The Tragedy of Overshoots

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ABSTRACT

Understanding historical overshoots is vital for policy-making, not at least when assessing the risk of future global overshoots. For this purpose a simple, unifying theory of overshoots is described and discussed for a variety of observed overshoots. For undesired and avoidable overshoots, misperception at some level must be a major cause. Laboratory experiments support this hypothesis and point to dynamics as the main complicating factor. The theory suggests that misperceptions may cause global overshoots both because of climate change and scarcity of cheap fossil energy. New generations of dynamic simulation models are needed to assess the risk of overshoots, test policies for likely sustainable development, and to aid information dissemination.

Key words: overshoot, management, resources, climate change, energy, globalization, dynamics, welfare, simulation

Introduction

The Brundtland Commission (1987) contributed importantly to put sustainable development on the political agenda. Consistent with their definition, sustainable development means absence of overshoots and subsequent reductions in economic activity and welfare. Historically, overshoots have been a recurring problem: individuals have experienced overshoots in private affairs, asset and commodity prices have soared and fallen, businesses have over-expanded and gone bankrupt, natural resources have been overharvested and depleted, and the global economy has gone through expansions and depressions. Logically, undesired and avoidable historical overshoots suggest that overshoots have not been properly analyzed, informed about, or understood by policy-makers for them to act in time.

First, a simple, unifying theory of overshoots is discussed in light of literature dealing with the types of overshoots mentioned above. Underlying processes are described in terms of a funnel and glass analogy and a corresponding generic dynamic model. Observed overshoots are seen in light of model predictions. The role of misperceptions is demonstrated by references to laboratory experiments. With minor adaptations, the theory explains seven important problems, suggesting generalizability of the theory. To avoid confusion, the Tragedy of the Commons (Gordon 1954; Hardin 1968) is not a prerequisite for the type of overshoot discussed here.

Second, when applied to problems of climate change and scarcity of cheap fossil energy, the theory of overshoots warns about a potential for global overshoots. The theory in its simplified form cannot produce accurate forecasts. However, it provides a tool to understand past experiences and it raises important questions about policies for the future.

Third, it is argued that importance, complexity, and misperception call for new methods and institutions for analysis and information dissemination.

Theory of overshoots

1. A simple analogy of filling a glass with water through a funnel illustrates the unifying theory of overshoots. Figure 1 gives a graphical overview of system structure (differential equations). There are two stocks (states): the funnel and the glass. Since the stocks accumulate water over time, the time dimension becomes vital. Stock values change through flows. A person controls the faucet flow; the amount of water in the funnel influences the funnel outflow and thus the glass inflow.

Filling the glass consists of a growth phase and a goal-seeking phase. To fill the glass in a few seconds, there must be a minimum amount of water in the funnel to get a sufficient funnel outflow. Thus, controlling the faucet flow involves comparing the actual water in the funnel to the desired amount of water in the funnel.

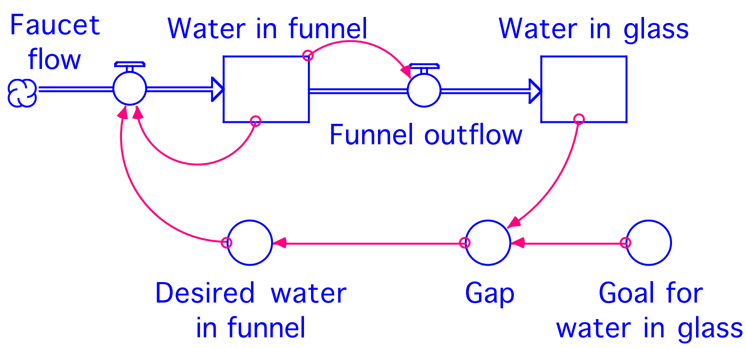

Figure 1: Stock and flow diagram of system with funnel and glass. Rectangles denote stocks, double arrows denote flows in and out of stocks, thin arrows denote instantaneous cause and effect relationships, and circles denote effect calculations or constants.

The growth phase ends when focus shifts from growth to goal seeking. Ideally, when the sum of water in the funnel and the glass equals the goal for water in the glass, the faucet should be closed. This operation requires attention to stock assessment for both funnel and glass, summing of estimates, and comparison to the goal. Using an easier and boundedly rational strategy, only water in the glass is considered, as illustrated in Figure 1. When water reaches the goal, the faucet is closed. Since water is still in the funnel, an overshoot is inevitable. In spite of the transparency of this particular system, people occasionally experience overshoots. Repeated experiences teach individuals to start closing the faucet before the goal is reached allowing sufficient time for the adjustment process.

The funnel and glass example illustrates the basics of a unifying theory of overshoots: a ‘funnel’ and a ‘glass’ stock, a growth process, and a boundedly rational goal seeking process. The following cases share these basic attributes. In these cases, bounded rationality does not necessarily follow from efforts to save on deliberations, it may also follow from misperceptions and unconscious misrepresentations of system structure.

2. Juvenile drinking behavior frequently leads to overshoots and costly accidents including deaths. When drinking, alcohol passes quickly into the stomach (funnel), however diffuses only slowly into body waters (glass). Using a simulator experiment, Moxnes and Jensen (2009) found strong indications of misperception. High school students produced an average overshoot of 86% of an explicit goal for blood alcohol concentration of 0.8 g/l. Since alcohol in the stomach is not observable, the growth phase had to be controlled by prior knowledge. For both short and long stomach delay times, goal seeking was well explained by one simple feedback strategy where drinking was simply related to the gap between goal and current blood alcohol concentration (BAC), see Figure 2. Very few juveniles (and adults) are aware of the stomach’s ‘funnel effect’. Still they are likely to think of their own decision rule as rational. Lack of theory forces them to seek external explanations of overshoots, e.g. mood and type of alcohol. Accordingly they are observed to learn only slowly from own experiences.

