Ore Money Ore Problems: A Resource Extraction Game

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Abstract:

The economic theory of natural resource exploitation predicts that scarcity crises will not arise because forward-looking resource owners, to maximize their profit, will smooth their extraction over time. The model that provides this result can seem opaque and technical to students, but its intuition can be learned from experience. This paper shares a game that provides that experience. Participants play the role of mine owners who must decide how much to extract in each of two periods. In addition to showing how price signals through markets can prevent sudden increases in scarcity, the game also provides lessons about intertemporal choice, market power, information, and property rights. I provide all materials needed to play the game as is or to customize it for alternative learning outcomes.

Keywords: classroom game, natural resource extraction, Hotelling rule, active learning

JEL Codes: A20, Q30, D25, D40, Q02

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Our modern lifestyles rely on a wide array of non-renewable resources that we are consuming a rate that may seem alarming. Whether it be phosphorous (Grossman, 2019) or oil (Bardi, 2019), our attention is often called to a looming scarcity that we are told will imperil our continued comfort and happiness. Economists typically brush off such concerns by arguing that markets handle scarcity reasonably well. The standard textbook coverage of natural resource economics (e.g., Hanley et al., 2019; Tietenberg and Lewis, 2018), based on the seminal and still central model by Hotelling (1931),[i] demonstrates that future scarcity sends signals to the present through prices, thus encouraging reactions like conservation and substitution and thereby preventing such crises before they arise. This model is a compelling piece of microeconomic theory that has received increasing empirical support in recent years (e.g., Anderson et al., 2018; Atewamba and Nkuiya, 2017). However, students often struggle with the mathematics used to represent the model. Therefore, in this paper, I present a new game that lets students interact with and learn from an intertemporal resource extraction problem in several settings.

In the game, participants play the role of mine owners. They play through a series of scenarios. In each scenario, they must allocate their extraction from their mine across two time periods. They receive "earnings" for the scenario equal to the present value of the stream of profits from the mine across the two periods. The game is engaging and interactive, making the intuition of the model more accessible to students at all levels. As Ball et al. (2006) show, interactive games can help students learn. I recommend paying some randomly chosen participants money proportional to their earnings in the game to further heighten engagement, as suggested by Holt (1999). This game works well in classes of any size, and is well suited to classes that cover either natural resource economics or policy or intertemporal decision-making. It can be used with participants at any level of technical background; more advanced undergraduate or graduate students (those with substantial mathematical background) can link the intuition from the game to the mathematical models they are learning in the course, while the game will give less technically inclined students access to key insights from the model that the mathematics precludes them a formal understanding of.

The game supports many learning objectives. In natural resource economics, of course, participants learn this workhorse theory, including learning about depletable natural resource management, scarcity rent, and economical and uneconomical reserves. In addition, the game provides interesting applications of broader microeconomics concepts including intertemporal decision-making, scarcity, information, market power, and common pool resources.

The game can be easily run as is with the provided materials, or customized. With this paper, I provide many editable resources to make the game easy to use and flexible. Appendix A provides instructions for participants. Appendix B explains (for instructors) how to run the game in step-by-step detail. There are additional online supplementary materials:[ii] Crucially, the spreadsheet needed to play the game, in addition to editable versions of the participant instructions and the instructor how-to, a mathematical derivations appendix that solves the Hotelling model for several cases, and slides that can be used while playing the game.

This paper proceeds as follows. First, I provide some background on the economic model of natural resource extraction; the target audience for this section is the instructor, but some instructors may choose to share some of the content or sources contained therein with students. Next, I describe the game in detail, with in-depth discussions of each scenario including theoretical predictions and discussion topics, as well as advice for post-game discussion and assignments. I then suggest some modifications and extensions that can be made to the game. Next, I share feedback from my use of the game in classes, and finally I conclude.

BACKGROUND: NATURAL RESOURCE ECONOMICS

Waves of concern about natural resource scarcity seem to be a recurring phenomenon. This concern was perhaps never a larger part of the public consciousness than in the late 1960's, when biologist Paul Ehrlich wrote the bestselling book *The Population Bomb* (1968). He argued that human population growth would ravage the earth's resources and soon lead to a crash as resources were depleted. As described by Sabin (2013), Ehrlich's claims eventually sparked a public bet between him and skeptical economist Julian Simon: they would monitor the prices of five metals for ten years, and if the prices went up, indicating increasing scarcity, Ehrlich would win, whereas if they went down, Simon would win. In the end, Simon won unequivocally.

It is obvious why Ehrlich would worry that resources would run out: key materials (like copper and nickel, which were part of the bet) exist in fixed quantity; if use trendlines are extended into the future, exhaustion of the resource followed by a crisis seems inevitable. Why, then, was Simon so sanguine? In a word, markets. The economic theory of natural resource extraction holds that if markets function well, future scarcity gets "priced in" now. Earlier use is moderated by expectations of later demand; that is, the promise of selling to a resource-hungry future market incentivizes behavioral responses in the present. This theoretically yields a smooth pattern of extraction over time leading to a gentle transition to an alternative (backstop) resource. In other words, given a particular set of assumptions, scarcity takes care of itself.

As noted by Devarajan and Fisher (1981), the economic approach to modeling natural resource use is rooted in Hotelling (1931). Hotelling assumes a mine owner chooses how to allocate their extraction of a fixed supply of a resource over time to maximize the net present value of their stream of benefits. His central result is that, in a competitive market, the net profit from mining a mineral resource will rise over time at the market rate of return. That is:

$$p_t - c_t = (p_0 - c_0)(1+r)^t, \quad t = 0,\ldots,N,$$

where at time t, p_t is the market price of the resource, c_t is the marginal extraction cost, and r is the interest or discount rate.[iii] Thus, the mine owner will extract at a pace that forces the resource in the ground to appreciate at the same rate as other potential investments. Further, this also maximizes social welfare because the extractor internalizes both current and future profits.

This can be shown graphically in a two-period setting like that in this game. As shown in Figure 1, resource extraction in the first and second periods can share a horizontal axis if the resource will be exhausted, since the sum of the two extracted amounts equals the stock size. Then one can plot the present values of net marginal benefits of extraction in each period together: the first period from left to right and the second from right to left. Each curve is the demand curve for the resource in that period minus the marginal extraction cost. The private optimum is where the curves cross, that is, where the present values of net marginal benefits are equalized. If the extractor's values are aligned with society's, this is also the social optimum.

[Insert Figure 1 about here]

Imagine if this condition did not hold. For example, if the present value of net marginal benefits were higher in the second than the first period, then the last unit extracted in the first period would generate more profit if it were saved for the second period; that shift of a unit from present to future would drive the first period price up and the second period price down, bringing them closer together. Thus, it can't be an equilibrium choice for present value of net marginal benefits to rise over time, and of course the same thought experiment can be performed in the other direction to show it can't fall.

This model predicts that even in a competitive market, the resource price will not be driven down to the marginal extraction cost. It is higher by an amount known as the *marginal user cost* or the *scarcity rent*. This value represents the opportunity cost of using a unit of resource now when that takes away from future use; it is a profit (rent) that accrues to the resource extractor because of natural scarcity. Thus, the scarcity rent is the best measure of true economic scarcity. Note that the remaining stock of a resource is not a good measure of scarcity because some units of that stock may not be economically worth extracting (as discussed below) and because true scarcity depends not only on supply but also demand. It is for this reason that the outcome of the Simon-Ehrlich bet was change in resource price, because if marginal extraction cost varies little, then change in price is a good reflection of the change in scarcity.

