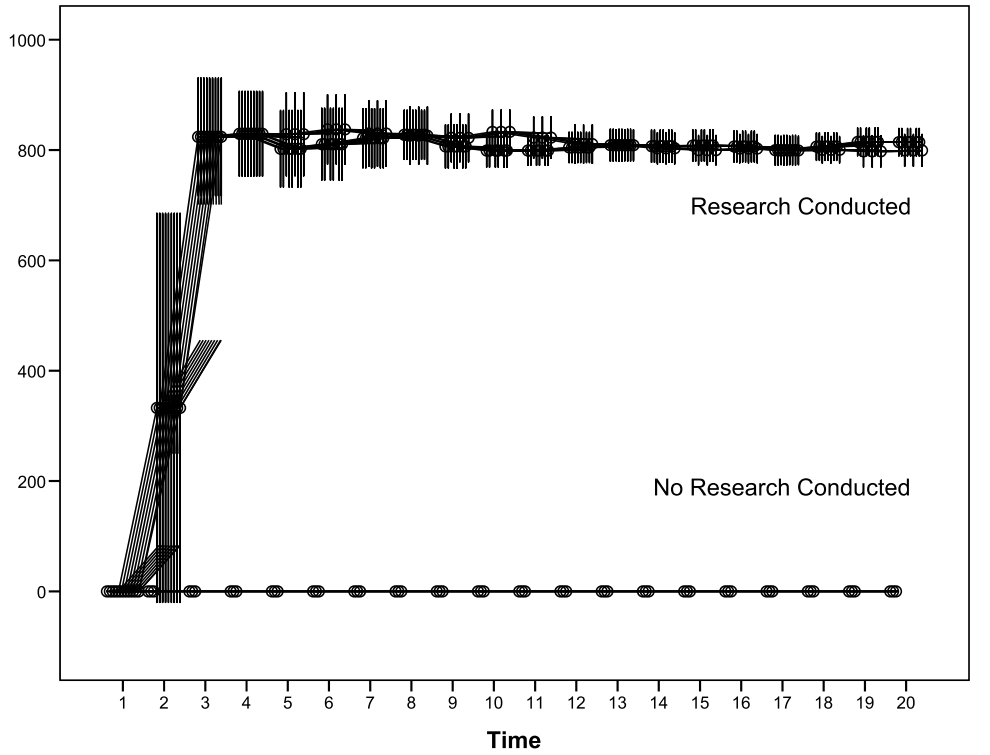

Figure 2 Research allows government to distinguish the difference between the environmental footprints of hybrid and conventional vehicles (Scenario 0: conventional firms and consumers). Vertical axis measures additional gallons of fuel consumed per conventional vehicle as an estimate of incremental environmental impact; horizontal axis measures time in years. Absent research, government assumes that there is no performance difference between conventional and hybrid vehicles. With research, government quickly develops a fairly precise estimate of the environmental performance difference.

both vehicle types drop over time, but that of the hybrid vehicle drops much more dramatically, as it started at a very high level (see figure 4). Firms must set the prices of both hybrid and conventional vehicles to be equal, because innovative firms cannot expect conventional consumers to pay more for a feature they do not value. Because consumers are also indifferent about whether a firm is innovative, they purchase the hybrid vehicle in proportion to its ubiquity, about $3/(8 + 3) = 27\%$ of the time. Only when aggressive advertising sways many consumers to seek out hybrid vehicles does their market share move higher.

Figures 5 and 6 show an important strategic result for firms. In figure 5, the profitability of conventional firms that do not do research is dramatically affected by public policies. Conventional firms hit with a production ban on conventional cars must shift to hybrid car technology and suffer dramatic short-term losses as a result. When hit with taxes or adverse information, they struggle to sell an undesirable product and slowly descend into unprofitability. Of course, under laissez-faire conditions, they remain happily profitable. Innovative firms are shown in figure 6. They exhibit a slow rise to profitability under all policy cases, although they do not strike it rich. Thus, environmental research successfully dampens swings in profitability due to changing public policies. With the Scenario 1 assumptions, a niche market for green products never really emerges; instead, firms merely produce greener products in anticipation of or in response to regulation, depending on their hard-wired strategies for managing uncertainty.