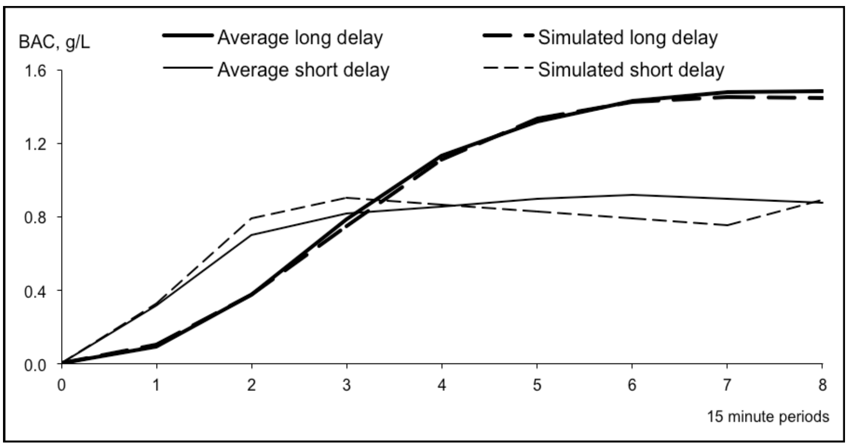

Figure 2: Average and simulated BAC for short and long stomach delay time

3. Many commodity markets produce repeated over- and undershoots; i.e. cycles. Production capacity on order (funnel) increases by ordering and decreases by delivery into the stock of

capacity (glass), which in turn decreases by scrapping, see Figure 3. To maintain the glass analogy, imagine that water can be sucked out of the glass. In established markets, the initial growth phase is over and goal seeking dominates. However, there is no obvious goal for individual firms (assuming constant costs and competition). Still, at the aggregate level, ordering of new capacity takes place in a goal seeking feedback loop – known as Adam Smith's invisible hand.

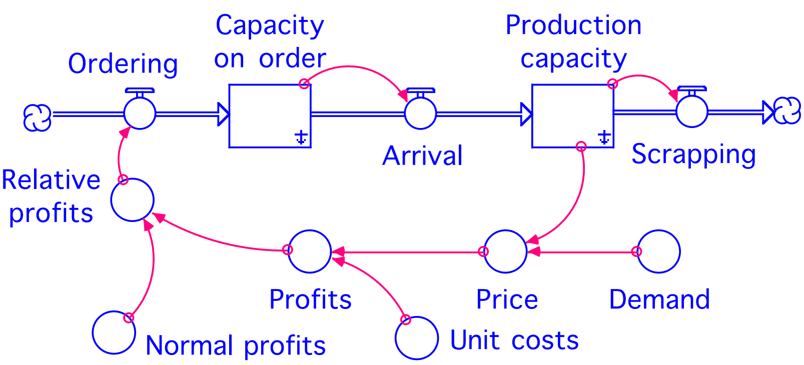

Figure 3: Stock and flow diagram of commodity market

Demand serves as an implicit goal for total capacity. When capacity is insufficient, prices stay above equilibrium levels and vice versa. Price influences profits and ordering of new capacity. To the extent that prices and price expectations only reflect current capacity (glass) and not poorly observed total capacity on order (funnel), overshoots can occur.

Scrapping of capacity enables undershoots and hence repeated cycles. Scrapping also means that the long-term goal for the funnel is no longer zero; in equilibrium new orders are needed to replace expected total scrapping. Again, data is lacking and estimates of expected total scrapping will be uncertain or missing.

How likely is it that investment decisions are dominated by recent prices to the neglect of capacity on order and scrapping? Using a funnel and glass model for capacity, and including a stock for product inventory, Meadows (1970) replicated the different cycles for chicken, hog, and cattle markets. He assumed that breeding decisions were influenced by adaptive price expectations found in studies of farmers. By redesigning earlier Cobweb experiments to include cohorts for capacity and capacity on order, Arango and Moxnes (2012) were finally able to generate price and capacity cycles in a laboratory experiment. Reliance on price increased with complexity.

Also professional forecasts tend to be strongly linked to recent observations of the variable to be forecasted (Sterman 1987) as if they are based on anchoring and adjustment heuristics (Tversky and Kahneman 1974). According to this heuristic, recent commodity prices represent the anchor and capacity on order and expected scrapping represent prior information that is insufficiently adjusted for. All this should not come as a surprise because prediction is complicated. Accordingly, a book on forecasting recommends to "Use extrapolations when the forecaster is ignorant about the situation." (Armstrong 2001, p.236).

A narrow focus on reliable and easily available data is also indicated by other studies. Insufficient adjustment for supply lines has been observed in a management experiment (Sterman 1989) and it has been observed that people tend to underestimate both length and importance of (funnel) delays (Brehmer 1989). Experiments have found that people tend to focus on conspicuous problems (Dörner 1996) and that they fail to perform backward induction (Smith 2010). Furthermore, emotions may give priority to actions (Pfister and Bohm 1992) and these emotions may not rely on cognitive appraisal (Zajonc 1984). If so, it seems natural to think that the heat of the moment gets too much weight.

