Games People Play: What Games Teach Us About Conserving Ground Water

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> *If a person puts more cattle into his own field, the amount of the subsistence which they consume is all deducted from that which was at the command, of his original stock ; and if, before, there was no more than a sufficiency of pasture, he reaps no benefit from the additional cattle, what is gained in one way being lost in another. But if he puts more cattle on a common, the food which they consume forms a deduction which is shared between all the cattle, as well that of others as his own, in proportion to their number, and only a small part of it is taken from his own cattle. In an inclosed* [sic] *pasture, there is a point of saturation, if I may so call it, (by which, I mean a barrier depending on considerations of interest) beyond which no prudent man will add to his stock. In a common, also, there is in like manner a point of saturation...*
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> *William Forster Lloyd, "Lectures on the Checks to Population" (1833)*

Introduction – The "Tragedy of the Commons"

Whatever we might think of population control as a viable strategy for the sustainability of a free society, and however much we might deplore those who advocate its implementation by various means, we have to attend honestly to the concrete limitations and that 19th-century British economists have laid before us, economists like William Forster Lloyd[2] and W. Stanley Jevons[3]: the natural endowments we enjoy and from which we extract our economic livelihoods are finite, shared, and (therefore) vulnerable to oversubscription. The first claim, that our natural resources are finite, is necessarily implied by either of two prior claims: (a) if the earth's mass is finite, so must be any of its material subsets, and/or (b) the incoming solar radiation that fuels the earth's biological processes[4] arrives at a finite rate determined by solar output (another finite, if variable, quantity), the earth's cross-sectional area (also finite), and the distance between the earth and the sun (also finite, if slightly variable). Whether the natural resource is static or (in some sense) renewable, it is *finite*, either in extent or in its rate of replenishment.

The second claim is a regional truism rather than a purely global one. Even at the scale of individual families, natural resources are *shared*; just ask the two siblings trying to stalk the same, prime deer feeder on Grandpa's ranch. Air resources are shared globally, as is seawater, although their quality varies regionally. Still, it is obvious that given a natural resource, we can probably draw a boundary within which that resource is shared between or among two or more interests.[5]

Far from debunking the "Peak Oil" hypothesis, as some claim,[6] the United States' resurgence as the world's leading extractor of fossil fuels has merely demonstrated that the confluence of economic forces and technological advances can help us increase the recoverability of fossil fuels locked away in tight or inaccessible formations. But increasing the recoverability of resources is not the same thing as increasing their abundance, an axiom that one supposes the Massachusetts Institute of Technology would be teaching its brightest students.[7]

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[2] Lloyd, W. F. 1833. Two lectures on the checks to population. Reprinted (in part) in by Hardin, G. (ed.) 1964. *Population, Evolution, and Birth Control*. San Francisco: W. H. Freeman. p. 37.

[3] Jevons, W. S. 1866. The Coal Question: An Inquiry Concerning the Progress of our Nation, and the Probable Exhaustion of Our Coal-Mines. London: Dodo Press. 237 pp.

[4] I assume that the earth's biological processes are responsible for the vast majority of the earth's fossil-fuel endowments over geological time scales.

[5] The astute reader can easily imagine a circumstance in which a natural resource is purely an individual's sole proprietorship. If that individual has more than one heir, however…

[6] The MIT-educated Michael Lynch gloats repeatedly that "Peak Oil" advocates have been getting it wrong for decades and still haven't learned their lessons. See e. g. Lynch, M. 2018. What ever happened to Peak Oil? *Forbes*, 29 Jun (accessed on the Internet 22 Feb 2020 at https://bit.ly/3bWgcMR); and Lynch, M. 2019. The Peak Oil denier takes a victory lap. *Forbes*, 04 Nov (https://bit.ly/2SN9vFn).

[7] Lynch (2019) concedes *en passant* that oil resources are "renewable, generated from organic material by geophysical processes, *albeit very slowly*" (emphasis mine). Interestingly, he then proceeds to write as if renewability (albeit slow!) were tantamount to inexhaustibility, giving negligible shrift to the transient conservation-of-mass law that he presumably learned in his first semester of differential equations at MIT.

Add to all of those considerations one more, social truism: each of us uses natural resources to add value to his life. That value might be mere survival or sustenance, or it might be increasing the availability of personal, leisure activities, or it might be simply scratching the itch to feel useful. Whatever else we may be, we are self-interested consumers of our finite, often shared, natural endowments. That implies the third claim: the shared resources upon which we all draw are *vulnerable to oversubscription*,[8] a reality that Lloyd (1833) famously illustrated with apocryphal neighbors raising cattle on pasture and which later became known as the "tragedy of the commons." Left to our own devices, interests, and values, our finite, shared resources face concrete, geophysical limits that arise even when scarcity begins to effect price signals that modulate our behavior.[9] We may use the term "common-pool resources" to refer to the broad range of finite, shared, natural endowments that are subject to the dynamics of scarcity and the competitive impulses that arise among the users of those endowments.