The model as outlined here indicates that reduction in current use (movement along the demand curve) of the resource is incentivized by future scarcity through current price increases. That reduction can happen through reductions in resource-intensive activities, such as driving less, or shifts to more resource-conserving ways to do those activities, such as driving a more fuel-efficient car. Also, the resource demand curves, and therefore the present value of net marginal benefit curves, hit the vertical axes at finite prices, so there is a maximum price people will pay for the resource. This is called the *backstop price*, and is commonly thought of as the price of the best alternative (the backstop); for example, people will stop buying gasoline if it becomes so expensive that electric cars are always cheaper to drive. In an infinite-period version of the model, the resource price resource rises over time to the backstop price, and when it does there is a smooth transition to the alternative.

Richer models incorporate additional responses to scarcity in response to rising prices: exploration and innovation, which shift the curves in Figure 1 rather than initiating moves along them. First, the rents provided by scarcity give an incentive to find new sources (Pindyck, 1978), which expands the available stock, thus expanding the horizontal axes of the diagram and causing the intersection to occur at a lower price. Second, higher prices render users of the resource willing to pay more for technical efficiency improvements that allow more consumption to come from a given amount of resource. For example, high gas prices increase demand for fuel efficient cars, and this incentivizes firms to innovate hybrid cars that still use gas but go many more miles on a gallon. Third, the returns to developing (or bringing down the cost of) alternatives (backstops) to the resource, also become much higher. Either of these latter two will likely shift the demand curve down (though by the Jevons paradox, as discussed in Alcott, 2005, improved technical efficiency could increase demand, but this is less likely), which will drive down the price and thus the scarcity rent: with less demand for the resource, it literally becomes less scarce in an economic sense.

The model as I have described it so far assumes a perfectly competitive output market for the resource. As early as Hotelling (1931), economists have theorized that firms with market power will extract the resource even more slowly than competitive firms, because that will drive up the prices and thus profits even more in early periods.

I have also described a situation in which all of the resource will eventually be depleted. However, in many cases, some of the resource is so costly to extract that it will never be profitable to do so at any price the market will bear. These are called *uneconomical* deposits of the resource. For example, a number of factors have rendered coal largely uneconomical in the United States, and coal power plants are being closed as a result (e.g., Haggerty, 2021). A formerly economical resource can become uneconomical when the demand curve shifts down, including through regulation or technology changes, or as marginal extraction costs rise. Many resources have some deposits that are higher cost to extract and some that are lower cost to extract; for example, oil accessed through a conventional well is typically relatively cheap to extract, while shale oil, offshore oil, and tar sands (bituminous) oil tend to be more expensive. These more expensive deposits will only be economical if market prices are high (above their marginal extraction costs).

For a time, as summarized in Krautkraemer (1998), empirical evidence appeared to contradict the theory laid out in Hotelling (1931). Notably, natural resource prices often tend to decline over time. However, Slade and Thille (2009) note that modifications to the theory can make it more realistic, and show that while research to that date found mixed evidence in support of the basic Hotelling model of rising prices, a good body of work supports U-shaped curves. Slade and Thille (2009) categorize three main reasons that prices could fall: exploration (Pindyck, 1978), technical change (Slade, 1982), and recycling (Levhari and Pindyck, 1981). They further note difficulties in testing the Hotelling theory empirically, including endogeneity, non-stationarity, and the difficulty of measuring marginal user costs, in addition to significant short run volatility that adds noise to long term trends.

More recently, new work has incorporated more nuanced modeling and econometric techniques to improve the alignment of the Hotelling (1931) model with reality. For example, Atewamba and Nkuiya (2017) study 14 nonrenewable resources, developing a new more flexible empirical model that allows resource extraction costs and demand to vary in realistic ways. They find support for their model. As another example, Anderson et al. (2018) study oil extraction from wells in Texas, showing that oil prices affect drilling of new wells and extraction costs but not oil production from existing wells. They augment the Hotelling (1931) model to reflect the fact that as oil is extracted, oil pressure in a well declines, and show that this modified model explains oil drilling and extraction in Texas relatively well.

Of course, these results only show that a firm's extraction decision smooths scarcity over time; it does not prove that the outcome is efficient. There are many potential reasons that privately optimal extraction decisions may not maximize social welfare. For example, if the firm uses a higher discount rate than society does, it will extract the resource faster than is efficient. A second example is that if the entity extracting the resource does not have secure property rights, there is an incentive to extract too quickly because future profits from the resource may not belong to them. Perhaps most importantly, if the extraction or use of a resource causes negative externalities, then because these costs are outside of the extractor's incentives, the firm will extract the resource faster than is socially optimal and, crucially, more of the resource will be privately economical than will be socially economical to extract; in other words, society would be better off if more coal, oil, and natural gas were left in the ground than firms would choose.

THE GAME

This is a roleplaying game in which participants play mine owners in a two-period setting, with several variations to demonstrate features of natural resource economic theory. In this section, I first give an overview of the game, then describe the game scenarios in detail, finishing with advice for discussions and assignments related to the game. This section stays at a relatively high level; I provide additional materials that serve other purposes:

- Participant instructions (Appendix A; editable version in electronic supplementary materials): instructions and recording sheet for game participants

- Instructor how-to (Appendix B; editable version in electronic supplementary materials): detailed point-by-point guide to running the game
- Recording spreadsheet (electronic supplementary materials): worksheets for recording decisions and calculating payoffs, and a worksheet showing optimization solutions
- Mathematical derivations (electronic supplementary materials): derives solutions to the optimization problems for most of the scenarios
- Slides (electronic supplementary materials): to show while playing the game (if desired)

The game is structured around a basic decision by a mine owner: how much of their valuable natural resource to extract in each of two periods. I provide six scenarios (essentially, experimental treatments) that vary the decision environment in empirically relevant ways. These scenarios and their learning objectives are described in Table 1.

[Insert Table 1 about here]

The Standard Discounting scenario, listed as the second scenario, is the base configuration off which all other scenarios are built, but I suggest running it after the No Interest scenario, since it is easiest for participants to start learning the model without discounting and then to learn how interest changes the outcome.

The game can be played entirely in person, entirely remote (e.g., on Zoom), or with some participants remote and some in person. It should be played synchronously.

An instructor can choose to run any subset of scenarios and in any order. It may be fruitful to repeat some scenarios; the materials I provide repeat the Competition scenario (which particularly benefits from repetition) twice. Instructor can also create their own scenarios; see the

Possible Extensions and Modifications section for some ideas. How long the game takes depends on whether participants read the instructions in advance, which scenarios are chosen, how many times they are repeated, how big the group is, and how much discussion there is. A fast game with little discussion and the simpler scenarios (No Interest, Standard Discounting, Future Demand Boom, and Competition, for example) can take 30 minutes; the full set of scenarios with moderate discussion can be executed in a 50- or 75-minute class period. While the Competition and Common Pool Resource scenarios are the most complicated and difficult to understand, and thus time-consuming, at least one of them should be included because those are the only scenarios in which participants' actions affect each other's outcomes, a feature participants tend to enjoy. Additional activities can be built around the game to create a larger course module, as I note in the Suggested Related Assignments and Activities section.

Basic Game Structure:

In each scenario, there are two time periods. They can be described to participants as sequential years, though if so participants must understand that these are the only years that exist (so there's no reason to conserve the resource past the second period); alternately, the periods can be described simply as Now and the Future (which have similar durations).

Each participant is a mine owner who can extract the resource in these periods and who has earnings from selling the extracted resource on an output market. My materials call the resource bitcoinium, but the instructor can choose to change that to a name that resonates with participants (e.g., a real resource or something based on the school mascot). I recommend that after the game, at least one participant be paid an amount of money proportional to their earnings in the game. The spreadsheet I provide converts earnings to be in the range of approximately $10 and randomly chooses two participants for payment, though the instructor can change the conversion rate or otherwise manage the incentives differently: pay more or fewer participants, provide a different form of reward (e.g., donation to a charity chosen by the students, snacks or coffee for the group, extra credit), or provide no reward at all.