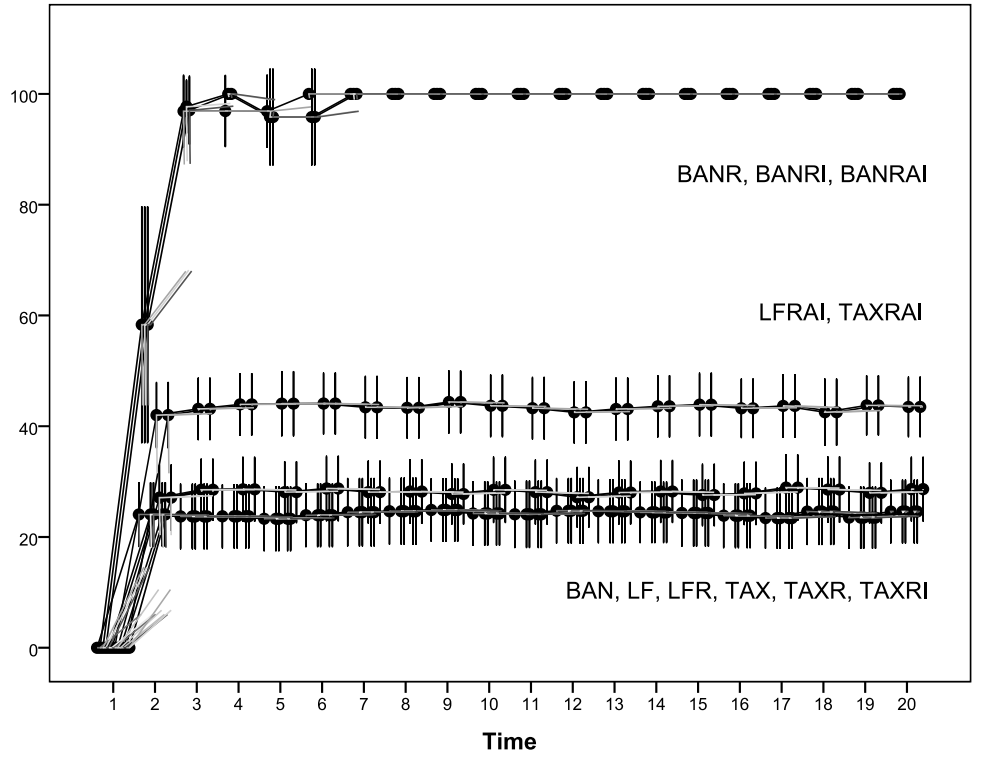

Figure 3 Hybrid vehicle market share (percentage) under policy cases (Scenario 1: conventional and innovative firms, conventional consumers). Vertical axis measures the hybrid vehicle market share in percentages; horizontal axis measures time in years. A ban on conventional car production ensures 100% market share for hybrids, whereas taxes and information dissemination result in smaller market shares. Aggressive information dissemination boosts the market share for hybrid vehicles by introducing relatively more consumers to this option. LF = laissez-faire government; BAN = ban on conventional car production; TAX = tax on conventional cars; LFR = laissez-faire research; BANR = laissez-faire research plus ban; LFRAI = laissez-faire research plus aggressive information dissemination; BANRI = research, ban, and information dissemination; BANRAI = research, ban, and aggressive information dissemination; TAXR = research and tax; TAXRI = research, tax, and information dissemination; TAXRAI = research, tax, and aggressive information dissemination.

Scenario 2 Results

In Scenario 2, where the market includes both green and conventional consumers, a green niche market finally emerges. Relative market shares for hybrid vehicles under different policy cases are not dramatically different than in Scenario 1 (see table 3). The details are substantially different, however. First, the innovative firms tend to offer the hybrid vehicle to green consumers, whereas the conventional firms offer the conventional vehicle to conventional consumers. The hybrid vehicle costs more than the conventional vehicle, as innovative firms can expect green consumers to pay a premium, which makes the innovative firm strategy more profitable. Conventional consumers purchase the conventional vehicle except when governmental information dissemination persuades some of them to choose a hybrid. With aggressive information dissemination helping their cause, innovative firms eventually (by about cycle 9) find it profit-maximizing to lower the hybrid vehicle price to attract conventional consumers as well as green consumers.

In policy cases where hybrid vehicles command a relatively small share of the market, green