As we will hear from Dr. John Tracy in this conference,[10] the Ogallala Aquifer is a classic common-pool resource whose vulnerability to oversubscription was already regionally manifest in the 1970s.[11] More specifically, the Ogallala comprises at least two such aquifers: the southern half, which does not recharge appreciably, and the northern half, which does recharge, though at a rate limited by the precipitation patterns and trends over its recharge zones. Whichever regional recharge scenario we consider, however, the ground water in the Ogallala formations is unquestionably shared, and unquestionably finite. The Ogallala Aquifer's long-term status as an endowment for sustainable, regional, economic activity is therefore in question.

Or, as Dr. Tracy's title provocatively suggests, *perhaps the Ogallala's long-term status is not in question after all*.

Managing Common-Pool Resources

In their report to the Texas Department of Water Resources, Bell and Morrison (1978) concluded that the usefulness of the Ogallala Aquifer as an endowment to support agricultural livelihoods in the southern High Plains would be influenced by precipitation patterns, labor and energy costs, improved irrigation and precipitation-enhancement technologies, and "most important[ly]," *human behaviors*.[12] Today, the aquifer's decline and the attending influences are not news; that decline continues to hit the mass media even as I write this article. Assuming for the sake of argument that climatic, meteorological, and economic factors are externalities that we are largely unable to influence at the regional scale and in the near term, what human-behavior tools do we have at our disposal to modulate the aquifer's decline? Those tools fall into at least three categories: technology, regulation, and voluntary, collective action.

<u>Technology</u>

Research and development in irrigation technologies have been enormously fruitful over the past 40 years, and many of those technologies have resulted from research and demonstration investments right here at home, in the Texas High Plains. Surface irrigation (e. g., graded furrow irrigation; or in limited cases, level borders) in the region peaked around 1974 and then declined steadily, being replaced by center-pivot sprinklers, then by low-pressure spray systems, and now by subsurface drip irrigation (SDI).[13] Technologies that have indirectly improved irrigation efficiency have included, among others:

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[8] The word choice here is deliberate: *vulnerability* to oversubscription differs from oversubscription *per se*. As for "oversubscription" itself, the word may be understood generally to refer to aggregate usage that either (a) reduces a resource's quantity, (b) degrades its quality for its intended uses, or (c) both.

[9] Thus, the discipline of economics: mechanisms that allocate resources in a context of scarcity.

[10] Tracy, J. C. 2021. Sustaining an economy with an unsustainable resource: fighting, accepting or driving change. Presented at the Ogallala Aquifer Virtual Summit 2021, 24 Feb.

[11] Bell, A. E., and S. Morrison. 1978. Analytical study of the Ogallala Aquifer in Lubbock County, Texas. Austin, TX: Texas Department of Water Resources. Report no. 216. 63 pp. Accessed on the Internet at https://bit.ly/2wFnu7F.

[12] Bell and Morrison (1978), p. 10. At this point in the article, I have lumped together two different forms of human behavior specified by the authors in their conclusions: coercive ("federal crop acreage controls") and voluntary ("soil and water conservation measures…employed by the High Plains irrigator").

[13] Colaizzi, P. D., P. H. Gowda, T. H. Marek, and D. O. Porter. 2009. Irrigation in the Texas High Plains: a brief history and potential reductions in demand. *Irrigation and Drainage* 58(2):257-274.

1. Evapotranspiration-based, irrigation-scheduling systems, which provided irrigators with increasingly accurate estimates of crop water demand and therefore reduced their need to apply "insurance" water;[14]
2. Advances in crop breeding and genetics, which shortened the growing season for existing crops or permitted new, more profitable crops to be grown with less water;[15] and
3. Novel, high-value cropping systems that concentrate limited water resources on smaller acreages with higher net returns per acre.[16]

Alas, as W. Stanley Jevons warned us in 1866, improving resource efficiency through technology improvements can accelerate resource extraction rather than retard it. Speaking of the increased efficiency of coal-fired machines in British factories and machine shops, he wrote pointedly, "*it is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth*…it is the very economy of its use which leads to its extensive consumption."[17] Using the symbolic language of system dynamics, we proposed[18] that Jevons' Paradox applied equally well to irrigation efficiency (Fig. 1), a proposal that found empirical support in at least one study of irrigation practices in western Kansas.[19]

