

Not only the tragedy of the commons: misperceptions of feedback and policies for sustainable development

Erling Moxnes^a

Jay Wright Forrester Prize Lecture, 2000

Erling Moxnes is senior research economist at SNF (Foundation for Research in Economics and Business Administration) in Bergen, Norway. He has specialized in renewable resource management, teaches system dynamics at the University of Bergen, and he received a PhD in system dynamics from Dartmouth College in 1982.

Abstract

The article summarizes key insights from four laboratory experiments to study renewable resource management. The commons problem, which is widely held to be the cause of mismanagement of common renewable resources, was ruled out by the design of the experiments. Still the participants overinvested and overutilized their resources. The explanation offered is systematic misperceptions of stocks and flows and of nonlinearities. The heuristics that people apply are intendedly rational for static, flow resources, but not for dynamic, stock resources. Simplifying and reframing the management problem, by focusing on net growth rates, is suggested as a means to foster the use of more appropriate heuristics. Copyright © 2000 John Wiley & Sons, Ltd.

Syst. Dyn. Rev. **16**, 325–348, (2000)

This article summarizes key insights from four studies of renewable resource management. The first study is my article on fishery management called “Not only the tragedy of the commons: misperceptions of bioeconomics” (Moxnes 1998a), for which I have received the Jay Wright Forrester Award. The three other studies concern reindeer management (Moxnes 1998b and two unpublished studies). In short, the commons problem, arising from the competition between resource users, is widely held to be the cause of mismanagement of common renewable resources, such as the depletion of fish stocks and the build-up of greenhouse gases in the atmosphere. The laboratory experiments I have carried out show that this is not the only problem. Even professionals tend to misperceive the structure and dynamics of their renewable resources. These misperceptions typically lead to overinvestments and overutilization of the resources, even when there is no commons problem. Thus policies for renewable resource management that only address the commons issue may still fail to ensure sustainable resource use. Furthermore, the revealed misperceptions disguise the need for policies and institutions to solve commons problems in due time before the exploitation rates exceed limits for maximum sustainable resource extraction.

My studies build directly on the basic system dynamics literature. Already in *Industrial Dynamics* Jay W. Forrester (1961: 14) wrote: “Our intuitive judgment is unreliable about how these systems will change with time, even when we have good knowledge of the individual parts of the system.” Later he elaborated on this idea in “Counterintuitive behavior of social systems” (Forrester 1971). My work has also been inspired by the *World Dynamics* (Forrester 1971) and the *Limits to Growth* books (Meadows *et al.* 1972, 1992) and the debates following the publication of these books. One critic challenged the models by

^a SNF, Breiviksveien 40, 5045 Bergen, Norway. E-mail: Erling.Moxnes@snf.no

saying “human beings are not fruit flies”, meaning that people would use their intelligence and rationally manage the world’s resources sustainably. Historical occurrences of mismanagement indicated to me that the apparent differences between humans and flies could not be used to rule out the possibility that both species were capable of behaving socially suboptimally. To explore the issues, I decided to perform a laboratory experiment. The choice of methodology was easy after John Sterman (1987) had pioneered the use of experiments in system dynamics. My results are consistent with, and add to, the emerging literature on decision making based on laboratory experiments.

Here I summarize the key insights from the four experiments. First, I document that it is “Not only the tragedy of the commons” that is a challenge for proper resource management. Next, I discuss the nature of the revealed “misperceptions of bioeconomics”. Comparing the studies of fishery and reindeer management gives new insights into what factors are important for mismanagement. Then I consider policies with a focus on simplicity. Finally, I end with a few words about further research.

Not only the tragedy of the commons

Hypothesis and experiments

There are countless examples of overexploitation of renewable resources such as fish, whales, pastures, forests, complex habitats for biodiversity, and groundwater, as well as of resources that serve as regenerative sinks for pollution such as SO₂, NO_x, CO₂, industrial chemicals, pesticides, and nutrients. A related economic problem is overbuilding of harvesting capacity and low capacity utilization. Since Aristotle, there has been an awareness of the commons problem as a cause of this overutilization. In modern times, Gordon (1954) and Hardin (1968) formalized and contributed to awareness of the commons problem or the “tragedy of the commons”. The commons problem is real and one should not underestimate the efforts needed to build the necessary institutions to avoid the commons problem (e.g., Ostrom 1990).

However, it is pertinent to ask why in so many cases are institutions to address the commons problem still lacking? Why does the building of institutions often start after overexploitation is a fact (Wilson and Lent 1993)? Why do overutilization and overinvestment occur even when institutions to solve the commons problem are in place? Why do governments actively subsidize capital and guarantee loans in times of excess capacity (Flåm 1987)? Why do those who are thought to benefit the most from the institutions and regulations often voice strong opposition? The fishery economist Colin Clark (1985: 11) put it this way: “. . . the fishing industry’s apparent lack of concern over its own long-term welfare remains hard to explain, except perhaps on the basis of a real misunderstanding of the bioeconomic system.” Clark’s statement expresses the hypothesis I wanted to investigate.

The existing literature on misperceptions of feedback provided methodological guidance and strengthened my confidence in this hypothesis. Recent experimental studies of problems in this category show, with few exceptions, considerable deviations from normative standards, see Bakken (1993), Brehmer (1990), Brehmer (1992), Diehl and Sterman (1995), Dörner (1990), Funke (1991), Kleinmuntz (1985), Paich and Sterman (1993), Richardson and Rohrbaugh (1990), Smith *et al.* (1988), and Sterman (1989a); (1989b). There seems to be a general tendency that decision makers misperceive feedback in that they undervalue the importance of delays, misperceive the workings of stock and flow relationships, and are insensitive to nonlinearities that may alter the strengths of different feedback loops as the system evolves. The literature indicates that people lack good mental models and the cognitive capabilities to infer the behavior of more complex models. It seems that subjects tend to reason with rather static mental models, relying on outcome feedback to correct errors. Renewable resources typically involve important stocks and nonlinearities that produce complicated dynamics. Only a minor subset can be adequately treated as flow resources.

It is not easy to answer the question about misperception from historical observations. First, when institutions to solve the commons problem are not in place, missing incentives are most likely to cause mismanagement, independently of how the actors perceive or misperceive the resource management problem. Second, in cases where the commons problem is corrected by proper institutions, such as for instance private property rights, uncertainty about management goals makes it difficult to claim that resources are mismanaged. For instance, a high discount rate can make it profitable to exhaust a resource (Clark 1973). Third, unexpected and poorly measured natural environmental variations often provide alternative explanations to misperception. Altogether, these are likely reasons why the hypothesis about misperception of bioeconomics has not been thoroughly investigated by the use of historical observations.

To avoid these difficulties, I used laboratory experiments. In these experiments, the participants were asked to manage simulators portraying renewable resources:

1. The simulators were based on sufficiently detailed and established models as to be acceptable to researchers in the respective fields (see comments on parallelism by Smith 1982).
2. Of crucial importance, the experiments were designed such that the commons problem was ruled out, either by assigning private property rights (a private fjord in the fishery experiment) or by assuming perfect institutions to solve the commons problem (total reindeer quotas set by the participants). In this regard the experiments differ from the group simulation game Fish Banks Ltd (Meadows *et al.* 1993), which provided inspiration.