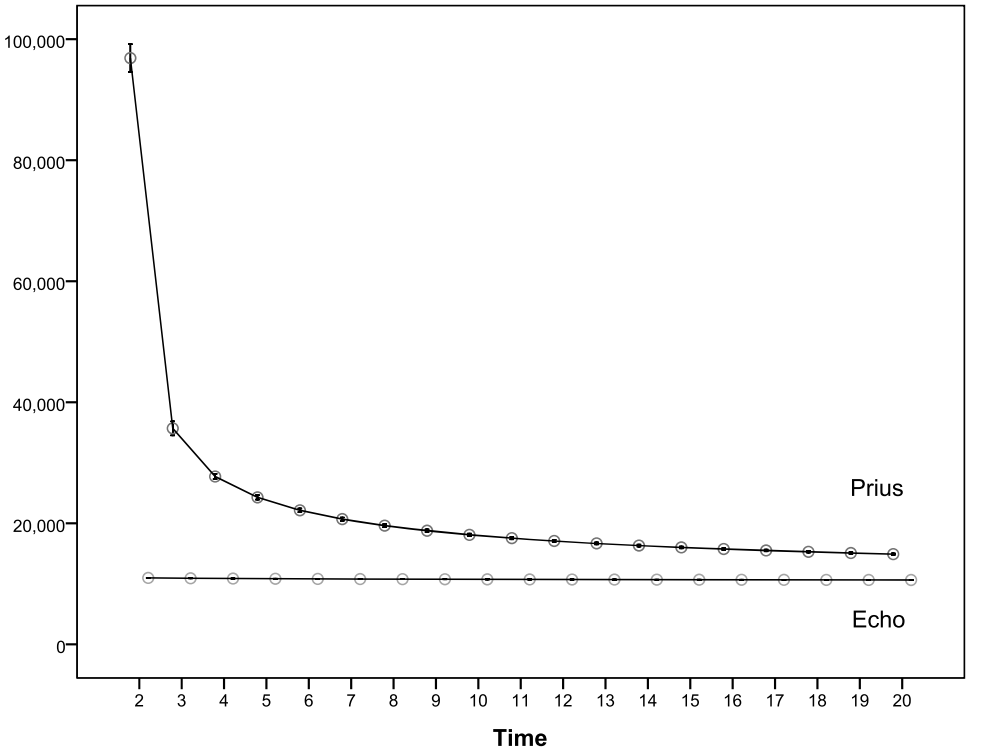

Figure 4 Dropping production costs (dollars per vehicle) for vehicles (Scenario 1: conventional and innovative firms, conventional consumers). Vertical axis measures the production cost per vehicle in dollars; horizontal axis measures time in years. Production costs drop along a learning curve, but the drop is much steeper for the novel Prius than the conventional Echo.

consumers make most of the purchases, thus providing a target for tailored governmental policies, as shown in figure 7. The model tracks the relative costs of implementing different governmental policies and shows that research and aggressive information provision achieve the same effect as the much more costly policy of taxing conventional vehicles plus doing those things. Meanwhile, innovative firms benefit from their efforts to reduce uncertainty by both anticipating future regulation and earning premiums from green consumers in the newly created niche market.

Scenario 3 Results

Adding rich and poor consumers to the mix produces especially interesting results that contradict some of the lessons learned from the earlier scenarios. The general evolution of market share is the same except in the last five time cycles, when the hybrid vehicle market share rapidly deteriorates under some policies.

In Scenario 3, the firms find that it maximizes profits to segment the market. The innovative firms generally target the hybrid vehicle to the rich green consumers, whereas the conventional firms tend to target the conventional car to rich conventional consumers. Poor consumers, both green and conventional, are priced out of the market. No firm ever targets the hybrid vehicle at the poor green market segment. Prices for hybrid vehicles remain above those of conventional vehicles. Under most policies, the hybrid vehicle remains cloistered in a niche market.

In the two policy cases wherein the government performs research and disseminates information but does not tax or regulate, something unusual happens: Conventional firms cut their