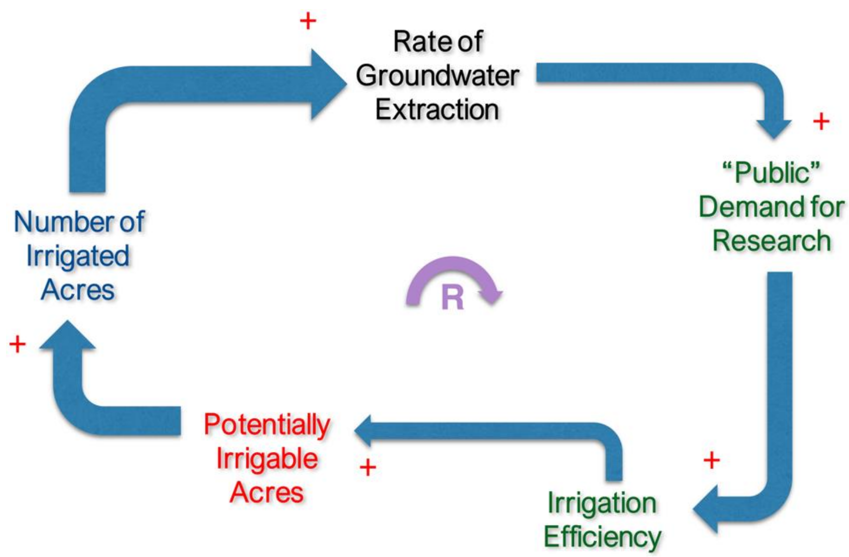

Figure 1. A causal loop diagram (CLD)[20] that purports to explain how increases in irrigation efficiency accelerate rather than retard ground water extraction. The product of the signs around a closed loop determines whether the loop is reinforcing (R; + feedback) or balancing (B; - feedback).

Note it well: we are emphatically *not* saying that we should abandon research and development programs aimed at improving irrigation efficiency. Those technology advances have, on the whole, increased marginal net

[14] See especially Figure 8 (p. 271) in Colaizzi et al. (2009).

[15] Colaizzi et al. (2009) documented the recent conversion of summer-crop acreage from corn to cotton in the northern Texas Panhandle. Cotton can be grown, and is grown in some areas of the southern High Plains, as a strictly rain-fed crop; corn is much more sensitive to the availability of soil water and is seldom grown as a rain-fed crop in the region. Cotton is more risky, however, in the northern Panhandle; the probability of insufficient "heat units" to support lint production increases as you move north into cooler sub-climates.

[16] For example, see Rho, H. T., P. D. Colaizzi, Q. Xue, and C. M. Rush. 2019. Acclimation of leaf physiological traits under high-tunnel production system increases radiation and water use efficiency in tomatoes and peppers. Presented at the 2019 ASA-CSSA-SSSA International Annual Meeting, San Antonio, TX, 12 Nov.

[17] Jevons (1866), pp. 75-76. Emphasis original. The dynamics that explain this phenomenon came to be known as "Jevons' Paradox."

[18] Applegate, T., *et al*. 2007. S1032: Improving the sustainability of livestock and poultry production in the United States. Project proposal to the Southern Association of Agricultural Experiment Station Directors (SAAESD). The group's proposal is available on the Internet; for the reference to Jevons' Paradox (aka, "the rebound effect") see footnote #2 at https://www.nimss.org/projects/view/mrp/outline/9096.

[19] Pfeiffer, L., and C. Y. C. Lin. 2014. Does efficient irrigation technology lead to reduced groundwater extraction?: empirical evidence. *Journal of Environmental Economics and Management* 67(2):189-208.

[20] The graphic in Figure 1 was taken from Auvermann, B. W. 2018. System dynamics and ground water conservation: irregular thoughts, unintended consequences. Presented at the Governor's Conference on the Future of Water in Kansas, Manhattan, KS, 14 Nov.

returns and make possible sustained profitability under reduced water use. We are saying, rather, that *relying solely on efficiency gains will not reduce resource extraction*. Clearly, as Pfeiffer and Lin (2014) have shown empirically, and as Jevons (1866) warned us, there is much, much more to ground water conservation than efficiency gains through technology research and development.

Regulation

The heavy hand of government fiat is always an option for influencing human behavior through subsidies (the "carrot"), regulations (the "stick"), or both. Within a single jurisdiction, constitutional constraints and socio-political norms determine the range of options available to the authorities, but where common-pool resources span political boundaries, treaties and compacts may be required to create new regulatory structures, especially if it can be shown that the constitutional constraints of one jurisdiction provide competitive advantages over those occupying the neighboring jurisdiction. Those competitive advantages may incentivize increased ground water extraction on one side of the boundary that reduces ground water availability (and therefore profitability) on the other.[21] In turn, the disadvantaged jurisdiction may change its self-imposed constraints to ensure a level playing field across the boundary, which increases ground water extraction still further. Once again, human dynamics push the users of common-pool resources toward self-defeating, resource-oversubscribing behavior.

Clearly, one approach to eliminating the competitive, transboundary dynamics – whether those boundaries are political (e. g., state lines) or incidental (e. g., fencelines between neighboring farms) – is to eliminate boundaries altogether. In the United States, the frustrations associated with differential regulation in neighboring states inevitably give rise to calls for federal intervention, again to level the playing field and eliminate the perverse incentives that drive disproportionate impact on shared resources. That impulse, to eliminate political boundaries and invest ever-greater authority in the resulting hegemon, has a long and storied history, formalized in the political literature by none other than Thomas Hobbes; William Ophuls called that impulse "recourse to the tragic necessity of Leviathan."[22] Leviathan, indeed.