3. The participants were paid in proportion to performance, providing financial incentives to maximize the net present value of the profits obtained during the simulation plus the resource value in the final year (see Smith (1982) and Forsythe (1986) on the control of the goal structure). Thus, besides maximizing profits, the participants were explicitly asked to manage the resource sustainably (infinite horizon).
4. By the use of different experimental treatments, I could test the importance of stochastic natural variation and of various types of information.

The fishery experiment

The fishery experiment started out with a virgin cod resource (*Gadus morhua*) and the participants were asked to build a fleet that maximized infinite horizon profits. They were also allowed to vary the utilization of their fleets through lay-ups. Fifty-nine of the 82 participants were professionals (fishers, managers, or researchers). The remaining 23 had varied backgrounds.

The median participant built a fleet 92 percent above the fleet size that maximized the net present value given full information, and 56 percent above a boundedly rational benchmark with imperfect information. The average fleet size was slightly higher. Only 4 percent of the participants underinvested. The majority of those who overinvested gradually built up the fleet over time. Among those who overinvested, many reinvested when a vessel was automatically scrapped because of its age in the final years of the experiment. For the subgroup with moderate overinvestments, 55 percent immediately reinvested when a vessel was scrapped. Hence, there was limited learning even after considerable evidence of overinvestment had been received. The median participant reduced the fish stock to 15 percent below the benchmark. In most cases lay-ups were used to protect the fish stock. Capacity utilization was reduced 52 percent of the time, with average reductions of 27 percent in years with lay-ups. Interestingly, only those with fleet sizes above average tended to overfish in economic terms, given established fleets.

The results are to a large extent consistent with historical observations. Clark (1985: 7) writes: "In practice, however, it often appears that the effort *capacity* of fishing fleets is much larger than twice the optimum level . . .". The aggressive use of lay-ups by many participants is representative of historical incidents of strong quota restrictions and bans on fishing. The observed tendency to overfish is less pronounced in the experiment than what is often seen in fisheries around the world. Several factors in addition to the exclusion of the commons problem could explain this. First, in 1990 when the experiment was performed, cod quotas and capacity utilizations were historically low. Consistent with this, many of the participants expressed deep concerns about the dangers of overfishing. Second, since the participants were awarded exclusive property rights, they could reduce capacity utilization without spending time on developing institutions and reaching consensus on

quotas. Third, cod have less schooling tendencies than the most frequently depleted pelagic species. For this reason, the participants received stronger and earlier indications of overfishing than has been typical in pelagic fisheries.

The reindeer experiment

All the reindeer experiments started out in a situation with overgrazed lichen, the limiting source of food that reindeer need to survive the winter. In the first experiment (Moxnes 1998b) none of the 48 participants had experience with reindeer management. Most of them had education at the masters level in economics, business administration, or geography. All of them realized that the main challenge was to cut back on the number of reindeer to rebuild the overgrazed lichen stock. Consequently, they reduced the number of reindeer in the first year of the simulation. However, this and subsequent cuts were typically far too small to avoid severe depletion of the lichen stock. The median participant ended up with a lichen stock of 3 percent of the carrying capacity and a herd size equal to 12 percent of the optimal herd size in the final year. Thus, instead of rebuilding lichen from its initial level of 32 percent, most participants contributed to its depletion, in spite of both short- and long-term economic incentives to do otherwise. The median participant obtained only 9 percent of the optimal infinite-horizon present value of incomes. Most participants were frustrated and surprised by the behavior of the reindeer simulator. Several participants sought explanations of lichen development outside the boundaries given by the introduction to the experiment, e.g. "has lichen been permanently injured?" and "few reindeer eat much".

The same experiment was replicated with 16 students in business administration and international marketing taking a class in social dilemmas and resource management at Odense University in Denmark. For the standard information treatment, the main results were not significantly different from the results of the first experiment. Fourteen of the Danish students also tried the same experiment a second time. The results improved, but the improvement was barely statistically significant, in part because five of the 14 did worse the second time.

A third experiment was performed with 21 Saami reindeer herders in Kautokeino. A new simulator was used with updated information about the relationship between the lichen stock and the net growth of lichen, and with a split of the lichen stock into easily available and less accessible lichen. The new relationship for lichen growth made it easier to stabilize and improve lichen conditions. The results improved, either because of the changed model or because the participants were professionals. However, still fewer than 50 percent of the participants were successful in improving lichen conditions within the 12-year time horizon used in the earlier experiments.

Again the results are consistent with historical observations. Probably the best documented case of severe overgrazing is given by Scheffer (1951).

Twenty-five reindeer were introduced to St Paul Island in Alaska in 1911. By 1938 the herd peaked at about 2000 animals, by which time nearly all the lichen was gone. The slaughter rate was increased far too late and too little to restore the lichen stock, and the herd collapsed to 8 animals in 1950. Importantly, at St Paul there was no commons problem present since there seems to have been only one herd.

St Paul is not the only example. According to the American Society of Mammalogists in 1950 (quoted by Scheffer), "Before any introduction [of reindeer in Ungava] is seriously considered, those persons involved in any planning are urged to make a thorough study beforehand of the problems of integrating lichen ecology, reindeer biology, and native culture—serious problems that have not been solved to date on any workable scale on the North American continent." While overgrazing is still observed in many district, it is rarely as severe as in St Paul and rarely as severe as for the median participant in the first two experiments. The third experiment seems more representative of most districts. Based on the debate among Nordic reindeer herders, there seems to be considerable frustration regarding low lichen stocks and no coherent view on appropriate policies. There is also a tendency to explain low lichen levels by other factors than reindeer grazing, such as pollution, trampling by berry pickers and hunters, and use of motor bikes and snow scooters.

Mismanagement without the commons problem

Altogether, the results of the four experiments suggest that it is not only the commons problem that has to be tackled. The findings indicate that misperceptions can cause mismanagement even in cases with private ownership and in cases where institutions set quotas for harvesting and capacity. However, in these particular cases, the resource users are likely to have incentives and financial resources for double-loop learning (Argyris 1985), i.e., to fund research, establish measurement schemes, employ modeling tools, and develop strategies. The fact that most of the professionals and highly educated participants erred in the direction of overexploitation indicates that such efforts have not yet succeeded in developing and diffusing intuitive understanding of renewable resource management.

Probably even more important, the results suggest that misperceptions are likely to camouflage the need to solve the commons problem in the first place. The typical behavior in all the experiments was to delay necessary protective measures, because the situation did not look sufficiently severe at the moment. Once the participants realized that developments had taken an unexpectedly negative turn, they were free to act quickly. In reality, there is an additional and time-consuming process of developing and agreeing on institutional arrangements. This process is likely to further delay the necessary actions, hence worsening overinvestment and overexploitation. In addition, the double-loop learning required to develop institutions to solve the

commons problem is likely to be weak. New institutions depend on agreement among resource users, politicians, and in many cases the electorate. Many of these actors have limited knowledge, and in many cases weak incentives to spend time and money on learning.¹ Thus they are likely candidates to suffer considerably from the misperceptions revealed in my studies. With threatened interests at stake, considerable frustration, and incongruent views of the problem, it is no wonder that the process can take too long, be violent, and lead to less than perfect policies.

Fortunately, all mistakes need not be repeated. For resources that are divided and distributed around the world, it is possible to learn from the experiences of others. Empirical investigations indicate that diffusion is an important explanatory factor when it comes to policy innovations.² The big challenge is to avoid overutilization of global renewable resources. For global problems like ozone layer depletion and climate change, it seems highly risky to depend exclusively on “learning-by-doing”, since we have only one chance to do it right.