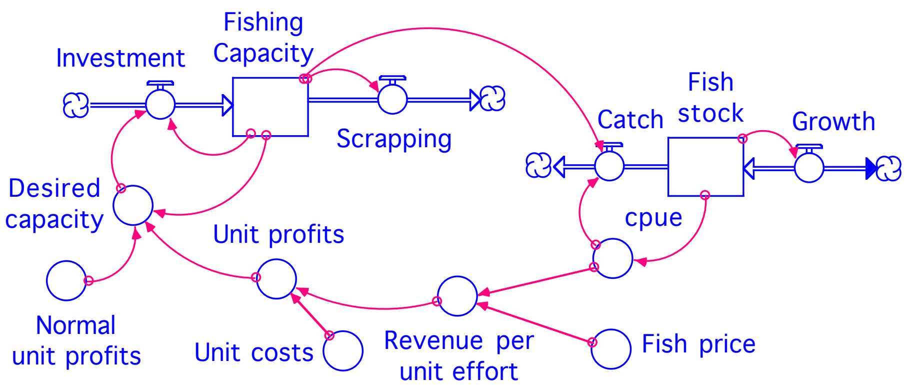

Figure 4: Stock and flow diagram of a renewable resource system

4. Exploitation of renewable resources has led to overshoots in capacity and undershoots in natural resources. In Figure 4 capacity to catch fish (funnel) increases by investments and is reduced by scrapping. A fish stock (glass) increases through natural growth and is reduced by catch. Similar to the water example, the funnel influences its own outflow and a flow

connected to the glass. It does not matter that there is no direct flow from the funnel to the glass. Causation is the same while the flows are measured in different units. There is also a difference in that the funnel influences the outflow from the glass rather than the inflow. The sign has changed, immediately suggesting that the fish stock may undershoot rather than overshoot. Similar to the commodity market, the long-term goal for the funnel is not zero and growth matters but with the opposite sign of scrapping.

In the open access situation depicted in Figure 4, individual fishing firms have no obvious long-term goal for capacity, similar to the commodity market. Desired capacity stays above current capacity as long as unit profits exceed normal unit profits in society. Hence investments are controlled by a reinforcing (positive) feedback loop.

As the fish stock is reduced, catch per unit effort (cpue) decreases, and so do unit profits. When unit profits have fallen towards normal unit profits, capacity expansion stops, catch exceeds fish growth, and the fish stock continues to decline. Capacity has overshot and the fish stock will undershoot desirable levels.

The reinforcing loop gives rise to exponential type growth, which is often seen as problematic because it leads to faster and faster absolute growth. Less obvious is it that the reinforcing loop also limits early growth and gives rise to a long period where growth activities are cultivated. A keen and institutionalized focus on growth may leave less room for attention to long-term goal seeking and to the commons problem. History shows that fishery policies have developed only gradually in response to experienced problems, from catch quotas to capacity control and to sanctuaries.

In regulated waters, the Tragedy of the Commons is no longer a sufficient theory to explain overshoots. In a laboratory experiment with private property rights (no commons problem), Moxnes (1998) found average capacity to overshoot the optimal level by more than 60 percent; the greater the overshoot in capacity, the greater the undershoot in the fish stock. Participants included fishing boat owners, regulators, and fishery researchers. A simple hill-climbing heuristic for investments was not rejected; growth in profits led to investments in new boats. At the point in time when expansion should stop, observed large and increasing profits dominated uncertain information about fish growth.

Using a hill-climbing strategy in the funnel and glass model, it can produce just as severe overshoots as open access. Figure 5 shows such an overshoot where model parameters are adjusted to roughly mimic historical records of herring catch in Norway. The figure also shows a simulated policy that limits capacity and catch to 95% of maximum sustainable yield, clearly suggesting that the overshoot was undesirable.

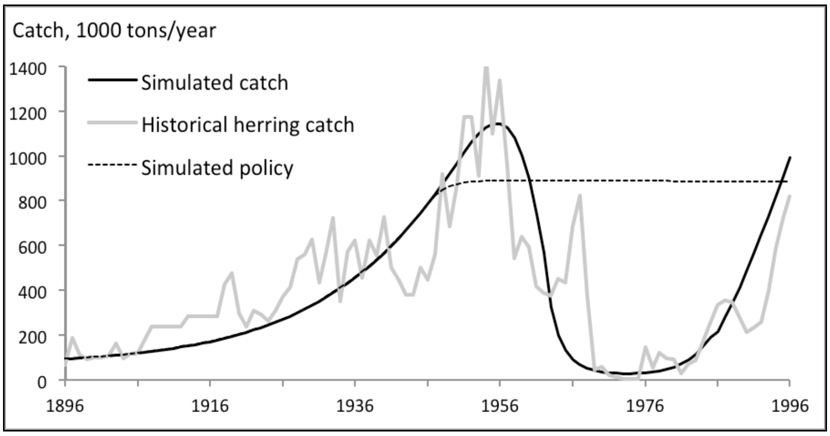

Figure 5: Simulated overshoot in catch with private property rights. Parameters are adjusted to mimic historical catch of Norwegian Spring-spawning Herring (1896 to 1996).