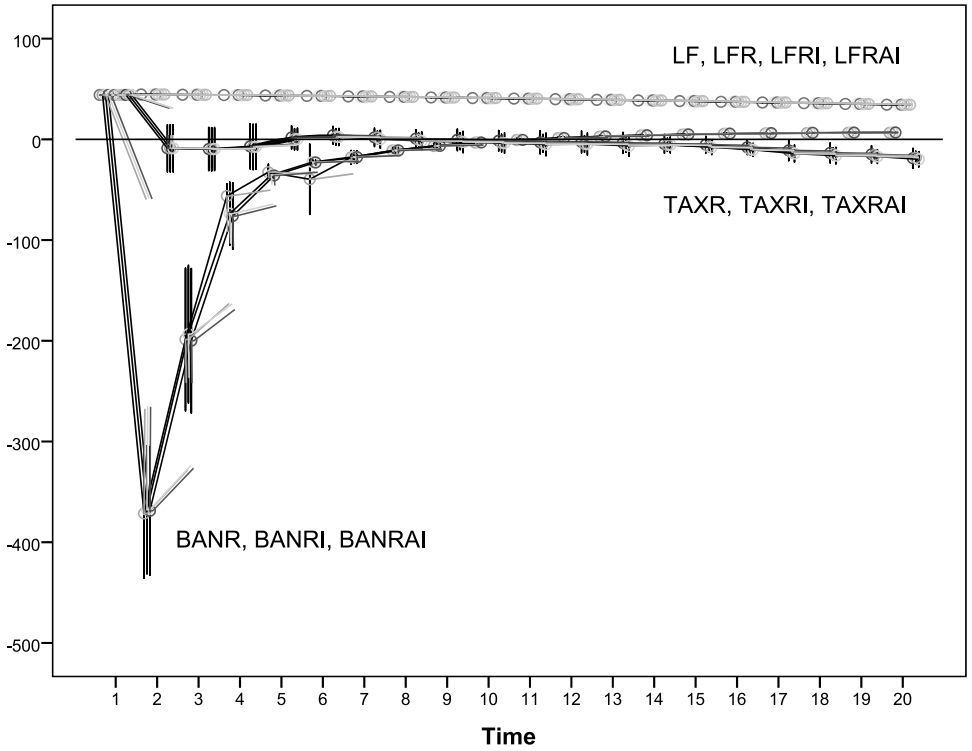

Figure 5 Government policies dramatically affect average profitability (profits as percentage of revenues) of conventional firms (Scenario 1: conventional and innovative firms, conventional consumers). Vertical axis shows the profitability of conventional firms, measured as percentage of revenues; horizontal axis measures time in years. Under laissez-faire policies, conventional firms do not produce hybrid vehicles, and they remain steadily profitable. Taxation policies send the profitability of conventional firms along a shallow downward-sloping trajectory. A ban on sales of conventional vehicles causes a massive disruption in the profitability of conventional firms, although, once retooled to produce hybrid vehicles, they eventually recover. LF = laissez-faire government; LFR = laissez-faire research; LFRI = laissez-faire research plus information dissemination; LFRAI = laissez-faire research plus aggressive information dissemination; TAXR = research and tax; TAXRI = research, tax, and information dissemination; TAXRAI = research, tax, and aggressive information dissemination; BANR = laissez-faire research plus ban; BANRI = research, ban, and information dissemination; BANRAI = research, ban, and aggressive information dissemination.

prices in the final cycles of the simulations. Two main factors are at play in this decision by conventional firms to cut their prices for the conventional car. The first relates to the existing segmentation of the market to exclude poor consumers. One option is to continue the status quo and price the conventional car to attract rich conventional consumers exclusively. If conventional firms cut their prices sufficiently, however, then poor consumers (both conventional and green) will be able to enter the market and buy the conventional car. A second factor relates to the soft preference of rich green consumers for the green car. If conventional firms cut their prices sufficiently, then rich green consumers can be expected to "defect" and settle for a much less expensive conventional car. Conventional firms thus consider several price points in terms of which consumer types could be attracted to buy the conventional car and the expected profits of each.

Government policy plays an important role in this decision making. Generally, when a tax

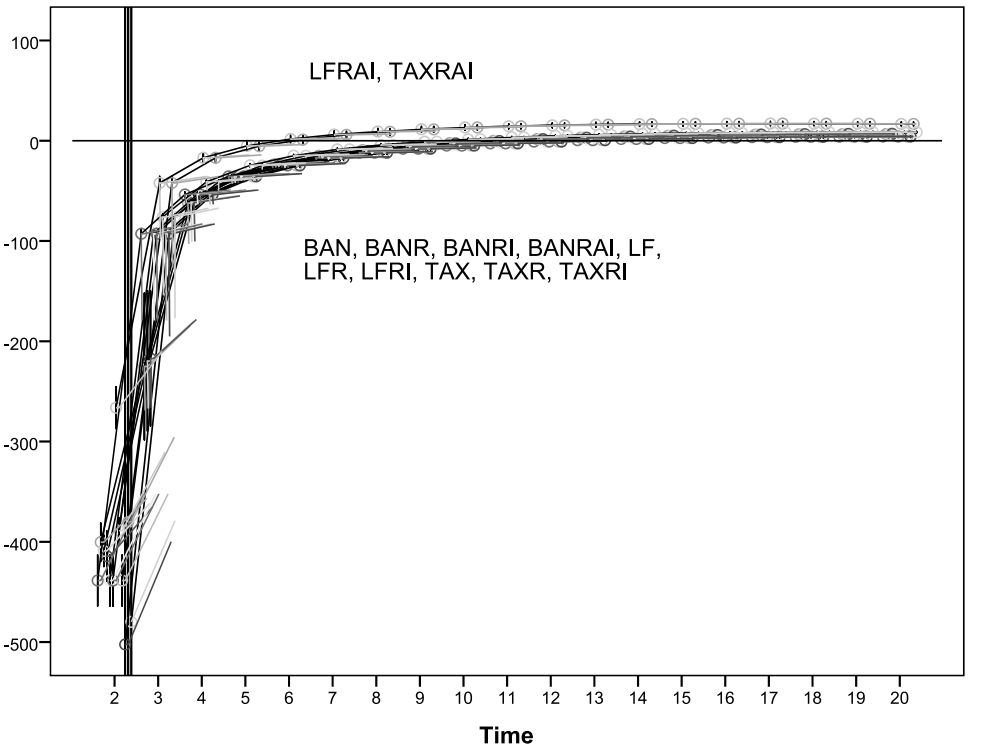

Figure 6 Government policies modestly affect average profitability (profits as percentage of revenues) of innovative firms (Scenario 1: conventional and innovative firms, conventional consumers). Vertical axis shows the profitability of innovative firms, measured as a percentage of revenues; horizontal axis measures time in years. In all policy cases, innovative firms start unprofitably, because it takes time to invent and then sell the first hybrid vehicles, but there is an inexorable rise to profitability regardless of policy case. Performance is slightly better when an aggressive information campaign by government provides free advertising. LFRAI = laissez-faire research plus aggressive information dissemination; TAXRAI = research, tax, and aggressive information dissemination; BAN = ban on conventional car production; BANR = laissez-faire research plus ban; BANRI = research, ban, and information dissemination; BANRAI = research, ban, and aggressive information dissemination; LF = laissez-faire government; LFR = laissez-faire research; LFRI = laissez-faire research plus information dissemination; TAX = tax on conventional cars; TAXR = research and tax; TAXRI = research, tax, and information dissemination.

on the conventional car is in place, a conventional firm's profit margin on each car sold is reduced. This reduced profit margin lowers the expected profit that lies in extending the conventional car market to include new consumer types, because the total profit associated with the additional volume is reduced. In particular, the presence of a tax reduces the attractiveness of dropping the conventional car price enough to attract poor and green consumers, because it is harder for the firm to make up for the profit it would forgo with its existing consumer base through the increased volume of new consumer types.