Misperception of bioeconomics; why?

The preceding section has summarized the tendencies towards overinvestment and overutilization in all four experiments. Only a few participants reached benchmarks consistent with the theory of rational economic decision making. In this section I discuss and compare explanations of observed mismanagement. In this regard the experiments with their treatments and questionnaires provide observations that can contribute to the evolving theory of misperceptions of feedback.

The fishery experiment

Figure 1 portrays the basic structure of the fishery problem, simplified compared to the actual simulator. Here the fish stock is represented by an aggregate level over all age classes. Recruitment, weight growth, and natural mortality are combined in the net growth rate (similar to the illustration in Figure 5). Thus, the portrayed biological model resembles a Schaefer model rather than the cohort model used in the experiment. Harvesting depends on the fleet size, the utilization of the fleet, and on catch per unit effort (CPUE), see Figure 2. The fleet size increases by investments (originally after a one year delivery delay) and the fleet is reduced by scrapping after an average lifetime of 20 years. The decision variables are the investment rate and utilization, shown as diamonds in Figure 1.

To investigate investment behavior in the fishery experiment, I formulated and tested a simple gradient search heuristic (hillclimbing):

$$p(o_t = i) = f_i(p\pi_t - r\pi_t, \varepsilon_t).$$

Fig. 1. Basic structure of the fishery management problem

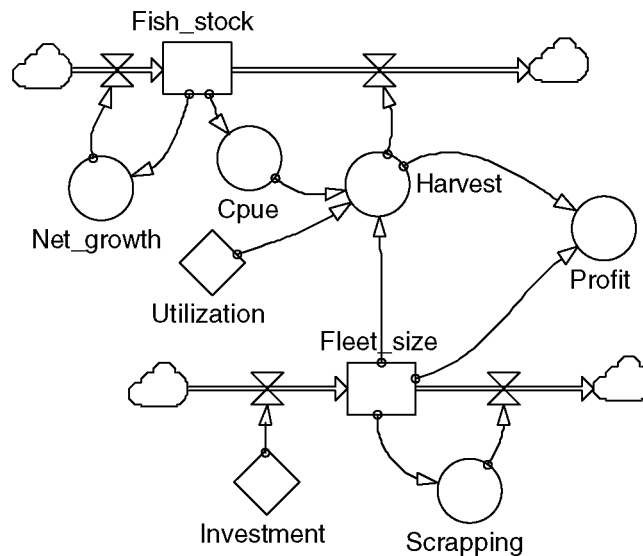
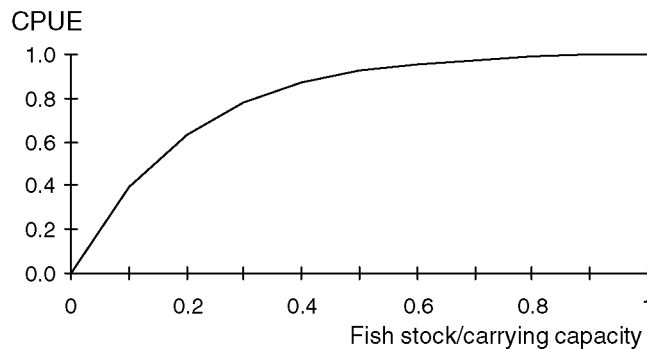


Fig. 2. Index for catch per unit effort as a function of fish stock relative to carrying capacity



The probability of ordering i vessels at time t ($o_t = i$) was hypothesized to depend on the perceived change in profits since the last increase in the fleet, $p\pi_t - r\pi_t$, where $p\pi_t$ represents perceived (delayed) profits at the moment, and $r\pi_t$ is the perceived reference profits at the time of the last order.³ The error term is denoted by ε_t . The intended rationality of the heuristic is to add vessels as long as it is perceived to be profitable to do so.⁴ The hypothesis was suggested by repeated comments by the participants justifying new orders on the basis of success in the recent past. It links the key decision variable, ordering vessels, to the criterion of success, the infinite-horizon net present value. With the low discount rate assumed in the experiment, maximizing the infinite-horizon net present value is nearly equivalent to finding the largest possible sustainable yearly profit.

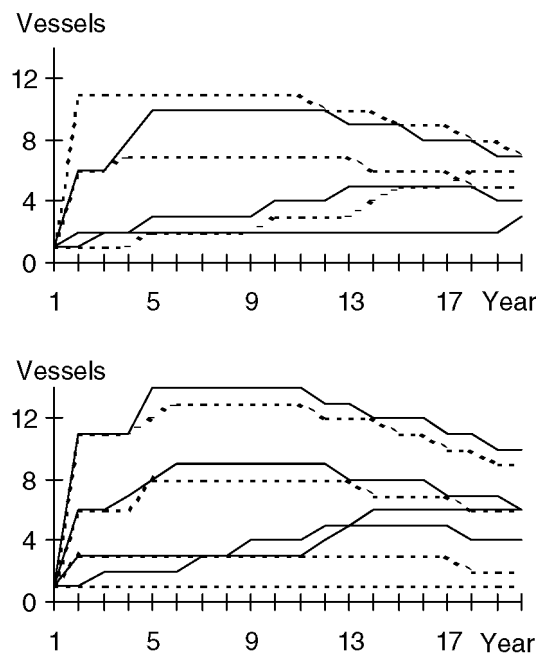
The search technique is often referred to as hillclimbing because of its similarity to practical searches for a hidden mountain summit. The aggressiveness of the response to recent changes in profits (how often and how many vessels to order for a given gradient) should ideally be calibrated by information given in the instructions to the experiment.

A potential problem with the gradient search is that this heuristic is meant for static problems where the location of the optimum in the search space does not change. The heuristic would work well for a flow resource that is available in given quantities each year, independent of previous harvests. As the harvest grew toward and passed the optimal rate, marginal profits would turn negative, indicating that the expansion of effort should stop. But hillclimbing can fail for dynamic problems such as the stock resource in the fishery experiment. I illustrate by referring to the structure in Figure 1. Assume for a moment that the net growth rate is zero while the initial stock is large. Then for several years one can step up the fleet size and observe that the harvest rate (and the profits) increase with each new vessel. Only when the stock is considerably reduced, does CPUE fall enough to halt the growth in the harvest rate and profits. At this point the investment ceases, but the fleet is far above the optimal level. Similarly, with a positive net growth rate, a gradient search heuristic could lead to a fleet in excess of what is needed to catch the maximum sustainable yield (MSY) or to maximize profits. In addition, the positive net growth rate would serve to slow down the reduction in the fish stock, leading to a higher CPUE and delayed feedback about stagnating harvests and profits.

A logit model was used to test the gradient search heuristic. The hypothesis was not rejected. Simulating the estimated heuristic produced the same type of overshooting behavior as observed in the experiment, with too frequent and too large additions to the fleet. Figure 3(a) shows some observed and Figure 3(b) some simulated fleet developments for one of the treatments. Note that the estimated heuristic is an average heuristic for all participants receiving the same treatment. The only differences between the simulations in the lower panel are random events ε_t (characterized by the estimated standard deviation) and first-year investments, which the heuristic does not explain. To illustrate the importance of randomness, pairs of simulations have the same first-year investments (shown by a solid and a dashed line). To illustrate the importance of the level of first-year investments, the following levels are used: 0, 2, 5, and 10 vessels. Comparisons between pairs of equal first-year investments show that randomness is most important for low first-year investments. The level of the first-year investment is very important. Interestingly, the same average heuristic seems able to mimic the main characteristics of observed behavior, independent of the size of the first-year investments. This feature reflects the path dependence implied by the decision rule, where first-year investments and randomness determine the path to follow.