Voluntary, Collective Action

The late, Nobel laureate Elinor Ostrom devoted much of her life to the human dynamics of common-pool resource dilemmas, noting at one point that

> …at the heart of each of these models [i. e., the descriptive frameworks of the resource dilemmas] is the free-rider problem. Whenever one person cannot be excluded from the benefits that the others provide, each person is motivated not to contribute to the joint effort, but to free-ride [*sic*] on the efforts of others. If all participants choose to free-ride, the collective benefit will not be produced. The temptation to free-ride, however, may dominate the decision process, and thus all will end up where no one wanted to be.[23]

We have to acknowledge that "free riding" is rational behavior at the individual level, and if all individuals using a common-pool resource behave rationally (in the same, self-interested sense), then everyone becomes a free rider, and resource oversubscription is inevitable.

Ostrom then asked[24] what analytical perspective might bring to light the key elements of these resource dilemmas, thereby permitting human beings to devise collective, resource-management systems that avoid both the free-for-all of unbridled self-interest and the Leviathan of coercive, centralized government. Her answer? Game theory.

[21] For a solid, layman's primer on ground water hydrology and its implications for transboundary aquifer governance, see Eckstein, G. 2017. *The International Law of Transboundary Groundwater Resources*. New York: Routledge. 174 pp. The principles (and regulatory discontinuities) at play need not be international to be significant, however; they apply equally well to boundaries between ground water conservation districts in Texas, between ground water management districts in Kansas, or between adjacent districts in neighboring states.

[22] Ophuls, W. 1973. Leviathan or oblivion? In: Daly, H. E. (ed.) *Toward a Steady-State Economy*. San Francisco: W. H. Freeman. pp. 215-230. The rather apocalyptic allusion is to Hobbes, T. 1651. *Leviathan or the Matter, Forme, and Power of a Common-Wealth Ecclesiasticall and Civil*. Recent editions of that classic text are widely available.

[23] Ostrom, E. 1990. Governing the Commons: The Evolution of Institutions for Collective Action. New York: Cambridge University Press. 280 pp.

[24] *Ibid*, p. 3.

What's in a Game?

Game theory, defined as "the study of multiperson decision problems,"[25] is a hybrid discipline involving both the social sciences and economics. A game-theoretic approach identifies the *players* (those making decisions), their available *strategies* (the options each player has before her), the *payoff structures* (the outcomes that will be experienced by each player for each combination of strategies played), and the *rules* of the game. When the game has been completely specified, the analyst then seeks through logical inferences the optimal strategy for each player; if such optima exist for all players, then the combination of those optimal strategies implies a set of payoffs that comprise the outcome of the game.

The most famous and widely cited example of game theory is the so-called Prisoners' Dilemma, which posits two, self-interested accomplices who have been caught by the police, accused of complicity in a crime, and interrogated independently in different rooms. The police have not accumulated enough evidence to convict them both. The two strategies available to each player are (a) to "fink," or confess on behalf of both players, or (b) to stay "mum," or silent. The interrogators promise a degree of leniency for single confessors in the form of reduced sentences, as shown in Figure 2.

		Prisoner 2	
		Mum	Fink
Prisoner 1	Mum	-1, -1	-9, 0
	Fink	0, -9	-6, -6

Figure 2. The Prisoners' Dilemma, represented in its "normal form." The payoffs are structured so that if both prisoners stay silent, each will get one year in prison for a lesser offense; if both confess, each will get six years in prison for the more serious offense; and if only one confesses, the confessor is released immediately, and the other gets nine years in prison (six for the more serious offense, and three more for obstruction).[26]

In this version of the Prisoners' Dilemma, the strategy set is the same, binary choice (Mum, Fink) for both players, and the payoffs are given in the number of years behind bars.[27] Notice also that the payoff structure is *symmetrical*; the payoffs for (Fink, Mum) are precisely the mirror image of the payoffs for (Mum, Fink).[28]

Before we can proceed to a rational outcome, we need now to specify the rules of the game. The simplest specifications are that (a) the players get only one shot to play the game (a *static* game), (b) both players are fully aware of the entire payoff structure (a game of *complete information*), (c) each player has to choose at the same time (a *simultaneous* game), and (d) both players are equally intelligent, rational, and self-interested. Given those rules, it can be shown[29] that the optimal strategy for both prisoners is to Fink, or confess, in which case they both get six

[25] Gibbons, R. 1992. *Game Theory for Applied Economists*. Princeton, NJ: Princeton University Press. 267 pp.

[26] *Ibid*, p. 3. The numerical values of the payoffs may vary among authors, but their interrelationships must remain the same for the game to be a true Prisoners' Dilemma. If the relative magnitudes of payoff pairs change, the game has a different name and a different, mutually optimal outcome (if an optimal outcome exists). For you who object that being penalized extra for refusal to incriminate oneself is unconstitutional in the United States under the Fifth Amendment: you're right, but we don't care. This is a thought experiment!

[27] The payoffs are given in negative numbers because they are *penalties*. If the payoffs were rewards, they would be given in positive numbers. The numerical comparisons between and among payoffs – less than, greater than, equal to – are fundamental to particular kinds of games and their rational outcomes.