Schrank (2003) quotes great optimism in a 1980 FAO document after the introduction of 200 mile economic zones in the late 1970s: "the opportunity exists, as never before, for the rational exploitation of marine fisheries." Schrank goes on to quote a 1992 FAO document saying: "…the situation is generally worse than it was ten years ago. Economic waste has reached major proportions; there has been a general increase in resource depletion…" Schrank further describes misguided attempts by individual nations to extend the growth phase by massive use of subsidies. Thus, public policies made capacity overshoots greater rather than smaller, a strong indication of misperception.

Similar overshoots have been observed for many renewable resources. For instance, reindeer management has produced overshoots in number of reindeer (funnel) and undershoots in lichen (glass). This has been observed in laboratory experiments (Moxnes 2004) and in the field, in spite of co-management and regulation. In 1950 the American Society of Mammalogists (Scheffer 1951) urged planners to make thorough studies of the "problems of integrating lichen ecology, reindeer biology, and native culture" because of "serious problems that have not been solved to date on any workable scale on the North American continent." Water aquifers and forest resources provide other examples of overshoots.

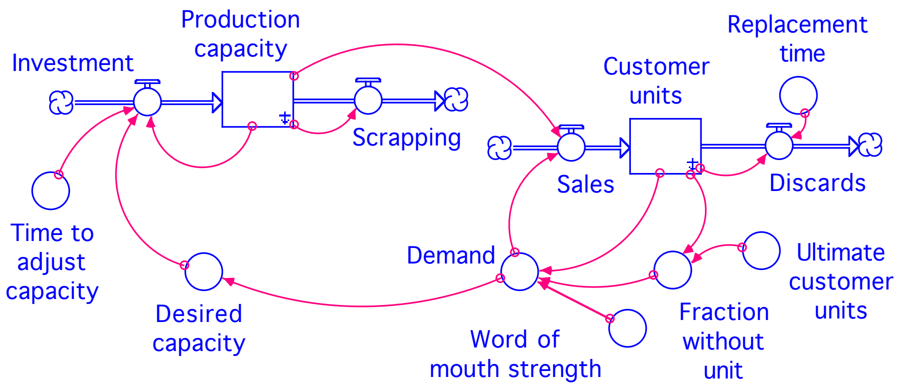

Figure 6: Stock and flow diagram of new durable good production

5. Overshoots also happen for manufacturing businesses. Consider a few firms being the sole producers of a new durable consumer good, a case adapted from Paich and Sterman (1993). Capacity (funnel) enables production and sales, Figure 6. Sales in turn lead to a build-up of the stock of units possessed by customers (glass). Growth is guided by a reinforcing loop where more capacity enables more sales, more word of mouth, more demand and more desired capacity. Growth stops when a large fraction of potential customers have bought the product. Then demand falls towards a low level of replacements for discards. A laboratory experiment by Paich and Sterman (1993) replicated capacity overshoots and bankruptcies observed in historical cases. In this case a certain overshoot in production and sales is optimal; bankruptcy is not.

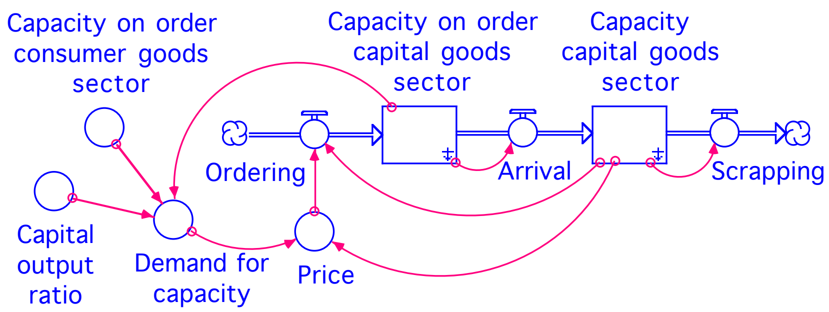

Figure 7: Stock and flow diagram of long-wave model

6. The great depression of the 1930s is probably the most well known example of over- and ensuing undershoots in modern economic history, a case adapted from Sterman (1986; 1989). Again consider the commodity cycle model with capacity on order (funnel) and capacity (glass), now representing the entire capital goods producing sector of the economy, Figure 7. In this model new capacity must be ordered from the sector itself. Self-ordering creates a bootstrapping, reinforcing growth loop that slows down and stretches the growth period in time. When the runaway goal for capacity expansion is reached, the capital goods sector reduces ordering to itself. Overcapacity is revealed, which leads to further reductions in prices and investments. Again, since the capacity stock has an outflow of scrapping, there is a potential for cycles to occur. A laboratory experiment by Sterman (1989) produced cycles with about 50 year long periods resembling data collected by the Russian economist Kondratiev.

A two stock model is an overly simplified representation of the world economy; a multitude of other mechanisms may dampen or prevent Kondratiev cycles. However, accumulation of capital is such a central factor in modern economies that self-ordering is bound to play a role. Since this is a recent theory, it seems highly unlikely that any policy-maker has ever reflected over self-ordering in the capital goods sector. Shorter-term business cycles can also be roughly described by a funnel and glass model, for instance the inventory-production (workforce) model by Metzler (1941).