While participants typically overinvest, they do not usually behave as aggressively as a formal gradient search implies. This is indicated by the

Fig. 3. Some
(a) observed (a) and
(b) simulated (b) fleet
sizes, treatment U



fact that most participants do not invest each and every year, while a gradient search would act at every opportunity. I see two possible explanations for this observation. First, the participants could have been ignorant about the stock nature of the resource while they let risk aversion temper the aggressiveness of the search. This is because uncertainty and ambiguity about the shape of the profit function could also lead to overinvestments in the case of a flow resource if the search progresses too rapidly (similar to numerical instability due to excessively long iteration steps). Second, the participants could have been aware of the stock nature of the resource or they anticipated delayed reactions.⁵ However, in this case they must have underestimated the length of the delay a type of misperception that has been observed by Brehmer (1989) and Sterman (1989a); (1989b). Hence, the explanations range from full ignorance of the stock nature of the resource to a misperception of delays.

Most participants who overinvested protected the resource by considerable reductions in capacity utilization. Does this observation prove that the participants understood the stock nature of the resource? Possibly, though there is an alternative explanation. During the expansion period, growing profits signaled further investments. As fish stocks dwindled, a falling catch per unit effort led to lower profits, signaling disinvestment. By the design of the experiment, disinvestments were not allowed, so the only other option available to subjects was to cut capacity utilization. This reaction does not

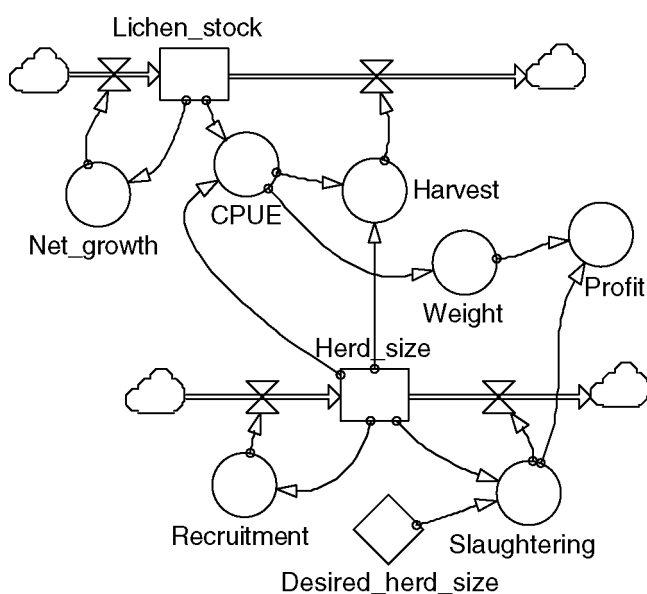
require a dynamic mental model—the same reaction would seem natural if one happened to overinvest in a flow resource. The option of reducing utilization is well known from historical quota reductions and it represents a rather cheap way to learn because it is not irreversible. In this regard, the reindeer experiments represent interesting alternative designs because they did not allow for reductions in capacity utilization.

Although I did not ask the participants about their knowledge of the individual parts of the system, it is highly likely that they knew that cod is a stock resource with a fairly long natural lifetime. The assumed lifetime was also mentioned in the instructions. Why then did the participants use heuristics that were largely incompatible with their knowledge about the structure of the problem? Similar inconsistencies are also found in other experiments, see for example, Broadbent *et al.* (1986) and Tversky and Kahneman (1974). The answer has to do with simplification. According to Tversky and Kahneman (p. 1124), “People rely on a limited number of heuristic principles which reduce complex tasks to simpler judgmental operations.” Ideally, simplification should not lead to biased decisions, only to less accurate ones. However, simplification is not a simple task. It is, for instance, one of the difficult challenges in modeling.⁶ In the fishery experiment a simple search heuristic was probably the central element, the anchor, and the stock nature was either ignored or insufficiently adjusted for. This type of simplification will lead to systematically biased decisions, just as Tversky and Kahneman found when they investigated anchoring and adjustment heuristics (and other heuristics) used to make judgments under uncertainty. Hence, a challenging information problem has been revealed: how to ensure that people make appropriate simplifications and avoid serious biases?

The reindeer experiment

Figure 4 shows a simplified flow diagram for the reindeer experiment. The basic structure is the same as in the fishery experiment, with a few exceptions. Lichen corresponds to fish and the herd corresponds to the fleet. Profits come from slaughtering reindeer and not from the harvest of lichen. Recruitment cannot be controlled—it follows from the herd size—while slaughtering can be changed by making decisions about the desired herd size (total quota). Thus, while the fleet size could be quickly increased and only slowly reduced, the herd size can be quickly reduced and only slowly increased. This difference does not seem very important for the major differences in results between the studies. The most important difference is that capacity utilization cannot be reduced in the reindeer experiment; reindeer will eat whenever there is food. It may also matter that the CPUE, also depends on the herd size and thus there is a crowding effect. This implies that if the herd size is reduced along with the lichen stock, the CPUE does not change very much until the lichen stock becomes very low. Hence, at moderate stock levels, reductions in

Fig. 4. Basic structure of the reindeer management problem



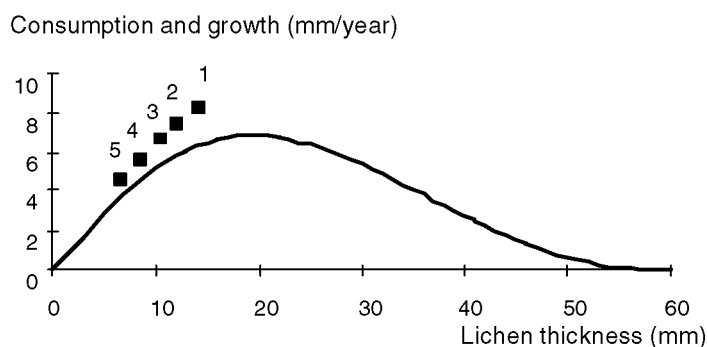
both the herd size and the lichen stock may not lead to noticeable reductions in profits. As already mentioned, the shape of the net growth curve assumed in the two first reindeer experiments may have affected the results. Finally, initial conditions differed. The reindeer experiments started out in a situation of overgrazing, while the fishery experiment started with a virgin resource at its carrying capacity.

Because of the low starting point for lichen, the overall goal of maximizing the infinite-horizon net present value of profits was probably quickly replaced by a more practical subgoal of rebuilding lichen. That subjects tend to redefine goals over time and act on conspicuous problems was also noticed by Dörner (1990). This subgoal is reasonable: from the instructions it is easily seen that rebuilding the lichen stock is necessary to maximize the net present value.

In the first reindeer experiment, the behavior of the majority of the participants was well described by a heuristic saying that the herd size should be reduced in pace with the observed reductions in the lichen stock. In mathematical terms, herd reductions were described by a linear function of lichen reductions. While this strategy may be intuitively appealing, it is in severe conflict with a correct stock and flow representation of the lichen resource. This point is best illustrated by focusing on the net growth of lichen.