This calculation changes when government performs research and disseminates information but does not impose a tax. Without a tax in place, conventional firms can expect greater rewards from expanding their consumer base to include poor and green consumers. In the final simulation cycles of Scenario 3, conventional firms reach a point in their production experience where it becomes profit-maximizing to cut the price of the conventional car to attract poor and green

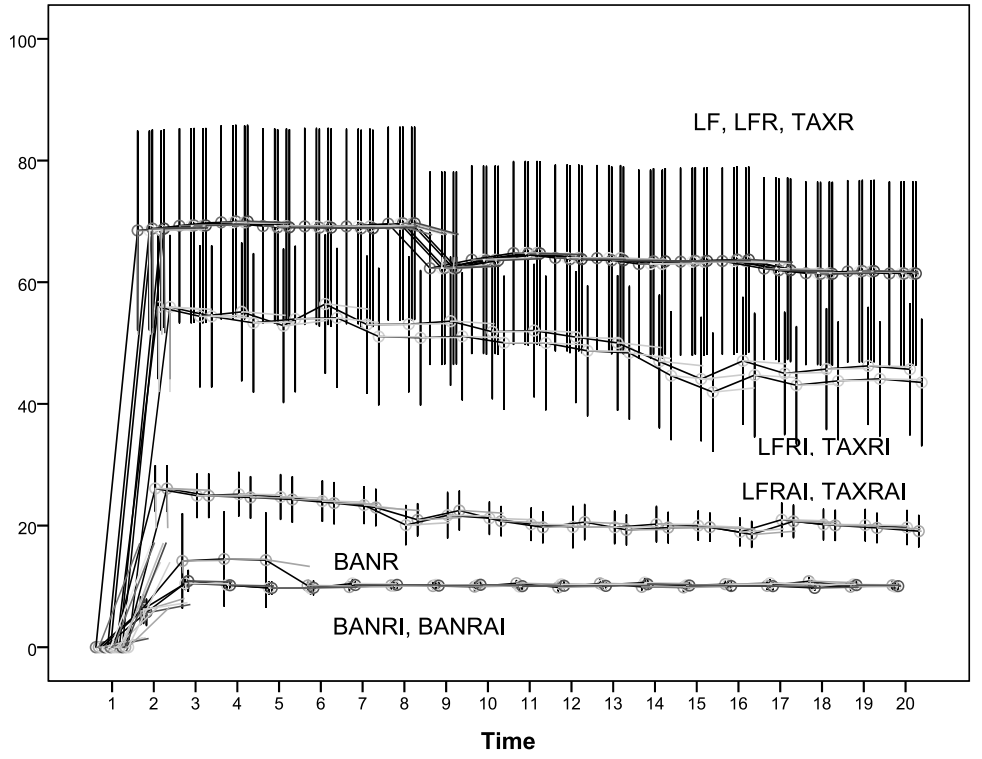

Figure 7 Percentage of hybrid vehicles purchased by green consumers under policy cases (Scenario 2: conventional and innovative firms, conventional and green consumers). Vertical axis measures the share of hybrid vehicles purchased by green consumers (as opposed to conventional consumers); horizontal axis measures time in years. When conventional vehicles are banned, green consumers are a small fraction of the total customer mix. Aggressive information dissemination attracts many conventional consumers, so green consumers are again a relatively small portion of the total. Under weaker policies, such as taxation or research, green consumers are by far the most important buyers of hybrid vehicles. LF = laissez-faire government; LFR = laissez-faire research; TAXR = research and tax; LFRI = laissez-faire research plus information dissemination; TAXRI = research, tax, and information dissemination; BANR = laissez-faire research plus ban; BANRI = research, ban, and information dissemination; BANRAI = research, ban, and aggressive information dissemination.

consumers. As the price of a conventional car steeply drops, poor consumers begin to enter the market, and the production volume of conventional cars explodes (see figure 8). Hybrid vehicle manufacturers have to reduce their prices to prevent their rich green customers from defecting. If information is being disseminated aggressively, this increases the production volume of hybrid cars as well, although by a much smaller amount (see figure 9). Both hybrid and conventional vehicle manufacturers increase their sales. This would not happen under regulation (the ban) or with a significant level of taxation, which counteract the conventional firms' cost-cutting strategy.