In the game, if x_t is extraction in each period $t = 1, 2$, the present value of profit is:

$$PV\Pi = \pi_1 + \frac{1}{1+r}\pi_2 = p_1 x_1 - c\left(x_1\right) + \frac{1}{1+r}\left(p_2 x_2 - c\left(x_2\right)\right),$$

where p_t is the price that prevails in period *t* and is derived from a demand curve, $c\left(x_t\right)$ is the cost of extraction, and *r* is the interest (and discounting) rate.

Participants technically have two decisions to make: x_1 and x_2. However, given a finite stock size of $S = 100$ and given that all units of the resource are economical to extract except in the Rising Marginal Extraction Costs scenario, in most scenarios it is assumed that $x_1 + x_2 = 100$. Therefore, participants only must state their x_1, and x_2 is inferred as the residual.

Participants record their choices in the table at the end of their instructions. Decisions can be declared verbally and recorded manually, or collected through a Google Form; the Instructor How-To explains how to do each. The instructor records decisions in the spreadsheet from the supplementary materials. Figure 2 shows an example of this spreadsheet for the Standard Discounting scenario. Note that the "Extract" column is highlighted to indicate where decisions are to be entered, and the highest profit earned is also highlighted.

[Insert Figure 2 about here]

After each scenario, the instructor can show participants the outcome and lead discussion. It is possible to defer all discussion until after all scenarios, but short discussions after each scenario can help participants process concepts in real time and apply what they learn in later scenarios. During discussions, the instructor can temporarily modify values in the "parameters" worksheet of the spreadsheet to show how outcomes change. In addition or instead, the instructor can show the "example calculations" spreadsheet, which calculates the optimal extraction choices for the given set of parameters in the monopolistic and competitive output market cases.

Scenario 2: Standard Discounting

I describe this scenario first, although I number it second and recommend it be run second, because it is the baseline off which all the other scenarios are built. In this scenario, the mine output is sold on a monopolistic market, allowing each participant to consider their decisions independently from each other. The demand curve each monopolist faces in each period is $p_t\left(x_t\right)=200-x_t$. The extraction cost is $c\left(x_t\right)=50x_t$. The interest rate is 10%.

The optimal choice for a monopolist maximizing net present value of profit across the two periods is to extract 51.19 units in the first period and 48.81 units in the second period.

If this is run after the No Interest scenario, then discussion after the scenario can focus on the role that discounting plays in altering the time path of extraction. Participants can also be reminded that while 10% is a relatively large discount rate, this is only a two-period model; a model with more periods, allowing for compounding, would show discounting shifting extraction more strongly into early periods. The instructor can encourage participants to speculate on whether mine owners discount the future at the same rate at which society discounts, and if they do not, what that divergence means for the efficiency of unregulated resource extraction: firms and individuals likely discount the future more steeply than society, and thus may extract too fast. Similarly, if the resource's extraction or use are associated with negative externalities, then society may benefit by extracting more slowly, which pushes damage costs into the future, or by leaving some (or even all) of the resource in the ground.

Scenario 1: No Interest

Again, I suggest this scenario be run first because it is the simplest and helps establish the model's intuition. In this scenario, all is as in the Standard Discounting scenario, except that the interest rate is zero. The profit maximizing extraction in each period is 50 units of the resource; that is, extraction is evenly split across the two periods.

If this scenario is run first, then after it is complete, participants can be queried on any unexpected choices they made, which often guides them to a stronger understanding. The diagram shown in Figure 1 can be replicated on the board to show how, with identical demand in two periods and no discounting, the present value curves will be symmetrical, yielding the equal-split outcome. If participants are more technically advanced, they can be reminded that a constant marginal cost often gives an indeterminate choice of output in other settings, and to reflect on why the outcome is uniquely determined in this situation.

If participants look at the "example calculations" worksheet, they may see that the present value of the marginal user cost (scarcity rent) calculated for this scenario rises across the two periods. That is because the marginal user cost is calculated as the difference between price and marginal extraction cost. However, this is only correct in a competitive market, because marginal cost under conditions of scarcity equals marginal extraction cost plus marginal user cost, and only in competition is it true that price equals marginal cost.

Scenario 3: Future Demand Boom

This scenario alters the Standard Discounting scenario by shifting out period 2 demand to 50 percent beyond its original position, so $p_1(x_1) = 200 - x_1$ but $p_2(x_2) = 300 - x_2$. A profit maximizing extractor will now save a great deal of extraction for the future: period 1 extraction is 27.38 units, and period 2 extraction is 72.62 units.

Relative to the Standard Discounting scenario, nothing has changed in the facts of the first period market. However, first period extraction should change dramatically because of knowledge that the second period will face greater demand. This means that information about future scarcity (which is created by greater future demand) makes profit-maximizing extractors moderate current extraction to alleviate the future scarcity. Conservation occurs, not driven by concern for the future of humanity but by prices: future scarcity pushes up the future price, which increases the return to waiting to extract the resource. Thus, as long as future scarcity is (in expectation) foreseeable, there will be no sudden "peak resource" with a precipitous decline, as has been feared for resources like oil and phosphorous.

The instructor can note that several possible responses to scarcity are shut off in this model, notably exploration for new resources and innovation to either increase resource use efficiency or develop or reduce the cost of substitutes. It is also worth discussing cases in which this process may be less successful, e.g., with imperfectly functioning markets, insecure property rights (e.g., concern that the mine will be expropriated), or truly unforeseen future shocks.

Scenario 4: Competition

This scenario modifies the Standard Discounting scenario by merging all mine owners' output markets, so that rather than each having monopolistic control of their market, they all compete in selling the resource. The combined market demand curve is the horizontal sum of the demand curves of the individual markets from the monopolistic scenario. The competitiveness of the market depends on the number of participants; technically this is a Cournot oligopoly, and thus it approaches perfect competition as N approaches infinity. Especially in a small group, participants may even try to collude to drive prices to monopolistic levels. For that reason, and because strategy in this scenario is overall difficult, I recommend running this scenario twice.

The theoretical privately optimal choice for each firm is 54.76 units extracted in period 1 and 45.24 units extracted in period 2. Thus, extraction is slower in the monopolistic case than in this competitive scenario, as theorists back to Hotelling (1931) have predicted: market power causes firms to restrict supply to drive up price, yielding a slower extraction path.

In discussion, participants can explore the intuition behind this market power result. Further, they can discuss the efficiency implications of market power in this setting. Participants may be accustomed to expect that monopoly is inefficient as compared to competition, and this is true if there are no other market failures. However, if firms discount the future too much or if extraction or use of the resource causes negative externalities, as discussed above, they may extract faster than is efficient, in which case market power's slowing of extraction could increase social welfare.

Participants may also note that even in competition, the market price of the resource is above the marginal extraction cost. This allows the concept of marginal user cost, also known as scarcity rent, to be introduced: it is the wedge between price and marginal extraction cost and it represents the opportunity cost of extraction now, since the resource is scarce and extraction now therefore comes at the cost of future extraction. The "example calculations" spreadsheet shows that in competition, the marginal user cost rises at 10 percent, the interest rate.

Participants may also enjoy discussing whether collusion between mine owners to drive up collective profits by extracting more slowly is feasible in this game, and whether it would be more or less likely to succeed in real-life resource extraction scenarios.

Scenario 5: Rising Marginal Extraction Costs

In this scenario, marginal extraction costs rise with the amount of resource cumulatively extracted so that the marginal extraction cost of a unit is three times the total amount of resource extracted up to this unit. This happens when marginal extraction costs vary, because resource extractors extract the cheapest-to-access units first. For example, in an underground mine, miners extract ore closer to the surface before digging (at greater expense) to access deeper-buried ore.