Figure 5 shows the net growth curve for lichen.⁷ At zero lichen, no growth is possible. Similarly at the carrying capacity (60 mm thickness), there is no net growth since limited growth due to crowding is offset by rotting at the bottom of the plants. At a lichen thickness of around 20 mm, net growth reaches its maximum, the maximum sustainable yield (MSY). The growth

Fig. 5. Illustration of lichen growth and reindeer consumption, *Source: Moxnes et al. (2000).*



curve is consistent with a stock resource that grows from year to year towards its carrying capacity, like a forest. In this respect lichen is different from grass, which is available in certain quantities each summer, then withers and disappears before the next summer.

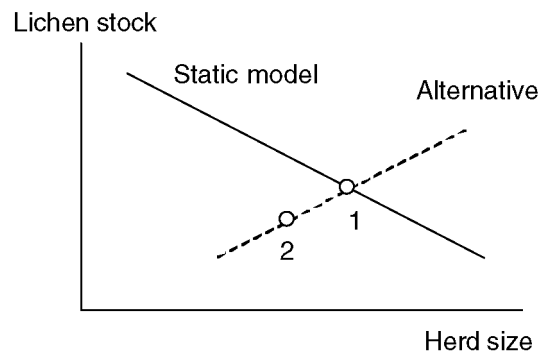
The reindeer experiment started out with a herd size capable of eating more than the MSY, indicated by black square number 1 in the figure. A person who reads Figure 5 correctly can easily see that the herd needs to be reduced by a considerable percentage to stabilize the lichen stock, at which point grazing will equal net growth. To rebuild lichen, grazing must be reduced below net growth.

However, the gradual approach chosen by most participants is very different. Most initial reductions in the herd size were not sufficient to bring grazing at or below the net growth rate. Thus, the decline in lichen continued. Subjects then cut the herd further, but allowed it to remain too high, so that lichen continued to fall. The same heuristic was typically applied year after year with little signs of learning. Since net growth tended to decline more or less in pace with the grazing pressure, the decline in lichen often did not come to a halt, as illustrated by the sequence of squares in the figure.

The failure to learn that small reductions in herd sizes are insufficient is a strong indication of a misperception of the stock and flow nature of the resource. The problem would go away, if net growth were constant, i.e. independent of the lichen stock. Then grazing and net growth would eventually meet, achieving equilibrium. For this reason, the observed behavior can be classified as a combined misperception of stocks and flows and of nonlinearities.

Both subjects' comments and decisions provided clear indications that static mental models were employed (Figure 6). When expressed in words the model sounds correct: a smaller herd leads to more lichen. Using such a model, it is not surprising that the users got frustrated when a reduction in the herd size from year 1 to year 2 led to a reduction in the lichen stock rather than to the expected increase. In the post-task questionnaire 92 percent of the participants expressed surprise at the results they experienced. Based on both the observed

Fig. 6. Illustration of static mental models



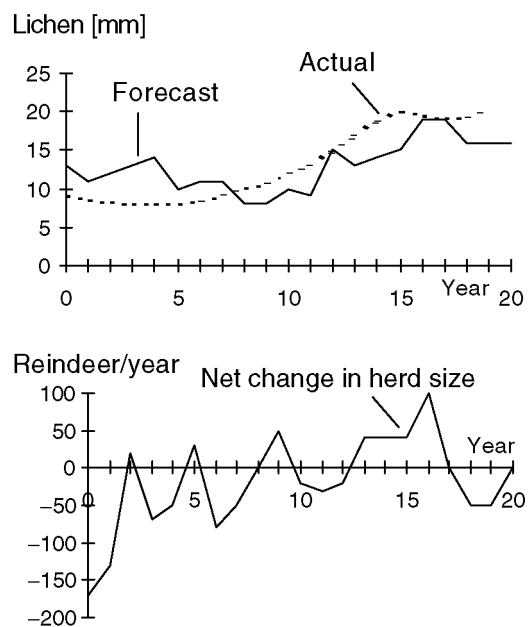
behavior and their frustration, it seems highly likely that a large fraction of the participants applied a static mental model or some heuristic that was inconsistent with the dynamic nature of lichen.

The frustration even caused a few subject to formulate the bizarre theory that more reindeer lead to higher lichen stocks. A written comment makes it sound plausible: “Things were better before when the number of reindeer was higher”. For many of the participants, data for the herd size and the lichen stock became strongly and positively correlated.⁸ While all participants in the first experiment reduced the herd size in the first year, 8 percent reversed decisions and rebuilt their herds above the initial level. In the post-task questionnaire 10 percent said they would have increased herds were the experiment to be repeated. Thirty-six percent of participants in the second experiment—playing for a second time—did worse the second time. Even in the third experiment with professionals, three participants tried increases in the herd size. The theory that more reindeer increase the stock of lichen indicates how frustrated some people became and how willing they were to formulate a contrafactual theory in an attempt to explain behavior that could not otherwise be explained when confined to static mental models.

To get an even better measure of the influence of static mental models, I equipped the third reindeer experiment with a forecasting task. After each year’s decision was entered, the Saami reindeer herders were asked to enter their forecast for the thickness of the easily available lichen the following year. The more accurate the forecast, the higher the payment to the subject. These forecast data provide a more direct measure of the subjects’ understanding of the system than observations of decisions. Subject decisions may be influenced by factors other than the subjects’ understanding of the system, including distorted goals or risk aversion.

Figure 7 shows a typical sequence of forecasts together with actual lichen thickness for one participant, a relatively successful one who managed to rebuild lichen after some time. Participants were not given information about the actual lichen thickness, only uncertain measurements of it. This explains

Fig. 7. Example of a sequence of forecasts and actual lichen thicknesses, together with net herd adjustments. The third reindeer experiment; initial herd size 750 animals



some of the variability in the forecasts. Until lichen is stabilized and starts to grow, the forecast is overly optimistic. In some of the early years in Figure 7, lichen thickness is expected to increase by around 50 percent after the early reduction in the herd size of around 35 percent. Once lichen starts to grow, the forecast is overly pessimistic.

The figure clearly indicates that risk aversion is not the major motivation for moderate reductions in the herd size. The participant expects the first reduction in the herd size to lead to a considerable increase in the lichen stock.

For seven consecutive years the participant overestimates the effects of the ongoing herd reductions. That is for the entire period when grazing exceeds lichen growth (see Figure 5). For nearly all the remaining years when grazing is less than lichen growth, the participant underestimates next year's lichen thickness. The forecast is adjusted upwards in pace with the observations of the lichen thickness. However, the thickness is expected to stay constant or decline over the next year, as the herd size is kept constant or is increased. These observations are largely consistent with a static mental model.

Of all the 21 participants in the third experiment, one participant did not produce forecasts and three made sufficiently large errors that we consider them outliers.⁹ The remaining 17 forecasts all showed the biases that a static mental model predicts. Among the seven participants who depleted the lichen to a greater or lesser extent, all systematically overestimated lichen growth for the entire period. Of the three subjects who were only able to stabilize the lichen,

overestimation was a clear pattern for a long time. Finally, among the seven participants who managed to rebuild the lichen, each and every participant tended to overestimate the lichen growth to begin with and underestimated it towards the end, i.e. they all produced the same pattern as shown in Figure 7.

The third reindeer experiment corroborated the earlier findings. Each and every participant, independently of whether they did poorly or well, had a biased view of the dynamics of the system in the direction of a static mental model. The very long periods with systematic biases in the forecasts apparently did not lead to revisions of mental models. Although some participants still did quite well, it is probably because they reacted more aggressively than others, based on a conviction that the only sensible thing to do was to reduce the herd size.