[28] In game theory, there is no general requirement that a payoff structure be symmetrical. For example, if the accomplices included one Roman citizen (e. g., the apostle Paul, ca. 62 C. E.) and one non-citizen (e. g., the apostle Peter), the latter's payoff structure might include crucifixion, while the former's would only (!) include beheading; if the accomplices were an adult and a minor, the former's payoff structure might include having his name plastered across the front page of the newspaper, while the latter's might preserve his anonymity; and so forth. Discerning the full scope of the payoff structure for a particular game is essential if the underlying dynamics are to be represented realistically; life can be, and often is, unfair.

[29] In this simple case, the optimal solution for each prisoner can be determined by selecting the superior strategy given the other prisoner's choice of either strategy. In the case of the Prisoners' Dilemma, assuming Prisoner 1 chooses to Fink, Prisoner 2's choices have the payoffs of (Fink - 6 years; Mum – 9 years), with a clear advantage for Finking. Assuming Prisoner 1 chooses to stay Mum, Prisoner 2's choices have the

years in the hoosegow. If only they had had a compelling reason to keep their mouths shut, they could both have gotten off with just one year!

A few observations are in order at this point. First, the static Prisoners' Dilemma with binary strategies, complete information, utterly rational and intelligent players, and simultaneous play is almost cartoonish in its simplicity. Seldom if ever does real life ever give us such clear, unambiguous structures and outcomes. But simple models also help us clarify our thinking, if only by pointing out that *the very structure of a game is what ensures its outcome, without necessarily implicating the moral postures of those involved*. The Prisoners' Dilemma always yields the same, self-defeating outcome[30] even though there was at least one combination of strategies that could have been a win-win for both players, at least in comparison to the outcome that they inevitably choose. Moving the frame of reference away from a *morality play* – "a generous, selfless prisoner would have stayed Mum no matter what his accomplice chose to do" – toward a consideration of *the game's structure as potentially dispositive for its most likely outcomes* was a tremendous contribution of the game theoreticians like John Forbes Nash.[31]

Second, the game-theoretic approach shows us clearly that *there is always an unacknowledged but highly significant player*: the rulemaker. If it is the complete structure of the game that ensures the unfortunate outcome, it follows that the rulemaker is herself implicated in ensuring that outcome. By isolating the two prisoners from one another, by forcing them to make one choice simultaneously, and by choosing the relative payoffs the way she does, the rulemaker ensures that self-interested actors end up in the cooler for a long, long time. Still, that yields another important insight: if the structure of the game is dispositive for its outcome, might a wiser rulemaker with a different agenda be able to devise a game structure that yields a win-win?[32]

Third, the game-theoretic approach provides a plausible framework in which *we can identify concrete points of leverage by which to move toward a win-win(-win) outcome*, if such an outcome exists.[33] For example, suppose that each of the players in a common-pool resource dilemma perceives the game's payoff structure differently. In such a case, we no longer have a game of complete information, and in fact, the information that the players have is at least partly incorrect. Only by remote chance, then, would all of the players reach a truly rational conclusion about what strategy to play to bring about their respective best interests; moreover, it is highly improbable that the game's rational solution will reflect the payoffs as they really are. The result, surely, will be disillusionment among all of the players when the actual response of the common-pool resource to what was thought to be the rational set of strategies differs from the response the players expected. Framing that situation in game-theoretic terms makes it clear that until all players share a common basis in fact concerning the payoff structure as it really is, finding a rational solution that actually conserves the resource is highly improbable. Whatever else the situation might require, some kind of workshop or symposium or educational initiative might be in order to reset all of the players on a common basis in fact.[34]

Application to Common-Pool Resource Dilemmas

What does all of that have to do with common-pool resource dilemmas, like the Ogallala Aquifer? Quite a lot,

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payoffs of (Fink – immediate freedom; Mum – 1 year), again with a clear advantage for Finking. No matter which strategy Prisoner 1 plays, Prisoner 2 is better off Finking, and because the payoff structure is symmetrical, the same logic holds for Prisoner 1. They both Fink.

[30] The seemingly paradoxical outcome of the Prisoners' Dilemma, wherein both players end up in the clink for six years even though both cooperating could have been sentenced to only one, is known as a *Nash equilibrium*, named after the mathematician John Forbes Nash. For a compelling account of Nash's troubled genius, see Nasar, S. 1998. *A Beautiful Mind*. New York: Simon & Schuster. 464 pp.

[31] None of us takes kindly to the implication that acting self-interestedly on behalf of our heirs makes us inherently immoral, but when we make life choices e. g. to increase our net income, we are implicitly acting to benefit precisely them. We can't take it with us!

[32] Perhaps we should have said a "win-win-win." Make no mistake: rulemakers bring their own agendas to the game. In the case of the Prisoners' Dilemma, the rulemaker's agenda can be inferred directly from the game's Nash equilibrium: the goal was a pair of convictions with long sentences, and the game design faithfully generated precisely that outcome. Whether or not that outcome constitutes socially advantageous justice is another question entirely.