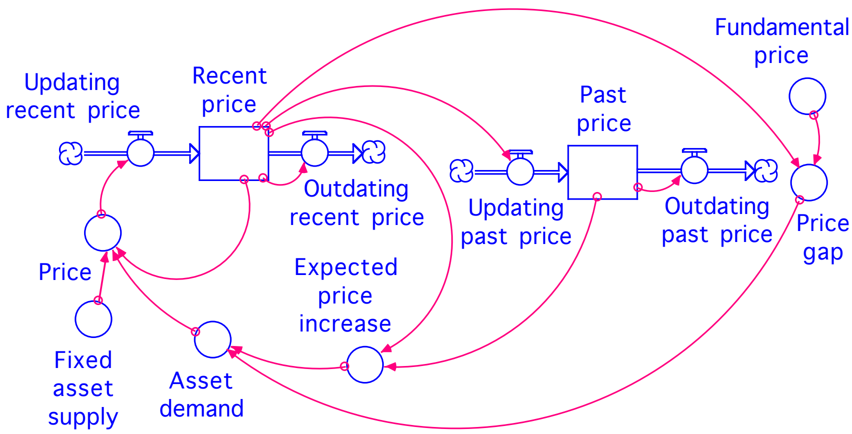

Figure 8: Stock and flow diagram of asset market

7. The final example is asset markets, where bubbles and bursts have been frequently observed. Asset markets differ from commodity markets mainly in that the assets themselves

can be easily traded and that supply is inelastic in the short run. Therefore, variations in demand tend to cause price variations rather than changes in the total stock of assets. The two stocks in Figure 8 are perceived recent price (funnel) and past price (glass). Both stocks are updated with new price information and reduced by outdated information. Information is derived from both stocks to form expectations about price growth. If price is below the fundamental price and is expected to grow, demand exceeds supply and an inner reinforcing loop is formed through price and recent price. As the price reaches the fundamental price, price is still expected to grow, and this expectation pushes the price above the goal. Eventually the gap between recent and fundamental price comes to dominate growth expectations and demand falls below supply. Then the inner loop changes from being reinforcing to being goal seeking and the price decays towards the fundamental price. This model replicates bubbles and crashes produced in a laboratory experiment by Smith et al. (1988), see Figure 9 and supplementary material.

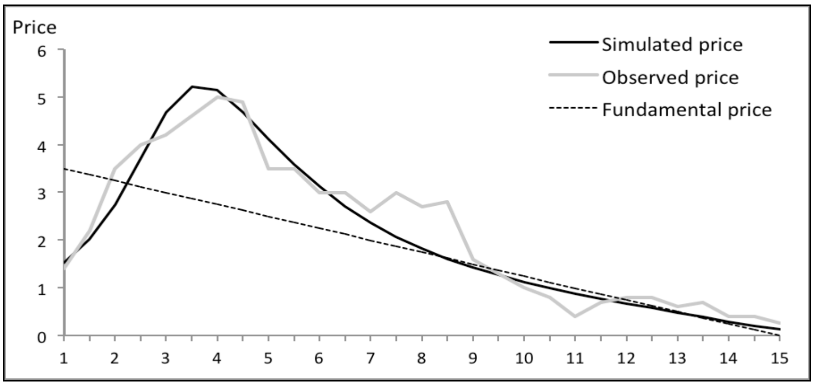

Figure 9: Fundamental and simulated price, together with observed price in a laboratory experiment (Smith et al. 1988).

The above examples show that funnel and glass systems can overshoot when combined with boundedly rational decision rules. They do not rule out that overshoots can be prevented or that people learn from repeated experiences. However, as in the case of alcohol, theory seems important to speed up the learning from experience. For potential future global overshoots, there are no directly relevant repeated experiences to learn from, theory is a prerequisite in order to transfer knowledge from history to the future.

Global natural resources

In the following, the theory of overshoots is applied to global climate change and depletion of nonrenewable fossil energy.

A model similar to that for renewable resources in Figure 4 can be used to describe climate change, see Figure 10. Global production capacity (funnel) increases by investments in capital and decreases by scrapping. Production capacity enables emissions of greenhouse gases (GHGs) that flow into the stock of GHGs in the atmosphere (glass), a stock that is only slowly reduced by removal. The combined lifetime of these two stocks is probably close to one hundred years. GHGs in turn influence global temperatures and climate.

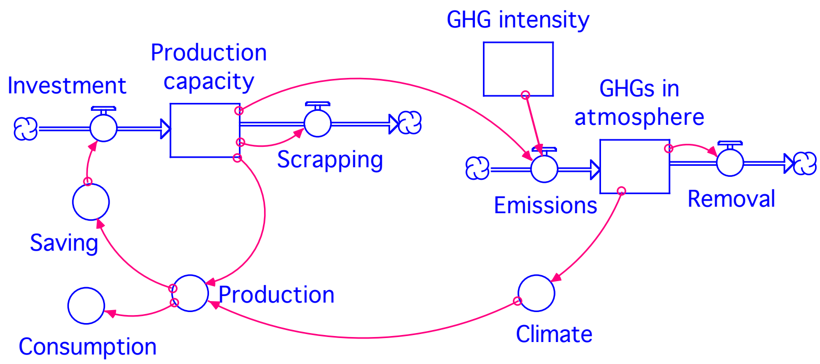

Figure 10: Stock and flow diagram of climate change problem

Growth in GHGs is driven by the reinforcing growth loop of the economy involving production capacity, production (GDP), saving, and investment. Capacity is composed of capital, technology and population. With no theory of climate change, there would be no announced long-term goal or upper limit for the GHG concentration. Growth would go on until likely future climate change reverses economic growth.