I did not ask the participants about their knowledge of the individual parts of the system. However, the Saami reindeer herders are able to correctly describe how numerous species of lichen grow and are eaten by reindeer. The inexperienced participants obtained sufficient information to figure out the structure of the model. In addition, half the participants in the first reindeer experiment received a description of a bathtub analogy to help them think about stocks and flows, with no significant effect on behavior. In the second experiment, half the group got a warning against using the static model shown in Figure 6 (solid line) and were advised to employ a relationship between the herd size and the rate of change in lichen (see Figure 8 in Moxnes 1998b). This treatment also had no statistically significant effect. As in the fishery experiment, participants appear to be firmly anchored to search heuristics that are intendedly rational for a static system. Again, the challenge for the future is to ensure that decision makers make use of unbiased heuristics and model simplifications.

Unlike the fishery experiment, most participants in the reindeer experiments did not get early warnings in terms of reduced CPUEs and they were not able to cut back on "lichen utilization" by reindeer. They were forced to make more lasting reduction in the herd size. These differences are likely to explain the more pronounced tendency towards resource depletion in the reindeer experiments than in the fishery experiment.

Policies and simplicity

The correct level of complexity of policy analyses and of suggested strategies depends on the audience. When institutions are in place and actors have appropriate incentives to make good decisions, group model building, simulation, and optimization are all interesting options, see for example, Morecroft and Sterman (1994). Today, for instance, proposed quotas in many fisheries are based on input from different modeling studies. In spite of this,

the experiments indicate that managers and researchers would still benefit from better intuitive understanding of the management problems and from more appropriate heuristics. One of the treatments in the fishery experiment may explain why current modeling is biased towards the biological side of the problem. Among the 18 percent of the participants who received information about the size of the MSY, the average investments were still sufficient to catch the MSY. They did not realize that the economically optimal fleet size was lower than the one needed to take the MSY. Thus they seem to have misperceived the importance of the nonlinear CPUE relationship.

Before institutions and incentives are in place to solve the management problem and the commons problem, the audience is a very different one. As I have argued previously, this audience could include decision makers with little detailed knowledge and weak incentives for learning. At the same time the double-loop learning required to develop institutions can be quite complex. For this audience, simplicity is likely to be very important. The empirical diffusion literature (Rogers 1995) ranks complexity among the five most important attributes explaining diffusion. The more complex an innovation is, the slower is its diffusion. Furthermore, two of the remaining four attributes, trialability and observability, are closely linked to complexity and learning.

The problem of complexity is probably underestimated by most analysts. Most of us have no doubt been disappointed at times with audiences that do not seem to get the point. Beginners at times spend much time explaining that problems are complex and contribute little beyond that. While complexity is real and an important motivation to use system dynamics, at the end of a study we should offer simplicity! This is particularly important when the audience is large and diverse.

One can simplify too much and too little. Once when I presented the first reindeer experiment, a person asked why I did not just give away the correct answer to the subjects. While that might work in isolated experiments, in reality numerical advice and “optimal strategies” are perceived to be uncertain and unreliable; they have to compete with alternative suggestions. Weights on different suggestions often reflect the authority of the change agents and not the appropriateness of the strategies. To evaluate the appropriateness of a policy, one needs to know why it is effective. If the explanation is too complex, the explanation will be just as confusing as reality itself. The challenge is to present solutions that are congruent with the mental models and heuristics of the audience, or to change their mental models and heuristics. That this is not always easy is illustrated by the effects of information treatments in the first and second reindeer experiments. Fifty percent of the participants in each experiment were given explicit policy suggestions and explanations that one could characterize as “giving away the answer”. As mentioned earlier, this information had no significant effect on behavior.

The tendency to use a search heuristic that is only appropriate for static problems implies that the problem must be reframed such that decision makers

choose a heuristic that takes account of the dynamics of the problem. Luckily, such a reframing seems to be possible by focusing on the net growth curve for the resource. The concept of a net growth curve for renewable resources is not new, dating back at least to Schaefer (1957). The problem is that most people do not know of or do not apply this curve, nor are they able to reinvent it when current practices fail. Thus people need to learn about the net growth curve. Mere knowledge of the curve might lead to a spontaneous replacement of current heuristics. However, using the curve may also require some training and it will require reliable and understandable data.

Logically, the net growth curve (see Figure 5) allows for the use of a simple heuristic to search for the MSY. If the resource stock is declining, harvesting, indicated by black squares, must be higher than the net growth. To stop the decline, harvesting must be reduced below the net growth. If initial reductions are not sufficient, it follows from the model that a stronger reduction is needed. There is nothing confusing about that, using this model. The exact speed of the adjustment is usually not very important for the net present value of profits. Trial and error is acceptable, such that the search heuristic does not require complex calculations.

Does this reframing of the problem lead to better results in practice? The first reindeer experiment gave 50 percent of the participants (as part of a factorial design) exact numerical and graphical information about the net growth curve for lichen. This treatment had a significant, positive effect on behavior. In the fishery experiment, 18 percent of the participants were given (uncertain) information about the MSY (the maximum of the net growth curve). Behavior improved.

However, most participants given the net growth curve were far from reaping the full potential. Most participants either used the net growth data to insufficiently adjust the suggestions following their normal heuristics, or they simply misread the curve. Quite a few interpreted the curve with a static lens and set the grazing rate (i.e. the herd size) equal to the maximum net growth. Thus, they ignored that it takes time and persistent undergrazing to increase the lichen stock. For these reasons it seems important to carefully explain the logic of the net growth curve: that there is a stock situated between the net growth rate and the harvesting rate, and that the present net growth rate is given by the current stock level. It may also be necessary to explain and exercise how the simple heuristic described above can bring the system towards a desired state, e.g., the MSY.

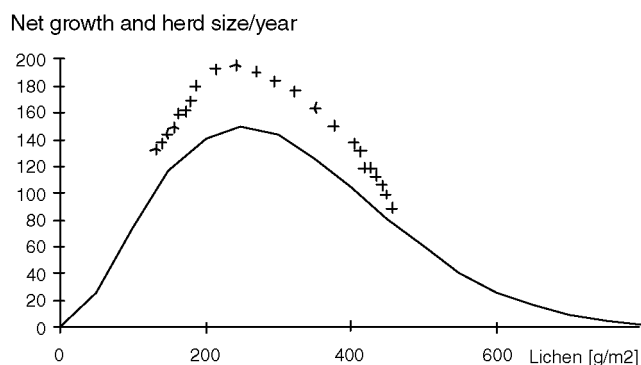
Then, to the question about data. Net growth rates and net growth curves are not measured precisely and often not known at all. This is, however, not a reason to give up on the net growth curve model. Even with no information about the growth curve, except that there is no growth at an empty stock and at carrying capacity, this is a better model for reasoning than the static model. Furthermore, focusing on the net growth curve leads to a demand for appropriate data, and it leads to discussions about the correctness of the data.

In an ongoing project (Moxnes *et al.* 2000), a computerized decision support tool has been developed in which the net growth curve has a central role. The focus is on the estimation of the curve from one's own data and experience. The basic idea of client involvement is similar to that behind group model building; however, here the focus is on "group model estimation". The importance of such data is stressed by Homer (1997), who writes: "In my experience, the models that prove most compelling to clients generally have two things in common: a potent stock and flow structure and a rich fabric of numerical data for calibrating that structure."