The cost function in the first period is $c_1\left(x_1\right)=1.5x_1^2$. The cost function in the second period must recognize that the first unit extracted in the second period will be more expensive to get out because of how far down in the mine it is and how much harder the extraction work therefore is. Thus, the cost function in the second period is $c_2\left(x_2 \mid x_1\right)=1.5\left(\left(x_1+x_2\right)^2-x_1^2\right)$.

I do not provide an analytical solution to this scenario because the math is more complicated than the previous scenarios, though the supplementary material shows the first steps. However, the prediction is that it is not privately optimal to extract all of the resource, as some of it has a marginal extraction cost above the price that could be obtained on the market; in other words, some of it is uneconomical.

In discussion after this scenario, participants should be able to come up with examples of resources that have some uneconomical stock, such as lithium sparsely distributed in soils and shale gas deposits in the western US. It is also useful to discuss parameters that can shift a resource deposit into or out of being economical, such as shifts in demand (e.g., from business cycles or regulations such as carbon taxes) or improvements in technology (which shift marginal extraction cost down, as with the advances in horizontal drilling and ground imaging that made shale gas economical in the first place).

Some participants may enjoy discussing theoretical points related to rising marginal extraction cost. For example, as marginal extraction cost rises, marginal user cost declines because the net value of the resource is declining, until (in a competitive market) the last unit that is economical has a scarcity rent of 0, since it is no longer an economically valuable resource.

Scenario 6: Common Pool Resource Mine

In this scenario, participants are grouped into pairs or trios. Each small group has a shared mine; that is, the participants in a pair or trio own mines that are physically connected, or own separate access points to a large deposit they all have rights to extract from. The total per capita resource stock size is the same as in the other scenarios.

Since extraction decisions are simultaneous, this configuration gives a financial incentive for players to extract the resource from the shared mine more quickly in an effort to appropriate as much of the resource as possible. In each period, the spreadsheet determines whether the total amount participants try to extract exceeds the amount left in the mine. If it does, everyone's attempted extraction is adjusted down proportionally so that the mine is exactly fully depleted.

Because of the complexity of this scenario and the necessity of basing any solution on assumptions (e.g., symmetry), I again do not derive a precise solution. However, the incentive to "beat" other miners to extraction will weigh against the quadratic impact of extraction on profits (which pushes toward having extraction more evenly split across the two periods), so it is likely that there will be a great deal of extraction, but not over-extraction, in the first period, with some resource left over for the second period, in which there will be a scramble to grab the last units.

Discussion can ensue regarding common pool resources, introducing examples such as fisheries and aquifers. Most likely, completely rapacious behavior will not ensue in all groups; participants can consider how social preferences such as altruism or warm glow (Andreoni, 1989) may contribute to restraint. The work of Elinor Ostrom (1990) can be introduced to discuss the complexities and opportunities associated with collective governance of the commons. Still, participants may wonder whether real life resource extraction settings are likely to give rise to good governance or whether profit motives may lead to unfortunate outcomes. International agreements to bind behavior may also arise as a point of discussion (Barrett, 2016).

Wrap-up and End-of-Game Discussion

After all scenarios are complete, the instructor should show participants the "summary" tab of the spreadsheet, an example of which is shown in Figure 3. The first set of columns summarizes each participant's total earnings, and shows the conversion to potential dollar earnings. This worksheet also contains cells that randomly select participants for payment.

[Insert Figure 3 about here]

After summarizing the outcomes and, if desired, paying selected participants, more extensive discussion can be productive. It can go in many directions, but I suggest some here.

Most simply, discussion can help participants process what they learned across the scenarios and air questions they have about the model. It is useful to probe for elements they still find confusing or unclear in the model. The "example calculations" tab of the spreadsheet can help in this, as can changing values in the "parameters" sheet and seeing how values in the worksheets for the scenarios change, or sketching manipulations of a two-period diagram of present value of net marginal benefit (like Figure 1) on the board.

Participants can also explore ways in which real world resource management scenarios may deviate importantly from the model; for each, they should consider and contrast the private optimum and the social optimum. Participants can also think of various natural resources and consider whether the problems posed by their management differs from the model presented in the game. For example, as suggested in the Possible Extensions and Modifications section, fisheries and water resources like aquifers do regenerate, but extraction rates often exceed regeneration rates.

The game as I present it does not demonstrate any regulatory interventions. Participants can discuss what kinds of regulation might be useful from an efficiency standpoint or to achieve other considerations; for example, Collier (2010) argues that the value of mineral resources in a country rightly belongs to its citizens, so if private actors are extracting the resources, governments may choose to tax away as much as possible of the scarcity rent.

After the session, the completed spreadsheet with everyone's decisions in it should be shared with the participants. They can be encouraged to explore it on their own time.

Suggested Related Assignments and Activities

Participants can be asked to do interpretive work. Most simply, participants can write an essay on what they learned from the game, studying the spreadsheet and discussing what participants chose, why they chose it, and whether the choices offer evidence of confusion. They can write more broadly on how the theory shows that intertemporal scarcity is a problem that markets and forward-looking agents can solve in some circumstances and when those are likely to hold. The instructor can pose specific circumstances and ask whether the extraction choice of profit maximizing extractors would lead to an efficient outcome. As another example, participants can be asked to vary a parameter in the "example calculations" worksheet and log how the optimized values change, and write some interpretation based on that observation.

Participants can be asked to draw the two-period present value of net marginal benefit graph (see Figure 1) and be given shocks to play out in the diagram: for example, a demand shock, a change in discount rate, a technological innovation that reduces the marginal extraction cost, or a technological innovation that allows the resource to be used with more technical efficiency (e.g., more energy or consumption can be gotten from the same amount of resource).

In more technically advanced classes, in which students are comfortable with constrained optimization, students can solve two period (or even longer-term) models similar to those in the game. The instructor should be aware that the supplementary material for this paper contains solutions to the optimization problems represented in the first four scenarios, so any graded assignment should vary from those problems in some way.

POSSIBLE EXTENSIONS AND MODIFICATIONS

Alterations that do not affect the payoff structure are easy to implement. For example, the resource can be given a different name. Alternatively, any scenario can be repeated as desired, and could be repeated with different parameters, e.g., different interest rates. This would help participants interpret the parameters and relate them to real-world settings.

Elements of the scenarios I provide can be combined. Each scenario differs from the Standard Discounting scenario by a single alteration; those alterations can be layered. For example, most scenarios have monopolistic market structures to remove the strategic element from decisions. However, competition could be made the baseline structure. This would replicate many textbook presentations of this model, and would allow marginal user cost (scarcity rent) to be calculated as the difference between price and marginal extraction cost.

My materials contain only two periods in each scenario as that is the minimal number to observe intertemporal arbitrage to solve scarcity problems. With extensive modification, the game could be modified to comprise three or more periods to demonstrate longer run dynamics.

Uncertainty can be incorporated. For example, future demand or future marginal extraction cost could have a mean zero random shock. This would allow discussion of risk aversion. If random changes in future extraction costs were influenced by innovation investments by the firms, this can spur discussion of the riskiness of innovation, innovation as a public good, and society's interest in encouraging certain forms of risk-taking.

Technical change can be incorporated as a reduction in future marginal extraction costs or an increase in future technical efficiency of use, allowing each unit of the resource to do more work. This, would likely reduce demand for the resource, though by the Jevons paradox (Alcott,

2005) it is possible demand would increase, so the instructor could implement it either way and lead a discussion about the rebound effect.

Recycling, as originally noted in Hotelling (1931), can be allowed. The cumulative amount extracted can be reclaimed in part to serve demand; the instructor can vary the recycling reclamation rate to observe the impact on extraction.

Negative externalities such as climate change can be explicitly incorporated as a damage cost, proportionate to the total amount of resource sold, subtracted from each firm's profit. This can feed into discussion of regulation of externalities and of how people behave when their actions create public bads, as it is likely that participants will show some restraint when their actions harm the whole group, even though the privately optimal choice likely changes little.