A theory of climate change exists, albeit debated. The theory of overshoots suggests that misperceptions work against the advice of theory. First, similar to forecasting of commodity prices, representativeness heuristics lead people to seek evidence of future climate change in recent weather observations rather than in theory. Second, people are not aware of or largely ignore the importance of funnels, in this case the stocks of capital and GHGs. Third, even if people know about and can name these stocks, they have a tendency to misrepresent accumulating stock and flow relationships with instantaneous cause and effect relationships (di Sessa 1993; Moxnes 1998; Sweeney and Sterman 2000; Cronin et al. 2009). For instance, most people seem to assume that the stock of GHGs in the atmosphere changes instantaneously and in proportion to global emissions (Sterman 2008) and this idea is not easily influenced by information (Moxnes and Saysel 2009). This misperception helps explain why one and the same person can both believe in the theory of climate change and vote for 'wait-and-see' abatement strategies (Sterman 2008). Fourth, with general agreement on 'wait-and-see' strategies, politicians and electorates may continue to focus on and spend their energy on conspicuous problems related to economic growth. Recall the subsidies to fishing firms in times of financial troubles.

Similar to GHG emissions, energy consumption is also driven by the reinforcing growth loop through production capacity (funnel). Energy consumption in turn adds to the stock of accumulated extraction of fossil energy (glass). Since fossil energy is non-renewable and non-recyclable, the ultimate goal for fossil energy use is zero. Hence an overshoot of the ultimate goal for fossil energy use is desirable and inevitable, recall the earlier new product case. As accumulated extraction increases, costs increase. A crucial question is if alternative energy sources will be developed early enough to prevent increasing energy costs from causing non-sustainable development.

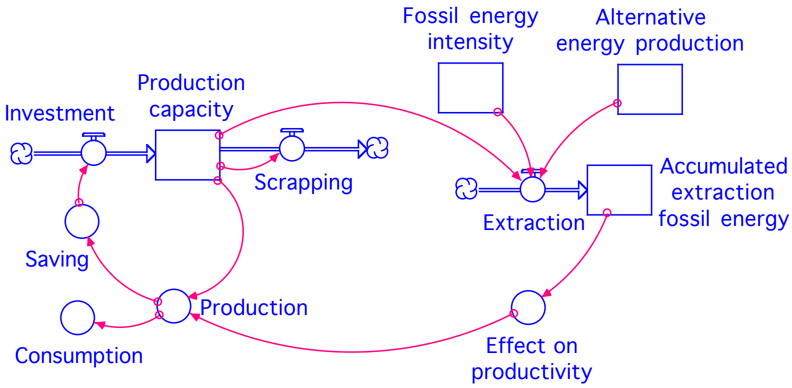

Figure 11: Stock and flow diagram of fossil energy scarcity

As for climate change, there is debate about what theory to believe in. Peak oil, peak gas, and peak coal theories warn about non-sustainable development while Hotelling's rule suggests that resource owners will slow down production to make prices increase faster than costs and thus encouraging the development of alternative energy sources. Similar to the climate change case, in choosing between these ways of thinking people are likely to rely on recent price observations, underestimate the importance of stocks, and focus on conspicuous problems. When facing increasing costs of fossil energy, a first reaction is likely to be subsidies either in financial terms or in terms of granting access to valuable land and sea areas.

Polices to prevent global overshoots due to climate change or increasing costs of fossil energy also involve funnel delays, only indicated in the figures. For both energy efficiency and alternative energy it takes time: to develop new technologies, for knowledge to diffuse, and for new technologies to replace old technologies with long lifetimes. A particular problem is that new technologies are typically considered uneconomical as they are introduced, before learning and scale effects bring costs down towards or below expected future costs of fossil fuels. This is similar to the renewable resource case where stopping investing seemed less profitable than continuing. Again, likely ignorance about inherent delays favors wait-and-see policies. The GHG intensity of production follows energy intensity and alternative energy production.

If delayed investments in energy intensive non-fossil energy sources have to be made over a relatively short period, the short-term effect would be to increase demand for energy. Thus, the underlying reinforcing loop could exacerbate overshoots in energy prices; recall the case with self-ordering of investment goods.

Likely misperceptions make it harder to solve the commons problems involved. Doubt about the theory of climate change and neglect of the need for early actions reduce the motivation to reach agreements. While countries, businesses and people have incentives to take individual actions to reduce their dependence on fossil energy, misperceptions reduce their incentives to cooperate to bring forth technologies for alternative energy production, i.e. to produce a public good. However, since laboratory experiments suggest that people are more willing to contribute to a public good than to prevent an identical public bad (Andreoni 1995), it may be politically easier to take actions to prevent a possible overshoot due to rising costs of fossil energy than to prevent severe climate change.

Simulation

Natural resources systems, economies, businesses, and private affairs involve complicating dynamics. Proper management requires understanding of system structure and behavior. Simulation is well suited for this purpose for three main reasons.

First, simulation models allow for dynamics and non-linear formulations (Sterman 2000), and thus escape some of the restrictions applied to models for econometric analysis and optimization.

Second, in addition to time-series data, simulation models can and must benefit from prior information about relationships and initial stock values, in accordance with Bayesian theory. Use of prior information also opens up for a variety of additional tests to judge validity (Forrester 1980; Zellner 1981).

Third, simulation models can be used to test popular policy suggestions and to search for policy improvements. This can be done for different model formulations and thus reveal how sensitive policy performance is to debated formulations and to different world-views (Moxnes 2005).