[33] The literature of game theory makes it clear that there are some games that simply do not have a unique Nash equilibrium or other forms of optimal strategy sets. For an extended, theoretical treatment of that question, see Gibbons (1992), among many other resources.

[34] We use the term "fact" a bit loosely here. As Eckstein (2017) helpfully notes, the status of recoverable water throughout an unseen aquifer cannot be known with perfect accuracy; it can only be approximated from a finite number of surface observations. Consequently, a comprehensive, game-theoretic approach to management of the Ogallala Aquifer would need to account for the uncertainty associated with our estimate of the aquifer's recoverable ground water, the uncertainty in the hydraulic parameters that we use to model ground water flows, and so forth. Thus, we use the word "facts" here to refer to an assembly of perceptions, estimates, modeling projections, and data that are held in common by all of the players, including the uncertainties associated with all of those things.

in fact, which we can show by relaxing some of the tight constraints that gave us the simple, Prisoners' Dilemma framework in the first place, and then mapping those relaxed constraints to a suite of management tools and strategies that Ostrom and others have used to good effect. As we map those tools and strategies, we will be assembling a basis for *cooperative game theory*, a branch of game theory that seeks cooperative mechanisms to prevent or reduce the influence of self-defeating behavior in public-resource dilemmas.

Static vs. Dynamic Games

Whereas the two prisoners had one shot at making their best choices – which we assumed would minimize their individual durations in the "big house" – managing an aquifer involves a series of strategy selections over a long period of time. Prisoner 1 was forced, again by the rules of the game, to assume something about what strategy Prisoner 2 would choose in a one-off scenario. As it turned out, the optimal solution for both prisoners was to Fink no matter what the other prisoner did, but because the decision was a one-off, and given that each prisoner's opponent had already identified himself as a rule-breaker,[35] the rational assumption was that the opponent would Fink; there was no obvious reason to conclude that the opponent had somehow come to his moral senses and adopted an altruistic posture. To the contrary, it is best to assume that the other criminal would reason the same way he is reasoning: minimize my own jail time however possible.

But what if the police had allowed the prisoners to revisit their choices two or more times, had given each prisoner information about what strategy the other prisoner had chosen in each of the previous iterations, and had let both of them know that they were going to change those two rules in those ways? Now we have a situation in which each prisoner can try to establish a reputation for altruism, thereby inviting his accomplice-turned-opponent to do the same. If Prisoner 1 learns that Prisoner 2 will learn of his first choice and that Prisoner 2 will have a chance to change his own choice in response, there is at least some, new possibility that Prisoner 1 will choose to stay Mum in round 1. There was no such chance with the one-off scenario, but there is now.

The new scenario is known as a *dynamic* game, a game in which strategies are chosen and re-chosen in multiple rounds and in which players learn to characterize their opponents based on their strategy choices over time. It is still possible to take advantage of the other player's apparent altruism for the sake of walking free, and in fact the Nash equilibrium still points to Fink for both players.[36] By playing the same game multiple times, however, each player has a chance to lead the other player toward the win-win outcome, and each player has a chance to follow the other player's choices…and punish him for defecting, even if in so doing he also punishes himself.

Pure, Mixed, and Iterative Strategies

In its original form (Fig. 2 and explanation), the Prisoners' Dilemma involves *pure* strategies, strategies that are simply the two or more discrete actions that a player could undertake when called upon to choose. We might imagine, however, that in a more realistic scenario, a player's strategies are contingent on circumstances somewhat beyond his reach or control and are therefore better understood as probabilities. In the original case, although Prisoner 1 knows what Prisoner 2's best strategy would be (Fink!), she does not know what Prisoner 2 will actually do; that is, she does not know for certain that Prisoner 2 will act with the same rationality as she is prone to exhibit. Based on her previous experience with Prisoner 2, Prisoner 1 might say that Prisoner 2 is 70% likely to Fink and 30% likely to stay Mum. Looking from the other side, Prisoner 2 might draw on his experience and say that Prisoner 1 is 35% likely to Fink and 65% likely to stay Mum. Those appraisals are no longer pure but *mixed* strategies. The game-theoretic landscape has now changed dramatically because the payoff structures depend explicitly on the various combinations of probabilities, and with the change in game structure, the optimal strategies and final payoffs for each player have also changed. Further, if the game is also dynamic instead of static, each player can adjust her appraisal of the opponent's proclivities as the *iterations* proceed. The ability to select a different strategy based on the historical or emergent behavior of one's opponent(s) allows us to consider *punitive* strategies, strategies intended to modify the opponents' behavior by affecting their short-term payoffs.[37]

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[35] How so? The police had arrested them with at least some evidence of criminal wrongdoing, even if it wasn't enough evidence to put them away for the most egregious offense. When it comes to criminals, it takes one to know one.

[36] Simply repeating the same Prisoners' Dilemma multiple times yields the same Nash equilibrium: both players Fink. See Gibbons (1992), pp. 82ff.