Exploration for resources can be incorporated. For example, each participant can have the option to invest independently in exploration with some chance of finding a deposit. As another example, a "gold rush" dynamic can be created with a spatial map in which deposits are randomly situated but spatially correlated with each other, so there is an incentive to explore and a further incentive to vigorously buy up land around sites on which deposits are found. This competition can be energizing for participants, and mirrors some historical resource hunts.

The resource can be given a slow but economically meaningful regeneration rate. For example, it could be framed as a fishery, where the regeneration rate is a function of the existing stock, as in Cortés et al. (2022). As another example, it could be framed as an aquifer, where the regeneration rate is exogenous. Either case can help participants explore conditions for sustainable harvest.

The origin of mine ownership rights can be studied by implementing an auction stage before the extraction decisions in a scenario in which each participant has the opportunity to bid for control of a mine. This can be made more interesting if there are a variety of mines available or if there is some uncertainty in the returns to the mine. This can highlight topics in auction design, rent seeking behavior, and valuation of assets that yield a stream of benefits.

Scenarios can be created to explore relevant policies or institutions. For example, severance taxes, which are commonly used to claim for the state some of the rents from privately extracted mineral wealth, could be implemented, and then discussed from practical and ethical perspectives. As another example, management rules could be implemented in the common pool resource scenario, for example regarding allocation of the resource when the mine is overdrawn, bargaining between mine owners, monitoring, and sanctions. Participants can be invited to propose their own policies, as in Secchi and Banerjee (2019), which can let participants explore peer or common governance, as discussed by Ostrom (1990).

CONCLUSION

Natural resource scarcity can create broad public concern. If markets function properly, scarcity can be a problem that solves itself, as prices encourage management of the resource; though other problems (like environmental damage) still persist. The game introduced in this paper gives participants experience with the classic Hotelling (1931) model of natural resource extraction to help them develop an intuitive understanding of the model. I provide the materials an instructor needs to run the game immediately or to modify it, plus topical background and suggestions for class discussions and assignments related to the game. The game can be a fun way for students to learn a topic that is very technical but has highly consequential applications.

NOTES

[i] According to Google Scholar, this paper has been cited 7,034 times, including 1,200 citations from 2016-2020.
[ii] Supplementary materials are on the author's website: https://econ.williams.edu/profile/saj2/.
[iii] In the game, I call *r* an interest rate to help participants conceptualize discounting using the intuition of the time value of money. Of course, social or personal discounting may use a rate that differs from the market interest rate.

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APPENDIX A: PARTICIPANT INSTRUCTIONS

Instructions for "Ore Money Ore Problems" Resource Extraction Game

Do you like mining? I hope so, because in this game, you are playing the role of a miner! Every participant in today's game owns their very own mine for the mineral bitcoinium. Your mine contains 100 pounds of bitcoinium (in total) that you could extract. You sell the bitcoinium you extract in a period on the bitcoinium market at a price determined by the market.

We will play through a series of configurations, which we'll call "scenarios." Each scenario consists of two periods: you can think of them as now and later, or this year and next year, but no more years exist after that. Your job is to decide how much you want to extract in each period. Each scenario is totally separate from the scenarios that come before and after, as if the universe was created anew for each, but within a scenario the second period is affected by the first period.

In each scenario, you will earn some money from your bitcoinium operation. Your earnings at the end of the game are based on the sum of these earnings across the scenarios. Two players will be randomly selected to each be paid their total earnings (summed across all scenarios) divided by $5,000. Since real money is on the line, make sure you pay attention and make the decisions that feel right to you!

More specifically, in any scenario, your profit in period 1 is $\pi_1 = p_1 x_1 - c(x_1)$, and your profit in period 2 is $\pi_2 = p_2 x_2 - c(x_2)$, where:

- π_1, π_2: profit in period 1, period 2
- p_1, p_2: market price of bitcoinium in period 1, period 2
- x_1, x_2: the amount of bitcoinium you choose to extract in period 1, period 2
- $c(x_1), c(x_2)$: the cost of extracting the amount of bitcoinium you extract in period 1, period 2

(Notice that in that profit equation, the subscripts refer to periods: period 1 is the first period, period 2 is the second period.)

Your earnings for a scenario are the total present value of your profit across the two periods. Present value is a way of making values that occur at different times comparable, since "time is money." The total present value of profit from the perspective of the first period is the first period profit plus the profit from the second period discounted back to the first period using interest rate *r*, which will be 10% except where otherwise noted. The present value of profit is:

$$PV\Pi = \pi_1 + \frac{1}{1+r}\pi_2 = \underbrace{p_1 x_1 - c(x_1)}_{\text{period 1 profit}} + \underbrace{\frac{1}{1+r}}_{\text{discounting}} \underbrace{\left(p_2 x_2 - c(x_2)\right)}_{\text{period 2 profit}}$$

In addition, each of the following elements will hold in most scenarios we play, but each item will change in some scenarios.

- Each miner is in a geographically isolated country, and there's no commerce with the other miners' countries. As a result, each miner sells bitcoinium on their own market, separate from all other markets; they are a monopolist.
- The price on your market in a period is \$200 minus \$1 times the number of pounds of bitcoinium you have extracted in that period. Therefore, prices are:

  $p_1 = \$200 - \$1 \times x_1$ and $p_2 = \$200 - \$1 \times x_2$

- Each pound you extract costs you \$50 to extract, and there is no fixed cost of extraction. Therefore, costs are:

  $c_1(x_1) = \$50 \times x_1$ and $c_2(x_2) = \$50 \times x_2$

Thus, plugging all the numbers and functions in, earnings for a scenario are generally:

$$\Pi = (\$200 - \$1 \times x_1)x_1 - \$50 \times x_1 + \frac{1}{1+10\%}\left((\$200 - \$1 \times x_2)x_2 - \$50 \times x_2\right)$$

Again, in each scenario, you must decide how much to extract in each period: x_1 and x_2. Except where otherwise noted, we will assume that you will extract your entire stock of 100 pounds across the two periods, so you will simply declare how much you want to extract in the first period (x_1) and that will determine the amount you will extract in the second period as $x_2 = 100 - x_1$.

If you would like to see the math behind this model of natural resource extraction, or to play around with the spreadsheet that will be used to record decisions – which also includes a simulator you can use to explore the model – these are provided as supplementary materials with the article that describes this game; if you can't access them, your instructor should be able to! But they might choose to ask you to wait until after you've played the game.

We'll progress through the scenarios together and synchronously. In each round, you'll either be declaring your decision out loud for the instructor to record, or entering it into a Google Form, whichever the instructor chooses.

<u>Scenario 1: No Interest</u>

First, let's simplify the situation one step further: there's no interest ($r = 0$). As a result, your earnings in this scenario will simply be:

$$PV\Pi = (\$200 - \$1 \times x_1)x_1 - \$50 \times x_1 + (\$200 - \$1 \times x_2)x_2 - \$50 \times x_2$$

<u>Scenario 2: Standard Discounting</u>

Now let's return to a situation with an interest rate of 10%. Your earnings in this scenario are:

$$PV\Pi = \left(\$200 - \$1 \times x_1\right)x_1 - \$50 \times x_1 + \frac{1}{1+10\%}\left(\left(\$200 - \$1 \times x_2\right)x_2 - \$50 \times x_2\right)$$

Scenario 3: Future Demand Boom

Before period 1 starts, you have learned some interesting information: by the time period 2 rolls around, a new technology will hit the market that turns bitcoinium into ice cream, shifting demand 50% higher in that period than it normally is. Therefore, your earnings will be:

$$PV\Pi = \left(\$200 - \$1 \times x_1\right)x_1 - \$50 \times x_1 + \frac{1}{1+10\%}\left(\left(\$300 - \$1 \times x_2\right)x_2 - \$50 \times x_2\right)$$

Scenario 4: Competition

It turns out that whole ice cream technology story was oversold by starry-eyed tech reporters; the system never got past the prototype stage, so future demand will be the same as current demand. But the world's trade barriers have come down! You and all of the other miners are selling on a single global market. This means that global demand is the horizontal sum of the demand functions in each market. It also means that the bitcoinium produced by *any* miner affects the price of bitcoinium for *everyone*.