Thus, unlike in Scenario 2, here the taxation strategy may be more effective in promoting hybrid vehicles than less costly policy alternatives, but it also keeps some consumers out of the market. Policy making needs to be sensitive to the existence of an untapped consumer population that may eventually become crucial to the growth of this market. With Scenario 3 assumptions—the most realistic among the four scenarios—the

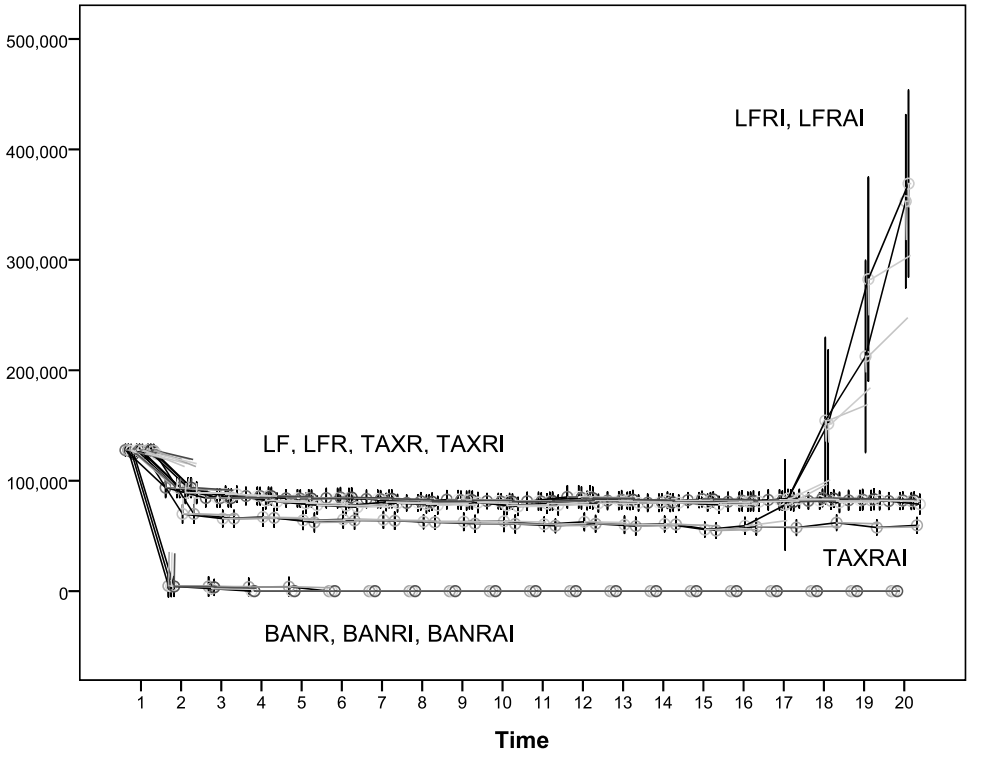

Figure 8 Production volume of conventional vehicles under policy cases (Scenario 3: conventional and innovative firms, conventional and green consumers, rich and poor consumers). Vertical axis measures the number of conventional vehicles sold; horizontal axis measures time in years. When conventional vehicles are banned, of course their production volume goes to zero. When taxation policies are in place, conventional vehicle production volumes are substantial and stable. When information dissemination policies (not combined with a tax or ban) are in place, then firms have an opportunity to try a low-cost/low-price strategy targeting poor consumers, and production volumes explode. LFRI = laissez-faire research plus information dissemination; LFRAI = laissez-faire research plus aggressive information dissemination; LF = laissez-faire government; LFR = laissez-faire research; TAXR = research and tax; TAXRI = research, tax, and information dissemination; TAXRAI = research, tax, and aggressive information dissemination; BANR = laissez-faire research plus ban; BANRI = research, ban, and information dissemination; BANRAI = research, ban, and aggressive information dissemination.

exciting possibility emerges that the green niche market can go mainstream, but policy making must be more nuanced to allow this to happen.

Summary of Results

When uncertainty and agents' responses thereto are incorporated into the model, the simulation framework is able to distinguish the effects of alternative policies and business strategies. With heterogeneity added to the model, results have become more interesting and more realistic. Innovative firms are a crucial element, without which no innovations will appear. Green consumers are helpful to make innovative firms more profitable while they innovate. An appreciation that both rich and poor people could become consumers of green products can drive market growth.

The extreme policy cases confirm intuition: Under a laissez-faire government, the hybrid vehicle never takes over the market, and when