[37] Formalized strategies of that kind in dynamic games include "tit-for-tat" strategies, which are intended to punish opponents' defections from mutually advantageous strategies by drastically reducing opponents' payoffs, even at a short-term cost to the punisher. Gibbons (1992) described the mechanics of "tit-for-tat" and related strategies in mathematical terms; Ostrom (1990) described how those strategies can be

In all but the most stylized, contrived scenarios, mixed strategies are probably the rule rather than the exception. In fact, mixed strategies are likely to be a necessary artifact of the next domain of game-theory rules: the completeness of information.

Complete vs. Incomplete Information

The original Prisoners' Dilemma assumed that both players have complete knowledge of both players' strategy sets and the full payoff structure. In addition, we tacitly assumed that both players know that both players have the complete knowledge set. In real life, however, we rarely encounter such a setting. Rather, we have a decent understanding of our own payoffs, but we may not have enough information at hand to project our opponent's payoffs accurately. Further, we may not know precisely how many different strategy options our opponent has nor precisely what those options are. All other things being equal, the player that has more comprehensive information about the whole game structure has a logical advantage over his opponent. Wherever and whenever possible, therefore, we like to gain leverage over a game's outcome by "playing our cards close to the vest;" we also like to conduct various forms of intelligence-gathering to bolster that leverage. Trade secrets, bank balances, insurance policies, and employee career plans or health statuses are just a few of the domains in which differential knowledge is power in competitive markets. That is no less true in public resource dilemmas.

In the realm of municipal ground water, we recently discovered through an informal survey[38] that the depth to ground water and the water-transmission characteristics of the aquifer under a residential landowner are pieces of information that a landowner might wish to keep private to ensure that development continues and that real estate values remain high, at least until she has a chance to cash out. On the other hand, dramatic asymmetries in information can reduce players' confidence in the integrity of the game, or perhaps as important, their confidence in the integrity of those who are setting the rules of the game. Lost confidence in the integrity of other players and/or the game's administration is a decisive impediment to cooperative behavior;[39] as a result, where information asymmetries persist, negotiations resulting in e. g. public non-disclosure agreements or other information-security arrangements may provide the extra measure of confidence required for cooperative behavior to emerge among players.

Two-Player vs. Multi-Player Games

Constraining a game to two players helps us see the most obvious dynamics, but common-pool resource dilemmas generally involve a considerably greater number of players. For example, there are thousands of users of the Ogallala Aquifer, each with her own set of available strategies, externalities, and payoff-influencing circumstances. To simplify what would otherwise be a game of bewildering complexity, we might group those ground water users into common classifications, each of which may then be treated as a single, composite player. Still, even as we aggregate users into larger and larger classifications, we eventually reach a point at which further aggregation dramatically reduces both the realism and the explanatory power of the game. Residential water users interested in maintaining the finest-looking front lawn on the block have little in common with the small-acreage farmer who is raising just enough marginally irrigable wheat and sorghum to remain viable, so we should not expect the two to share a common set of available strategies, still less a common payoff structure. In the general case, then, common-pool resource dilemmas involve at least a handful of distinct interest groups.

An Irrigation Game: Lessons and Questions

At this point, we have described game-theoretic (GT) approaches thoroughly enough to begin building plausible GT scenarios around the Ogallala Aquifer. Let us suppose that we have two groups of irrigators, designated Irrigator 1 and Irrigator 2. From the perspective of ground water hydrology, let us assume that the pumping behavior of each group causes crossover effects for the other group; that is, the static water levels, pumping-plant performance, and energy costs associated with pumping ground water within one irrigator group are affected by the

implemented in a cooperative setting among multiple players or groups. Ideally, for the punitive strategies to have their desired effects, the game structure must be one of complete information, wherein the punished player is able to interpret his circumstances accurately in terms of well known, fully understood rules.

[38] Auvermann, B. W. 2018. Bushland (TX) residential water well survey. On-line survey conducted on behalf of Texas A&M AgriLife Research – Amarillo, 01 May – 14 Jun.

[39] Hanley, J., J. Orbell, and T. Morikawa. 2003. Conflict, interpersonal assessment, and the evolution of cooperation: simulation results. Chapter 7 in Ostrom, E., and J. Walker (eds.). *Trust & Reciprocity: Interdisciplinary Lessons from Experimental Research*. New York: Russell Sage Foundation. Pp. 170-206.

pumping intensity of the other group.[40]

Figure 3 is the normal-form representation of our game, with payoffs expressed as the net present value (NPV) of the median fortune passed on to an irrigator's heirs within an irrigator group. The strategies available to each group are similar: one can either "pump like hell," which means pumping at the maximum conceivable rate without considering the consequences for the aquifer, for the other irrigator group, or even for one's own irrigator group; or one can pump at 25% of that rate. If both groups "pump like hell," both groups realize tremendous short-term profits and pass along estates valued at $300 million. If both groups choose to restrict their pumping rates to 25% of the maximum, they pass along estates valued at only $150 million. If the two groups choose different strategies, the group that pumps aggressively passes along estates valued at $250 million, while the conservation-minded group passes along estates valued at half that. The Nash equilibrium for this game, or the most rational solution for self-interested players, is to "pump like hell."