We represent the number of miners as *N*. Based on math you can see in the supplemental file, if we represent each miner's extraction in period 1 as x_{i1} and in period 2 as x_{i2}, global demand is:

$$p_1 = \$200 - \frac{\$1}{N} \times \sum x_{i1} \quad \text{and} \quad p_2 = \$200 - \frac{\$1}{N} \times \sum x_{i2}$$

where the big Σ indicates a sum of all the extraction choices listed next to it. Therefore, your earnings for each time we play this scenario are:

$$PV\Pi = \left(\$200 - \$1 \times \sum x_{i1}\right)x_{you1} - \$50 \times x_{you1} + \frac{1}{1+10\%}\left(\left(\$200 - \$1 \times \sum x_{i2}\right)x_{you2} - \$50 \times x_{you2}\right)$$

where we add the word "you" to the subscript for *your* extraction in each period for clarity. Notice that everyone's production drives the price down for everyone (so this is a competitive oligopoly), so your revenues are affected both by your choice and everyone else's choice, but your costs are only affected by your choice.

Since this is tricky, we'll play it twice (scenarios 4-1 and 4-2), each with two periods.

Scenario 5: Rising Marginal Extraction Costs

We now return to the world in which each miner sells in their own geographically isolated market as a monopoly. However, extraction costs are more complicated: they start at $0 and then rise by \$3 for each pound you extract, as you have to dig deeper to access them. In other words, your marginal cost to extract another pound of bitcoinium will be \$3 times the number of pounds you have already extracted across this whole scenario. Your marginal cost to extract pound x_1 in period 1 is $\$3x_1$; your marginal cost to extract the first pound in period 2 is $\$3\left(x_1+1\right)$ since you start period 2 already "in the hole" (with all the easiest-to-extract bitcoinium already extracted in period 1); and your marginal cost to extract pound x_2 in period 2 is $\$3\left(x_1+x_2\right)$.

This means your total extraction costs to extract amount x across the two periods would be $\$1.5\times x^2$ if there was no discounting, though with discounting, the period 2 extraction costs will be discounted.

Your earnings are therefore:

$$PV\Pi=\left(\$200-\$1\times x_1\right)x_1-\$1.5\times x_1^2+\frac{1}{1+10\%}\left(\left(\$200-\$1\times x_2\right)x_2-\$1.5\times\left(\left(x_1+x_2\right)^2-x_1^2\right)\right)$$

This time, you might not want to extract all your bitcoinium: some of it might cost more to extract than you can sell it for. Therefore, when you state your decisions in this scenario, you will declare both how much you will extract in period 1 and how much you will extract in period 2 (making sure the total is 100 pounds or less).

Scenario 6: Common Pool Resource Mine

We return again to our baseline configuration, but someone has made an intriguing innovation. It is now possible to drill for bitcoinium sideways for a short distance. As a result, pairs of neighboring countries effectively each have a shared two-country common pool of bitcoinium that both countries' miners can extract from. In this world, geography is such that pairs (or trios) of countries coexist on islands, so that each country shares one mine with one (or two) other country/ies. Each country's market for selling bitcoinium is still separate from other countries' markets.

Your profit will again be:

$$PV\Pi=\left(\$200-\$1\times x_1\right)x_1-\$50\times x_1+\frac{1}{1+10\%}\left(\left(\$200-\$1\times x_2\right)x_2-\$50\times x_2\right)$$

But now, you are paired with another miner. The pairing is by adjacent numbers. Miners 1 and 2 are paired, and 3 and 4, and 5 and 6, and so on. If there is an odd number of participants, the last one is added into the preceding pair, making a three-country cluster. Each two-country cluster will have 200 pounds in total to extract across the two periods; each three-country cluster will have 300 pounds in total.

Each miner will choose your extraction in period 1 simultaneously and independently; you must commit to your extraction before you see the choice of the country that shares your mine. Once everyone has made their decisions, everyone's decisions will be revealed. If the total amount the members of the cluster chose is greater than the amount of bitcoinium in the common pool mine, then each person's extraction will be reduced proportionately to bring the total down to the mine size. After period 1 is complete, if there is bitcoinium left in the mine, we will get each miner's extraction decisions simultaneously and independently for period 2; again, if miners in a shared mine collectively try to extract more than remains in the mine at the start of period 2, each person's extraction will be reduced proportionately.

For example, if there are 100 pounds left in a period, and the sum of everyone's extraction is 150 pounds (say, miner 1 wants to extract 100 and miner 2 wants 50), the total attempted extraction is 1.5 times the amount that's possible. Therefore, each miner will get the amount they attempted divided by 1.5: miner 1 gets 66.67 pounds and miner 2 gets 33.33 pounds.

Because you may not be able to actually extract what you hope to, depending on what others who extract from your mind choose, when you write your extraction amount in each period, make sure you leave room to cross it out in case you need to write in a revised amount.

Recording sheet:

Your miner number: ____________________

As we progress, enter your choices into the shaded cells below. Don't skip ahead – make your choices for a period at the same time as the rest of the group. In a period, after all decisions have been reported, you will learn the price and your profit in each period, as well as your total present value profit, so only fill those in then.

Scenario	**Period 1** **Extract** x_1	 **Price** p_1	 **Profit** π_1	**Period 2** **Extract** x_2 **Usually** $100 - x_1$	 **Price** p_2	 **Profit** π_2	**Total Present Value Profit** $\mathrm{PV}\Pi$
1: No Interest		$	$		$	$	$
2: Std Discounting		$	$		$	$	$
3: Rising Demand		$	$		$	$	$
4-1: Competition		$	$		$	$	$
4-2: Competition		$	$		$	$	$
5: Rising Cost		$	$		$	$	$
6: Common Pool		$	$		$	$	$
TOTAL							$

APPENDIX B: INSTRUCTOR HOW-TO

Instructor How-To for "Ore Money Ore Problems" Resource Extraction Game

This document is for the instructor who will be running the "Your Mine!" game with their group of participants. The purpose of this document is to give you detailed, step-by-step advice to make running the game as simple as possible for you.

The preparation for the game and its execution are not particularly different if some or all participants remote (e.g., through Zoom) as compared to entirely in person, so this document will be largely independent of mode of interaction.

Before the session:

- Decide which scenarios to run and whether to repeat any of them. Here are estimates of how long each scenario will take for a modestly chatty group of 20-40 participants.
    - Scenarios 1 (No Interest), 2 (Standard Discounting), and 3 (Demand Will Boom) will be relatively fast, about 5-10 minutes each.
    - Scenario 4 (Competition), 5 (Rising MEC), and 6 (Common Pool) are more complicated, and will take 10-15 minutes each.
    - More time is required in a session if the participants have not read the instructions in advance and will instead absorb them during the session; also, the less background the participants have, and the more discussion and explanation you plan to have, the longer the game will take.
- Prep the spreadsheet (many of these can be done on the fly during the session instead if desired).
    - In each spreadsheet, if you have more than 40 participants, fill the populated columns down by dragging down the miner number and the formulae in the other columns; delete rows if you have fewer than 40 participants.
    - Delete decision data (if any exists) from the yellow cells in all the sheets.
    - Duplicate sheets for scenarios you want to repeat. (Note: in the spreadsheet as shared, Scenario 3 (Competition) is already set up to run twice.)
    - Delete sheets for scenarios you don't want to run. (You can just ignore them instead of deleting them, but you'll want to fix up the "summary" sheet to be correct in any case.)
    - Add / delete columns in the "summary" sheet to reflect all scenarios you plan to run.
    - In the summary sheet, increase or reduce the number of people to be randomly selected to pay if desired.
    - If desired, change parameters in the "parameters" sheet.
- Instructions document:
    - Propagate any changes you make in the spreadsheet to the scenarios run (e.g., add / delete / repeat scenarios, change parameters) into the instruction text and decision recording table on the last page.
    - If desired, customize the setting; for example, change the name of the mineral.