Net growth curves are not common in current public debates, nor are data on net growth rates. The focus is typically on resource stocks and forecasts of these. Besides a lack of demand for growth rate information, this current focus may be explained by the fact that rates are not instantaneously measurable (Forrester 1968); they typically have to be derived from measurements of stocks. In the case of reindeer management, the first publication showing a net growth curve that I have come across is from 1990 (Helle *et al.* 1990). Their curve shows net growth per unit area. I have not yet seen a published net growth curve for an entire reindeer district. This is the curve that is needed to make comparisons between grazing (herd size) and net growth. A preliminary estimate of such a net growth curve for the district of Finnmark in Norway is shown in Figure 8. While the MSY is estimated at around 140,000 food rations per year, the actual herd size peaked at around 200,000. Currently, the herd size seems to have been reduced nearly parallel to the growth curve. Interestingly, these reductions are managed by institutions designed to avoid the commons problem. Knowing the logic of Figure 8, deriving a better policy recommendation is straightforward.

For many renewable resources, widespread knowledge of the net growth curve and an acquired heuristic compatible with this curve should help establish appropriate institutions and regulations. For some resources, however, it may also be necessary to have a certain understanding of the effect of the resource stock on profits or welfare (CPUE in Figures 1, 2 and 4). If this

Fig. 8. Preliminary estimate of the net growth curve for lichen in Finnmark, Norway, based on four satellite measurements. The plus signs represent herd size (grazing). Source: Moxnes *et al.* (2000).



effect is strong, it is no longer optimal to aim for the MSY. As already mentioned, the fishery experiment demonstrates that this effect is not well understood. This stock effect seems particularly important for pollution problems, where welfare losses are typically related to the stock levels of pollution. In general, the importance of the stock effect is to shift the goal away from the MSY (given that a maximum yield exists). Irrespective of exactly what the goal is, it still seems vitally important to employ the net growth curve model in order to reach the appropriate goal and not to overshoot it.

Further research

There has been a considerable amount of research on the commons problem. There are around 2000 references to Gordon (1954) and Hardin (1968) in the journals represented in the ISI citation database for 1987 to 2000. Several of these studies make use of laboratory experiments, e.g., Plott (1983), Walker *et al.* (1990), and Andreoni (1995). All the experiments make use of flow resources or equivalents thereof. I have not found other field studies or laboratory experiments explicitly investigating the role of misperceptions of stocks and flows and of nonlinearities in renewable resource management, for a recent survey see Ostrom *et al.* (1999). Hopefully, my work will spur further interest in the role of misperceptions regarding the management of private and common resources, and regarding the formation of institutions to solve the commons problem. More research is needed to clarify mental models and heuristics: it is important to find out how net growth curves or other pedagogical devices can best be used to avoid misperceptions both regarding management and formation of institutions. The results should be important for both policy making and education.

As well as field studies and gathering of data about different renewable resources, I think that laboratory experiments have a great potential in this area. Such experiments can contribute to the understanding of misperceptions of bioeconomics, as well as of misperceptions of feedback in general. In this regard, the following experiences from the use of experiments in other social sciences are interesting for the field of system dynamics.

First, a typical pattern in the emerging experimental literature is that experiments are repeated and redesigned over and over again to develop, test and refine theories of behavior, see Bar-Hillel (1982) for a notable example. Regarding experimental studies of misperceptions of feedback, I recall only one published replication of an earlier experiment (Richardson and Rohrbaugh 1990). Second, series of experiments contribute significantly to an accumulation of results within the social sciences. This may be of particular importance in the field of system dynamics, which is typically applied to widely different problems (see also Richardson 1996). Third, there seems to be a tendency to start out with complex situations, and then move towards

simpler representations, encouraged by evidence of misperceptions. In this connection Edwards (1982: 361) writes: “The simple example—didn’t occur to us; instead we were sure that we would need to use a fairly complex situation in order to get non-Bayesian behavior.” Fourth, the use of laboratory experiments is growing rapidly in many social sciences. Experimentation is an established method of scientific inquiry and can be used to produce data where field data do not exist. Well designed experiments typically produce questions for further experiments to answer. Fifth, it could be that good experimental studies have a greater potential than other methodologies to cross the borders between social sciences because of the common language used. As an example, results regarding judgement under uncertainty have traveled from cognitive psychology into the economics literature.

I expect that, as experimental studies of dynamic systems become simpler and more transparent, and as they are repeated and refined, they are also likely to receive more and more attention both inside and outside the field of system dynamics. For a long time there will be no lack of research questions. *A priori*, there is no reason to think that such a research program should become less successful than the experimental studies of judgements under uncertainty within cognitive psychology.¹⁰ My studies and the studies referred to earlier indicate that misperceptions of feedback are more devastating to human decision making than biases in heuristics dealing with uncertainty. For instance, the fishery experiment shows that the basic tendency towards overinvestment is not significantly altered by treatments including uncertainty in measurements and stochasticity in recruitment. Finally, it is my experience that experimental results serve as a strong motivation to study complex dynamic problems and to search for field data.

Acknowledgements

I am grateful for financial support from SNF’s Fund for Applied Research to write this article and from the Nordic Ministerial Council to run the reindeer experiment in Kautokeino. Thanks to Karen Anna Logje Gaup, Kautokeino and Eldar Gaare, NINA for helping to organize and run the experiment in Kautokeino. Thanks to Professor Suzanne C. Grunert for running the experiment in Odense in Denmark. Thanks to Professor John Sterman, MIT, for inspiration, encouragement, and detailed comments on the manuscript.

Notes

1. Elster (1989) calls this the second level commons problem.
2. See Moxnes (2000) for a short summary of research regarding diffusion of public policies.

3. Actually, a true gradient is found by dividing the change in profits $p\pi_t - r\pi_t$ by the number of vessels ordered last time. This somewhat more complex heuristic turns out to produce slightly higher average p values.
4. That investments stop when profits no longer increase is a desired feature when the heuristic is applied by a resource owner. The investment strategy is different from what is usually assumed for atomistic market actors (e.g., fishermen in an open access situation), who should continue to invest as long as the rate of return exceeds the normal rate of return.
5. As long as the harvesting strategy (harvest as a function of the stock level) intersects the net growth curve in a stable equilibrium, the effect of increased effort on the stock level can be approximated by a delay.
6. Sterman (2000: 166) writes: "... modeling is the art of simplification".
7. The curve shown is similar to the assumptions made in the third reindeer experiment. In the two first experiments the peak was situated on the right-hand side.
8. The positive correlation between reindeer population and lichen was highly significant. In one case I found a t -ratio of 19 for the relationship between herd size and lichen stock. Thus the experiment produces a textbook case illustrating the dangers of relying on correlations rather than on information about the structure.
9. The average root mean square error (RMSE) for the three outliers was 13.2 mm. Forecasting deviations were in the direction predicted by a static model. The average RMSE for the 17 included participants was 4.3 mm and the median 3.2 mm. The RMSEs for the three best forecasters ranged from 1.0 to 1.5 mm and were obtained in cases with declining and then stabilized lichen.
10. Since 1987 there have been around 10,000 journal references to Kahneman and Tversky.