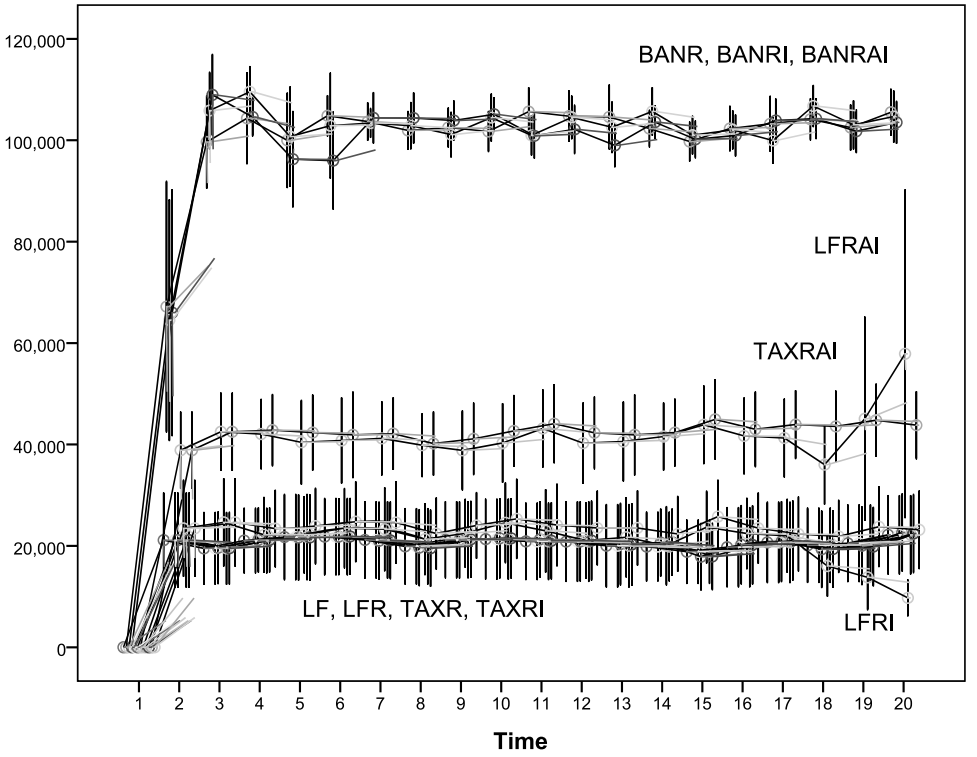

Figure 9 Production volume of hybrid vehicles under policy cases (Scenario 3: conventional and innovative firms, conventional and green consumers, rich and poor consumers). Vertical axis measures the number of hybrid vehicles sold; horizontal axis measures time in years. When conventional vehicles are banned, hybrid vehicle production expands to serve the whole market, of course. When aggressive information dissemination policies are in place, the free advertising attracts both green and conventional customers, yielding substantial production volumes. When policies with weaker information dissemination efforts are in place, only rich green consumers buy the hybrid car, and it remains a niche product. Only when cost-cutting competition brings poor consumers into the marketplace (policy case LFRAI) does the potential for the product to enter the mainstream appear. BANR = laissez-faire research plus ban; BANRI = research, ban, and information dissemination; BANRAI = research, ban, and aggressive information dissemination; LFRAI = laissez-faire research plus aggressive information dissemination; TAXRAI = research, tax, and aggressive information dissemination; LF = laissez-faire government; LFR = laissez-faire research; TAXR = research and tax; TAXRI = research, tax, and information dissemination; LFRI = laissez-faire research plus information dissemination.

government bans products that perform substantially worse than the hybrid vehicle in environmental terms, the hybrid vehicle wins 100% of the market. More interesting are the intermediate policy results.

Government research alone is not enough to transform the automobile market. Information travels too slowly through the market network, and there are too few green consumers to launch the hybrid vehicle into the mainstream.

Government research plus an additional policy, either an information dissemination campaign or a tax, can dramatically transform the automobile market. A modest information dissemination campaign that reaches one in seven consumers is not enough to make a difference. An aggressive campaign that reaches every consumer

pushes the hybrid vehicle's market share up significantly, however.

A tax can signal governmental concern over the environmental impacts of conventional products, thereby protecting the market niche of the green product. But a tax may not help the green product go mainstream; only successful cost-cutting can achieve that.

Conclusions

Governments need a better understanding of how they can intervene effectively in green niche market development. Multiagent simulation models such as the one described here can be helpful for designing policies and testing them *in silico*.[1] In illustrative multiagent simulations, successful niche market creation is strongly affected by synergy among public policies as well as by the characteristics of consumers and producers. Clear policy signals appear to have great value in cutting through the uncertainty surrounding relative product greenness. Equally important are educating consumers about the environmental implications of product choices, changing consumer values to a greener hue, and encouraging more proactive behavior among producers.

Future research should investigate additional policies, consumer characteristics, and producer characteristics. The topology of the market network could also be an important factor affecting niche market development. This model could be applied to a range of product types, such as green buildings, efficient appliances, or paper products. This type of analysis can make industrial ecology research more relevant to business and governmental decision makers. The efficacy of multiagent modeling for innovation-oriented environmental policy analysis will only increase as researchers collect better behavioral data, standardize their modeling frameworks, and harness greater computing power.

Note

1. *In silico* refers to testing that was done in the computer or via computer simulation.

References

Axtell, R., C. J. Andrews, and M. Small. 2001. Agent-based modeling and industrial ecology. *Journal of Industrial Ecology* 5(4): 10–13.

Dutton, J. M. and A. Thomas. 1984. Treating progress functions as a managerial opportunity. *Academy of Management Review* 9(2): 235–247.

Einstein, A. 1934. On the method of theoretical physics. *Philosophy of Science* 1(2): 163–169.