    - The instructions say two players will be randomly selected for payment; if you want to pay more or fewer, change that.
- Decide whether you will have subjects make decisions verbally, with you recording them manually, or electronically, entering them into an online form from which you will copy the entries into the spreadsheet after each period.
    - Verbal decisions can be more fun in some ways and avoid the complications of creating a form and making sure everyone gets the right link, and if someone's dithering they can feel pressure to respond more quickly in a verbal as opposed to online form format.
        - If you choose verbal decisions, no extra prep is needed.
    - On the other hand, an online form (Google Form,[2] Formstack, etc.) can make sure that everyone is making decisions simultaneously and independently from each other, and it can keep decisions anonymous.
        - For decisions to be anonymous, assign anonymous ID's to participants in a way that gives you a key linking participant ID to identity.
            - If you know who's participating in advance, you can pre-assign ID's and use a mail merge utility to email each person their own ID.
            - If you don't know who's participating in advance, you can have each participant Google "random number 1-10000" and use the result as their number, and have them enter their name / email address and the random number in a separate Google Form that you pledge not to look at until you execute payments.
        - If you choose to use a form, create a simple form with fields: "Scenario" (free text entry, or dropdown with the scenarios you will run), "Period 1 extraction" (numeric entry), "Period 2 extraction (only enter a value here in Scenario 5 (Rising MEC))" (numeric entry).
        - In advance, open up the spreadsheet that the results will get dumped into, and make sure you are comfortable retrieving the decisions and copying them into the spreadsheet.
    - If participants are engaging through a platform like Zoom, alternatively, they can declare their decisions through the chat.
- If you would like to use the slides I provide in the supplementary materials to give background and explain the game, open them and modify them as desired.
- Share materials with participants:
    - Instructions
    - (Optional) readings, including, if desired, this game's math appendix
    - (Optional but not recommended) game decision spreadsheet (it will help them better understand the model, but the calculated optimal decision is shown in the

[2] Google products do not work in China, so if some participants are in China, use a different system.

"example calculations" sheet, and that might reduce participant exploration if they see it in advance, so it may be better to share afterward)

Bring to the session (if it happens in person):

- Printouts of instructions

Start the session:

- Bring up spreadsheet on computer projected for all participants to see.
- If desired, use the slides I provide
- Explain an in introductory way the game setup.
- Explain a little natural resource economics theory (see the Background section of the paper describing the game for some key points).
- Explain whether anyone will be paid and how.
- If you do not need decisions to be anonymous:
    - Assign Miner numbers when you collect the first period of decision-making: just assign sequential numbers to participants as you ask them for their decisions.
    - In this case, participants should record their Miner numbers as they are assigned
- If you do want decisions to be anonymous (only possible if decisions are collected in an online form or through private chat):
    - Take the steps noted earlier to have participants log their Miner numbers before decision-making starts.

General advice for all scenarios:

- All cells in the spreadsheet in which you should be entering data are highlighted yellow, with some additional cells you may fill in highlighted in blue.
- To collect decisions:
    - By voice:
        - Participants should write down their decisions for a period before anyone starts reporting their decisions; this will commit them more strongly to making a decision independently.
        - Collect choices quickly. Use the same spatial pattern to request decisions – e.g., going across one row of seats and then the next and so on – so that everyone knows when they're about to be up; give a vibe of snappiness.
    - Using an online form:
        - Go to the spreadsheet output of the decision collection form and verify that all decisions are there.
        - Sort decisions by Scenario, then by Miner number.
        - Copy the Period 1 Extraction values for this Scenario into the Extract column, ensuring decisions are lined up with the correct Miner numbers.
- After decisions for a scenario are recorded, zoom and scroll around the spreadsheet if necessary to show participants the price and profit they earned in each period.

- If desired, at any time, temporarily change a parameter (e.g., discount rate) in the parameters worksheet, then go back to the decision sheet to show participants how values change as a result. Remember to change the parameter back before you proceed.

Scenario 1: No Interest (worksheet t1_nointerest)

- Explain that there's no interest
- Collect decisions for extraction in period 1; the spreadsheet assumes that period 2 extraction is 100 (the stock) minus that (i.e., that the entire stock gets extracted).
  - If you are assigning Miner numbers non-anonymously, as you get to each person and collect their decision, say their number and tell them to record it.
  - If you are using separately-assigned Miner numbers for anonymity, then from the spreadsheet output of the online form, copy the Miner numbers for this Scenario into the Miner numbers column (which is blue) in the "t1_nointerest" sheet (I recommend paste values to retain consistent appearance in the spreadsheet).
- Before decisions as you're explaining the scenario, or after decisions as you're discussing what choices people made, you might draw on the board the graph depicted in Figure 1 of the paper with dollars on the vertical axis, period 1 extraction on the horizontal axis increasing left to right, and period 2 extraction on the horizontal axis increasing right to left, and PVNMB curves crossing. If you draw it, you might leave it up so that as the game progresses you can discuss what changes from scenario to scenario.

Scenario 2: Standard Discounting (worksheet t2_standarddisc)

- Explain that there is now 10% interest; otherwise everything is the same.
- In the PVNMB graph, this manifests as a rotation downward of period 1 PVNMB.
- Note that even 10%, while larger than one sees in normal life, is not large as to make a sizable difference between the earlier period and later period optimal extraction; if desired, you can enter a larger interest rate in the parameter sheet.

Scenario 3: Demand Will Boom in the Future (worksheet t3_risingdemand)

- Explain the increase in future demand, and that current period demand does not change.
- In the PVNMB graph, this manifests as a shift upward of period 2 PVNMB
- In discussion after the decisions, make the point that period 1 extraction changed although nothing about period 1 changed; this shows how information about future shocks is incorporated into decision-making through prices.

Scenario 4: Competition (worksheets t4_comp1 and t4_comp2)

- The parameters spreadsheet determines the position of the combined the demand curve by counting the number of values in the "Miner" column of the t4_comp1 sheet, so make sure this is correct before you begin.
- I recommend running this scenario at least twice (the spreadsheet already has two copies of this worksheet) because this is a difficult problem for participants to solve. It can work particularly well to play both periods of the scenario once with no discussion, and then let

participants discuss before the second run of the scenario. Participants may or may not decide to collude to extract more slowly than the normal competitive outcome.

- Your participants may or may not find it interesting and useful to discuss, before or after the decisions, how the aggregated demand curve was created by summing individual market demand curves horizontally.
- After decisions are complete, discussions can revolve around topics such as market power, the challenges of collusion, and how the market imperfections of market power and environmental damage may counteract each other.

Scenario 5: Rising Marginal Extraction Costs (worksheet t5_risingcost)

- As you introduce this scenario, you might want to quickly sketch an increasing marginal cost curve and the quadratic cost curve it corresponds to, since participants often find it difficult to translate back and forth between marginal and total quantities.
- If desired, you can link this to changes in the PVNMB diagram, but that's tricky because the horizontal axis would have to shrink to include only the economical units.
- Emphasize that the costs increase cumulatively; they don't go back to zero at the start of period 2, because the remaining ore is still deep in the ground and hard to get out.
- In this scenario, since some units are uneconomical, each participant must report first their period 1 extraction, then their period 2 extraction. (It's probably fastest to get everyone's period 1 on one go-round, and then everyone's period 2 on a second go-round, since you can hit enter between typing each extraction decision that way.)
- Discussion after decisions are complete can revolve around the conditions that determine whether a resource is economical.