Dissemination

Misperceptions of dynamic funnel and glass systems represent a likely explanation of important and undesired historical overshoots. Turnarounds in public opinions after introductions of restrictions on smoking (Fong et al. 2006) and congestion charges (Leape 2006), illustrate that theory is a less effective teacher than experience, even when it comes to policy suggestions that are of direct benefits to majorities of people. Hence, dissemination of experience is important and not always trivial (Rogers 1995). Motivating recognition of new problems and first time policy innovation is even more challenging.

Analyses based on complex models can influence change agents such as managers, politicians, and activists. Simplified models that capture the essence of problems, such as those presented here, can be useful vehicles for dissemination of model insights and for learning from experience.

However, quite recent learning literature suggests that most people do not think in terms of models, they operate with what di Sessa (1993) calls phenomenological primitives. People perceive and characterize situations (pattern recognition) and this triggers predictions of behavior patterns based on stored experience. This produces quick responses of importance for species survival. E.g. football players develop “lookup tables” linking various types of kicks and resulting ball trajectories. Experience is gained through trial-and-error. This points to two essential elements in dissemination: recognition of situations and prediction of behavior.

So how can “lookup tables” linking situations and behavior be developed when there are no appropriate real world experiences to build on? Analogies seem essential. This is not a new idea. It is used in narratives, parables, and illustrative examples. What science can contribute to is to develop appropriate analogies and to unveil inappropriate analogies. An appropriate analogy is one that captures the essence of scientific understanding, which people recognize as representative for their problem situation, and that provides consistent predictions of behavior. Research is also needed to test the effectiveness of analogies. For instance, is the funnel and glass analogy effective in preventing undesired overshoots in alcohol intake and in GHG emission? Is it effective in limiting people’s use of explanations blaming external influences for man-made problems and reliance on ‘wait-and-see’ strategies?

Conclusion

A funnel and glass model serves as a unifying theory that seems able to explain a large set of overshooting phenomena. Real life experiences, laboratory experiments, and simulation models suggest that decision-makers misperceive dynamic systems and allow growth processes to bring funnels to excessive levels before goal seeking processes set in. Clearly, there is need for formal models and relevant analogies to judge the risks of overshoots and to learn from history. A fishery case demonstrated the potential of better policies.

To reduce the risks of potential global overshoots, it seems a small investment for world nations to invest in thorough studies of underlying dynamics. Both pessimists and optimists seem to rely on simplified and partial arguments. Similar to studies of climate change under the auspices of IPCC, the UN could coordinate research on potential overshoots due to climate change, scarcity of fossil energy, and other vital resources in limited supply. Importantly, there is need for competing models. No single institution is likely to produce unbiased results. Because of the tendency for misperceptions, advanced information dissemination is needed.

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Supplementary material

A model of boom and bust

Figure S1 shows a stock and flow diagram of the boom and bust model with parameter values to replicate typical laboratory experiments where the expected fundamental price declines linearly over periods. The model is fully described in terms of equations and parameter values in Table S1.

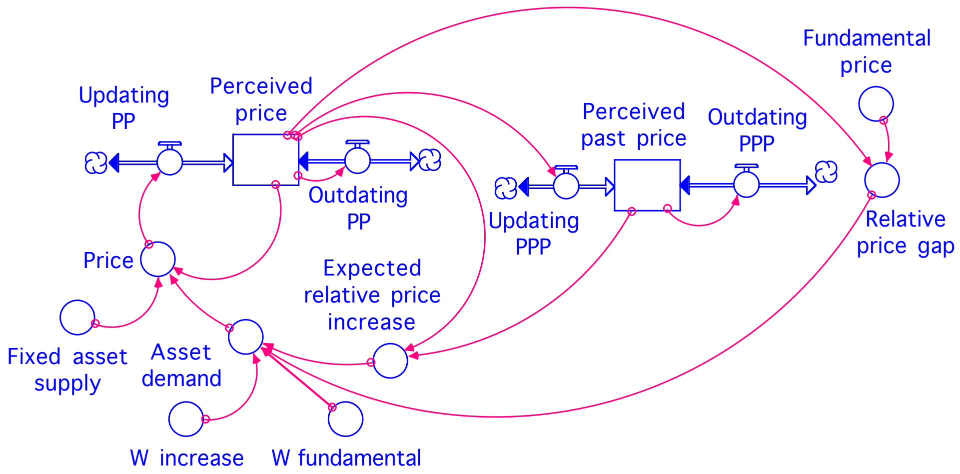

Figure S1: Stock and flow diagram of asset market

Table S1: Equations and parameter values for boom and bust model (Using Euler's method, stocks are updated with a time step of 0.05 period).

INIT Perceived_past_price = 1.0 or 3.75
Updating_PPP = Perceived_price/Time_to_PPP
Outdating_PPP = Perceived_past_price/Time_to_PPP
INIT Perceived_price = 1.25 or 3.5
Updating_PP = Price/Time_to_PP
Outdating_PP = Perceived_price/Time_to_PP
Asset_demand = 100*(1+W_increase*Expected_relative_price_increase_in_price)*
(1+W_fundamental*Relative_price_gap)
Expected_relative_price_increase_in_price = (Perceived_price-Perceived_past_price)/
(Time_to_PPP*Perceived_past_price)
Fixed_asset_supply = 100
Fundamental_price = 3.75-0.25*time
Price = Perceived_price*(Asset_demand/Fixed_asset_supply)^2
Relative_price_gap = max(-1, (Fundamental_price-Perceived_price)/
max(0.0001, Fundamental_price))
SWeq = 0 or 1
Time_to_PP = 0.5
Time_to_PPP = 2
W fundamental = 0.1
W increase = 0.3