References

- Andreoni J. 1995. Warm-glow versus cold-prickle: the effects of positive and negative framing on cooperation in experiments. *The Quarterly Journal of Economics* **110**(1): 1–21.
- Argyris C. 1985. *Strategy, Change, and Defensive Routines*. Pitman: Boston.
- Bakken BE. 1993. Learning and transfer of understanding in dynamic decision environments. Ph.D. Dissertation, MIT Sloan School of Management.
- Bar-Hillel M. 1982. Studies of representativeness. In *Judgment under Uncertainty: Heuristics and Biases*, Kahneman D, Slovic P, Tversky A (eds). Cambridge University Press: 69–83.
- Brehmer B. 1989. Feedback delays and control in complex dynamic systems. In *Computer Based Management of Complex Systems*, Milling P, Zahn E (eds). Springer Verlag: Berlin.
- Brehmer B. 1990. Strategies in real time, dynamic decision making. In *Insights in Decision Making*, Hogarth RM (ed.). University of Chicago Press: 262–279.

-
- Brehmer B. 1992. Dynamic decision making: human control of complex systems. *Acta Psychologica* **81**: 211–241.
- Broadbent D, FitzGerald P, Broadbent M. 1986. Implicit and explicit knowledge in the control of complex systems. *British Journal of Psychology* **77**: 33–50.
- Clark CW. 1973. The economics of overexploitation. *Science* **181**: 630–634.
- Clark CW. 1985. *Bioeconomic Modelling and Fisheries Management*. Wiley: New York.
- Diehl E, Sterman JD. 1995. Effects of feedback complexity on dynamic decision making. *Organizational Behaviour and Human Decision Processes* **62**(2): 198–215.
- Dörner D. 1990. The logic of failure. *Philosophical Transactions of the Royal Society of London Series B* **327**(1241): 463–473.
- Edwards W. 1982. Conservatism in human information processing. In *Judgement under Uncertainty: Heuristics and Biases*, Kahneman D, Slovic P, Tversky A (eds). Cambridge University Press: 69–83.
- Elster J. 1989. *The Cement of Society. A Study of Social Order*. Cambridge University Press.
- Flåm SD. 1987. Kvifor fiskerisubsidiene bør avviklast. *Nytt Norsk Tidsskrift* **4**(4): 51–56.
- Forrester JW. 1961. *Industrial Dynamics*. MIT Press: Cambridge, MA.
- Forrester JW. 1968. *Principles of Systems*. Wright-Allen Press: Cambridge, MA.
- Forrester JW. 1971. Counterintuitive behavior of social systems. *Technology Review* **73**: 52–68.
- Forrester JW. 1971. *World Dynamics*. Wright-Allen Press: Cambridge, MA.
- Forsythe R. 1986. The application of laboratory methods to testing theories of resource allocation under uncertainty. In *Handbook of Behavioral Economics*, Gilad B, Kaish S (eds). JAI Press Inc.: New York, 19–60.
- Funke J. 1991. Solving complex problems: exploration and control of complex systems. In *Complex Problem Solving: Principles and Mechanisms*, Sternberg R, Frensch P (eds). Lawrence Erlbaum Associates: Hillsdale, NJ.
- Gordon HS. 1954. The economic theory of a common property resource: the Fishery. *Journal of Political Economy* **62**: 124–142.
- Hardin G. 1968. The tragedy of the commons. *Science* **162**(13 December): 1243–1248.
- Helle T, Kilpelä SS, Aikio P. 1990. Lichen ranges, animal densities and production in Finnish reindeer management. *Rangifer* Special issue No. 3: 115–121.
- Homer JB. 1997. Structure, data, and compelling conclusions: Notes from the field. *System Dynamics Review* **13**(4): 293–309.
- Kleinmuntz DN. 1985. Cognitive heuristics and feedback in a dynamic decision environment. *Management Science* **31**(6): 680–702.
- Meadows DL, Fiddaman T, Shannon D. 1993. Fish Banks, Ltd. A Micro-computer Assisted Group Simulation that Teaches Principles of Sustainable Management of Renewable Natural Resources. 3rd edn. Laboratory for Interactive Learning, Hood House, University of New Hampshire, Durham, NH.
- Meadows DH, Meadows DL, Randers J. 1992. *Beyond the Limits*. Chelsea Green: Post Hills, VT.
- Meadows DH, Meadows DL, Randers J, Behrens W. 1972. *The Limits to Growth*. Universe Press: New York.
- Morecroft JDW, Sterman JD, (eds). 1994. *Modelling for Learning Organizations*. Productivity Press: Portland, OR.
- Moxnes E. 1998a. Not only the tragedy of the commons, misperceptions of bioeconomics. *Management Science* **44**(9): 1234–1248.

- Moxnes E. 1998b. Overexploitation of renewable resources: the role of misperceptions. *Journal of Economic Behavior and Organization* **37**(1): 107–127.
- Moxnes E. 2000. Diffusion of environmental policies: Bayesian learning or heuristics? R 14/00. SNF, Bergen.
- Moxnes E, Danell Ö, Gaare E, Kumpula J. 2000. A decision tool for adaptive resources management. In *The 18th International Conference of the System Dynamics Society*. System Dynamics Society: Bergen, Norway.
- Ostrom E. 1990. *Governing the Commons*. Cambridge University Press.
- Ostrom E, Burger J, Field CB, Norgaard RB, Policansky D. 1999. Revisiting the commons: local lessons, global challenges. *Science* **284**: 278–282.
- Paich M, Sterman J. 1993. Boom, bust, and failures to learn in experimental markets. *Management Science* **39**(12): 1439–1458.
- Plott CR. 1983. Externalities and corrective policies in experimental markets. *The Economic Journal* **93**(March): 106–127.
- Richardson GP. 1996. Problems for the future of system dynamics. *System Dynamics Review* **12**(2): 141–157.
- Richardson G, Rohrbaugh J. 1990. Decision making in dynamic environments: exploring judgments in a system dynamics model-based game. In *Contemporary Issues in Decision Making*, Borcherding K, Larichev OI, Messick DM (eds). North-Holland: Amsterdam.
- Rogers EM. 1995. *Diffusion of innovations*. The Free Press: New York.
- Schaefer MB. 1957. Some considerations of population dynamics and economics in relation to the management of marine fisheries. *Journal of the Fisheries Research Board of Canada* **14**: 669–681.
- Scheffer VB. 1951. The rise and fall of a reindeer herd. *The Scientific Monthly* **75**: 356–362.
- Smith VL. 1982. Microeconomic systems as an experimental science. *The American Economic Review* **72**(5): 923–955.
- Smith VL, Suchanek GL, Williams AW. 1988. Bubbles, Crashes, and Endogenous Expectations in Experimental Spot Asset Markets. *Econometrica* **56**(5): 1119–1151.
- Sterman JD. 1987. Testing behavioral simulation models by direct experiment. *Management Science* **33**(12): 1572–1592.
- Sterman JD. 1989a. Misperceptions of feedback in dynamic decision making. *Organizational Behavior and Human Decision Processes* **43**(3): 301–335.
- Sterman JD. 1989b. Modeling managerial behavior: misperceptions of feedback in a dynamic decision making experiment. *Management Science* **35**(3): 321–339.
- Sterman JD. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin/McGraw-Hill: Boston.
- Tversky A, Kahneman D. 1974. Judgment under uncertainty: heuristics and biases. *Science* **185**: 1124–1131.
- Walker J, Gardner R, Ostrom E. 1990. Rent dissipation in a limited-access common-pool resource: experimental evidence. *Journal of Environmental Economics and Management* **19**(3): 203–211.
- Wilson JR, Lent R. 1993. *Economic Perspective and the Evolution of Fisheries Management Methods: Towards subjectivist methodology*. Université du Québec à Rimouski: Québec.