Federal Highway Administration. 2001. *National Household Travel Survey (NHTS)*. http://nhts.ornl.gov/2001/pub/STT.pdf. Accessed 23 February 2009.

Frankel, C. 1998. *In earth's company: Business, environment, and the challenge of sustainability*. Gabriola Island, British Columbia, Canada: New Society.

Frosch, R. and N. Gallopoulos. 1989. Strategies for manufacturing. *Scientific American* 261(3): 144–152.

Fussler, C. and P. James. 1996. *Driving eco-innovation: A breakthrough discipline for innovation and sustainability*. London: Pitman.

GE (General Electric Co.) 2005. *Eco-imagination report*. http://ge.ecomagination.com/. Accessed 13 March 2007.

Green Car Congress. 2008. US sales of hybrids down 50% in November. www.greencarcongress.com. Accessed 10 December 2008.

Grossman, G. M. and A. B. Krueger. 1995. Economic growth and the environment. *Quarterly Journal of Economics* 110(2): 353–377.

Hertwich, E. G. 2005. Consumption and industrial ecology. *Journal of Industrial Ecology* 9(1–2): 1–6.

Huber, J. 1982. *The lost innocence of ecology: New technologies and superindustrial development*. Frankfurt am Main, Germany: Fisher.

Jarvenpaa, S. L. and E. H. Tiller. 1999. Integrating market, technology, and policy opportunities in e-business strategy. *Journal of Strategic Information Systems* 8: 235–249.

Morgan, M. G. and M. Henrion. 1990. *Uncertainty: A guide to dealing with uncertainty in qualitative risk analysis and policy analysis*. New York: Cambridge University Press.

MVA (Maryland Motor Vehicle Administration). 2004. *2004 car sales statistics*. http://mva.state.md.us/AboutMVA/statistics/04sum.htm. Accessed 30 August 2008.

Naughton, K. and A. Sloan. 2007. Why Toyota is becoming the world's top carmaker. *Newsweek*, 12 March. www.newsweek.com/id/36484. Accessed 23 February 2009.

NHTSA (National Highway Traffic Safety Administration). 2006. *Budget for CAFE standards*. www.nhtsa.dot.gov/nhtsa/whatis/BB/2006/pages/Environmental.htm. Accessed 30 August 2008.

NHTSA. 2008. *New fleet characteristics*. www.nhtsa.gov/portal/nhtsa_static_file_downloader.jsp?file=/staticfiles/DOT/NHTSA/Rulemaking/Articles/Associated%20Files/March_2008_CAFE_Summary.pdf. Accessed 30 August 2008.

Rugg, J., D. Rhodes, and A. Jones. 2002. Studying a niche market: UK students and the private rented sector. *Housing Studies* 17(2): 289–303.

Sen, S. and C. B. Bhattacharya. 2001. Does doing good always lead to doing better? Consumer reactions to corporate social responsibility. *Journal of Marketing Research* 38: 225–243.

Social Marketing Institute. 2007a. Success stories: Florida Truth Campaign. www.social-marketing.org/success/cs-floridatruth.html. Accessed 30 August 2008.

Social Marketing Institute. 2007b. Success stories: Why is this ulcer sufferer so happy? www.social-marketing.org/success/cs-hpylori.html. Accessed 30 August 2008.

Stirling, A. 2003. Risk, uncertainty and precaution: Some instrumental implications from the social sciences. In *Negotiating change*, edited by F. Berkhout, M. Leach, and I. Scoones. Aldershot, England: Edward Elgar.

Taylor, A., III. 2006. Toyota: The birth of the Prius. *Fortune* 153(4): 111–124.

Toyota Motor Corp. 2005. *Toyota in the world corporate profile*. www.toyota.co.jp/en/pdf/toyota_world/2005/toyota-pdf.pdf. Accessed 30 August 2008.

Treece, J. B. 1996. Toyota puts huge bet on alternate fuel R&D. *Automotive News* 18 November, 1.

Tukker, A. 2006. Identifying priorities for environmental product policy. *Journal of Industrial Ecology* 10(3): 1–4.

U.S. Census. 2008. *Income, earnings, and poverty data from the 2007 American Community Survey*. Table 5. www.census.gov/prod/2008pubs/acs-09.pdf. Accessed 30 August 2008.

USEPA (U. S. Environmental Protection Agency). 2006. *FY 2006 annual performance plan and congressional justification*. www.epa.gov/budget. Accessed 30 August 2008.

Villas-Boas, J. M. and Y. Zhao. 2005. Retailer, manufacturers, and individual consumers: Modeling the supply side in the ketchup marketplace. *Journal of Marketing Research* 42: 83–95.

Voss, G. B., M. Montoya-Weiss, and Z. Giraud Voss. 2006. Aligning innovation with market characteristics in the nonprofit professional theater industry. *Journal of Marketing Research* 43: 296–302.

Wang, J. and A. Y. Lee. 2006. The role of regulatory focus in preference construction. *Journal of Marketing Research* 42: 28–38.

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Supplementary Material

Additional Supplementary Material may be found in the online version of this article:

Appendix S1.

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