Price formation is inspired by a formulation in (Sterman 2000). Price is based on the perceived price (funnel) and is adjusted up if asset demand exceeds fixed asset supply and vice versa. If the weight on expected relative price increase is set equal to zero, the price will adjust to ensure that price follows the fundamental price since a price higher than the fundamental price will bring demand above supply and vice versa (in experiments the fundamental price is not certain, however is indicated by information about random dividend payments). A minor problem is that the price will lag changes in the fundamental price such that there will be a persistent small gap between the price and the fundamental price. When weight is put on the expected relative price increase, perceived past price (glass or second funnel) comes into play. This stock is needed to estimate the recent price increase. A first and good effect of considering price changes is that the minor persistent deviation is corrected. Figure S2 shows how Price follows Fundamental price. Behavior is clearly different from observed price in the experiment conducted by (Smith et al. 1988).

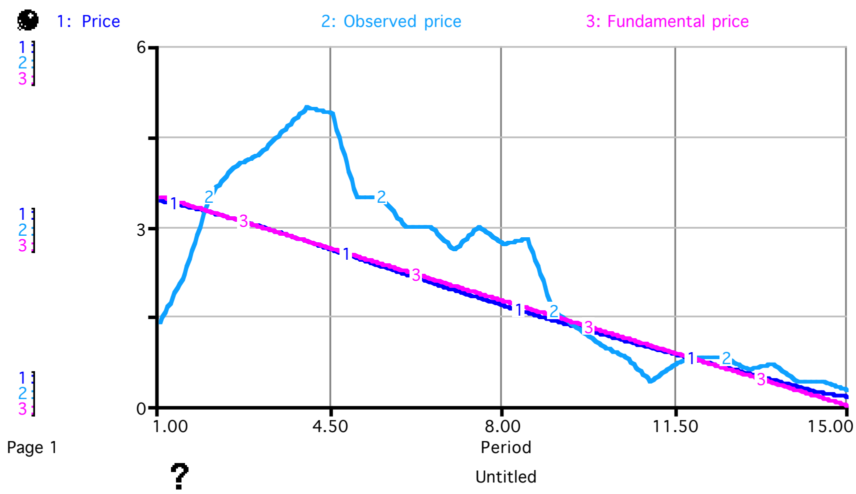

Figure S2: Price and fundamental price when the two stocks are initialized consistent with the fundamental price development. Observed price comes from Figure 9 in (Smith et al. 1988).

Next consider what happens when the model is initialized outside of the equilibrium path with initial perceived price equal to 1.25 and perceived past price equal to 1.0, consistent with observed prices in Smith et al.'s experiment. They explain: "What we learn from the particular experiments reported here is that a common dividend, and common knowledge thereof is insufficient to induce initial common expectations. As we interpret it this is due to agent uncertainty about the behavior of others." It also seems likely that the most risk-averse players prefer a lacking up-front payment instead of an uncertain stream of dividends. Figure

S3 shows that in this case the simulation model replicates observations very well. Initially the price is lower than the fundamental price and a positive expected relative price increase leads to high demand and rapidly increasing prices. The feedback loop through price and perceived price becomes a reinforcing one, leading to exponential type growth. Expected price increase pushes the price above the fundamental price. Price growth stops when the relative price gap becomes dominating and demand falls below supply. This turns the feedback loop through price and perceived price into a balancing (negative) one, leading to exponential decay and convergence towards the fundamental price.

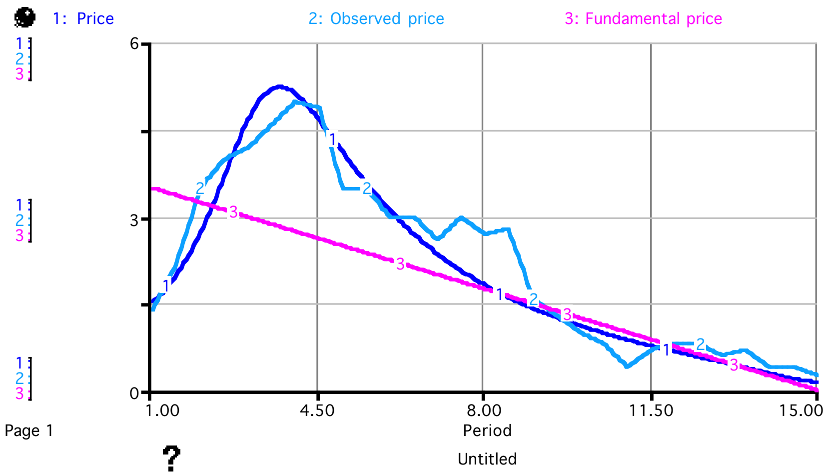

Figure S3: Model development when initialized outside of equilibrium path.

Clearly, the fit is very good and the model cannot be rejected on this ground. Equally important, the model structure represents easy to use heuristics that subjects are likely to be able to use, albeit not as precisely and consistently executed as done by the computer code. However, this does not mean that this is the one and only model that can explain observed price. For instance, no initial price trend (both stocks initialized at 1.25) combined with higher weight on the expected price increase gives approximately the same fit. Doubling of delay times for perceived price and perceived past price, combined with higher weights on both expected price increase and price gap, also gives a good fit to observed prices.