Scenario 6: Common Pool Resource Mine (worksheet t6_cpr)

- Assign people to mines by typing mine numbers in the blue "Mine" column. I suggest that you make most mines have two people (two neighboring rows); if there's an odd number, include three people in the last mine.
- Explain the rule by which over-extraction is proportionately adjusted down automatically in the spreadsheet (as explained in the participant instructions).
- If there is time to run this scenario twice, that could be fruitful.
- The PVNMB graph for this scenario is not as helpful as for early scenarios.
- Discussion after decisions can focus on the problems of common property as well as on the capacity of humans and their institutions to solve them. Participants may be able to suggest examples of important natural resources with this common pool characteristic.

After all periods of all scenarios:

- Show the "summary" worksheet, scrolling and zooming to show everyone's overall outcomes.
- Type somewhere in the spreadsheet to make the random number generator that selects participant(s) for payment run again, and then copy and paste-special-values the cells with the person/people selected so it doesn't keep recalculating.

After the session:

- Pay the winners.
- Share the completed decision spreadsheet with participants.

TABLES

Scenario	Features (Deviation from Standard Discounting)	Learning Objective
1: No Interest	No interest accrues between periods	Intertemporal choice without discounting
2: Standard Discounting	Monopoly output market; each mine owner owns a separate mine; interest accrues between periods; stable demand; constant marginal extraction cost	Natural resource management Intertemporal choice with discounting Scarcity
3: Future Demand Boom	Demand in second period is 50% higher	Transmission of information intertemporally through markets
4: Competition	Competitive output market	Market power
5: Rising Marginal Extraction Costs	Marginal extraction cost rises linearly	Economical vs uneconomical resources
6: Common Pool Resource Mine	Mine owners are grouped into pairs or trios and all members of a group extract from a pooled mine	Common pool resource management

Table 1: Game Scenarios

FIGURES

Figure 1: Optimal Resource Extraction

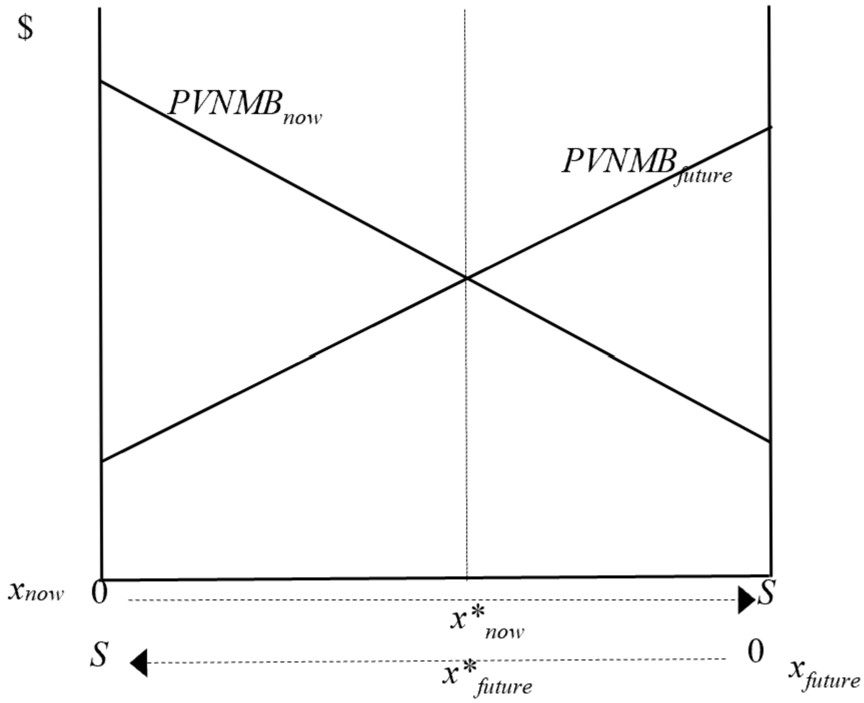

Figure 2: Game Spreadsheet Example (Standard Discounting Scenario, Simulated Data)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1		**Period 1**			**Period 2**				**Total**		**Total extraction**	**Period 1**	1930	**Total profit**	$311,818.18
2	**Miner**	**Extract**	**Price**	**Profit**	**Extract**	**Price**	**Profit**	**PV Profit**	**PV Profit**			**Period 2**	2070		
3	1	10	$190.00	$1,400.00	90	$110.00	$5,400.00	$4,909.09	**$6,309.09**						
4	2	20	$180.00	$2,600.00	80	$120.00	$5,600.00	$5,090.91	**$7,690.91**						
5	3	30	$170.00	$3,600.00	70	$130.00	$5,600.00	$5,090.91	**$8,690.91**						
6	4	40	$160.00	$4,400.00	60	$140.00	$5,400.00	$4,909.09	**$9,309.09**						
7	5	50	$150.00	$5,000.00	50	$150.00	$5,000.00	$4,545.45	**$9,545.45**						
8	6	60	$140.00	$5,400.00	40	$160.00	$4,400.00	$4,000.00	**$9,400.00**						
9	7	70	$130.00	$5,600.00	30	$170.00	$3,600.00	$3,272.73	**$8,872.73**						
10	8	80	$120.00	$5,600.00	20	$180.00	$2,600.00	$2,363.64	**$7,963.64**						
11	9	90	$110.00	$5,400.00	10	$190.00	$1,400.00	$1,272.73	**$6,672.73**						
12	10	100	$100.00	$5,000.00	0	$200.00	$0.00	$0.00	**$5,000.00**						

Figure 3: Summary Worksheet (Simulated Data)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	**Miner**	**T1: No Interest**	**T2: Std Discounting**	**T3: Rising Demand**	**T4-1: Competition**	**T4-2: Competition**	**T5: Rising MEC**	**T6: Common Pool**	**Total**	**Earnings**			**ID**	**Earnings**
2	1	$6,800.00	$6,309.09	$14,490.91	$9,056.14	$9,056.14	$3,068.18	$2,672.73	$51,453.18	$10.29		**Person chosen for payment**	**14**	**$12.00**
3	2	$8,200.00	$7,690.91	$13,600.00	$9,180.45	$9,180.45	$4,045.45	$4,963.64	$56,860.91	$11.37		**Person chosen for payment**	**5**	**$12.44**
4	3	$9,200.00	$8,690.91	$12,600.00	$9,304.77	$9,304.77	$4,522.73	$6,872.73	$60,495.91	$12.10				
5	4	$9,800.00	$9,309.09	$11,400.00	$9,429.09	$9,429.09	$4,500.00	$8,400.00	$62,267.27	$12.45				
6	5	$10,000.00	$9,545.45	$10,000.00	$9,553.41	$9,553.41	$3,977.27	$9,545.45	$62,175.00	$12.44				
7	6	$9,800.00	$9,400.00	$8,400.00	$9,677.73	$9,677.73	$2,954.55	$10,309.09	$60,219.09	$12.04				
8	7	$9,200.00	$8,872.73	$6,600.00	$9,802.05	$9,802.05	$1,431.82	$10,690.91	$56,399.55	$11.28				
9	8	$8,200.00	$7,963.64	$4,600.00	$9,926.36	$9,926.36	-$590.91	$10,690.91	$50,716.36	$10.14				
10	9	$6,800.00	$6,672.73	$2,400.00	$10,050.68	$10,050.68	-$3,113.64	$10,309.09	$43,169.55	$8.63				
11	10	$5,000.00	$5,000.00	$0.00	$10,175.00	$10,175.00	-$5,000.00	$9,545.45	$34,895.45	$6.98				