		NPV of Fortune Inherited by Progeny	
		Irrigator 2	
		Pump Like Hell	0.25 x Pump Like Hell
Irrigator 1	Pump Like Hell	$300M, $300M	$250M, $125M
	0.25 x Pump Like Hell	$125M, $250M	$150M, $150M

Figure 3. The normal-form representation of a two-player irrigation game whose payoffs are given as inheritances. The game's Nash equilibrium implies that both groups will pump at their maximum rate. There is no incentive to restrict one's pumping rate no matter what one's opponent chooses to do.

Thus far, the irrigation game is solely about the magnitude of the fortune that irrigators can pass along to their heirs at retirement or death. Applied economists will interpret the game in terms of a high discount rate, meaning that $1 of profit today is worth somewhat more than $1 of profit next year. If we ask the ground water hydrologists, however, to project for each combination of strategies the number of years that the aquifer will yield profitable irrigation rates, suppose that they returned the game shown in Figure 4.

		Usable Aquifer-Years Remaining	
		Irrigator 2	
		Pump Like Hell	0.25 x Pump Like Hell
Irrigator 1	Pump Like Hell	50, 50	100, 100
	0.25 x Pump Like Hell	100, 100	250, 250

Figure 4. The normal-form representation of a two-player irrigation game whose payoffs are given in terms of the aquifer's remaining economic life (in years). The game's Nash equilibrium implies that both groups will pump at the reduced rate, assuming the aquifer's longevity is the decisive payoff.

[40] If there were no hydraulic linkage between the two groups' water wells, we would not have a common-pool resource scenario in the first place; these two groups would be independent, at least in the context of ground water hydrology. For a useful discussion of where game theory does and does not have a role to play in common-pool resource dilemmas, see Diekert, F. K. 2012. The tragedy of the commons from a game-theoretic perspective. *Sustainability* 4(8):1776-1786.

Combining the insights from Figures 3 and 4, we conclude that the economic incentives are contrary to the hydrologic incentives. Note in Figure 4 that the payoffs for any pair of strategies are equal for both players, an indication that the costs of behavior changes are borne privately, but the benefits are enjoyed by all players. As we saw previously, those conditions lead ineluctably to the tragedy of the commons, as John Tracy has assured us. Some of the questions that we might consider, then, include:

1. Under what circumstances or interventions might the rulemakers reduce the discount rate (i. e., the discount rate implied by the payoff structure in Figure 3) such that the Nash equilibrium shifts from ground water mining ("pump like hell") toward resource conservation?
2. Municipal and residential users of ground water appear to have much different payoff structures than agricultural irrigators, so games pitting municipal/residential users against agricultural users are inherently asymmetrical. What interventions might be devised to put the two opposing user groups on a common payoff footing? How might those interventions accommodate the fact that 80-90% of the ground water extracted from the southern Ogallala Aquifer is used in irrigated agriculture?
3. To what extent, if at all, does the discontinuity between Texas' "rule of capture" and Kansas' state ownership of ground water result in a net flow within the Ogallala Aquifer from Kansas to Texas? If that net flow exists, what is its economic value? To what extent, if at all, do the rules adopted by Texas' ground water conservation districts mitigate that net flux of ground water and its associated economic value? How great must be the economic impact of that interstate discontinuity before federal intervention is warranted?
4. Are there any practical ways to avoid the tragedy of the commons on the Ogallala Aquifer without recourse to Leviathan?
5. The historical research agendas directed at ground water conservation in the southern High Plains have traditionally centered on the technical aspects of improving irrigation efficiency, even though increases in resource efficiency have been shown to accelerate rather than retard resource extraction. What changes ought we make in the research agenda on the Ogallala to stem the tide?

Summary

Someone has rightly said, "all models are wrong; some are useful."[41] So it is with game-theoretic models. Still, we've shown that a game-theoretic approach gives us access to insights that may not be obvious from models of other kinds, such as general equilibrium models in economics. We've seen that the common-pool resource dilemmas that we face can be framed in game-theoretic terms, and the simulation behavior of those models replicates observed behaviors like the tragedy of the commons. The Ogallala Aquifer is a common-pool resource that is undergoing yet another manifestation of that tragedy, driven in part by Jevons' Paradox, which suggests strongly that the public research portfolio directed at conserving the Ogallala has been poorly balanced. The modest contributions that technology advances can make to extending the aquifer's useful life will be most fully realized in a larger context of innovations in cooperative resource management; those innovations will require rethinking parochial assumptions about resource ownership, property rights, land use preferences, and the time scales that define our planning horizons and economic forecasts. Recent developments in the application of cooperative game theory can provide conceptual support for voluntary associations who embrace the ineluctable dynamics at play on the Ogallala and take bold, experimental steps toward self-organization. If both the tragedy of the commons and Leviathan are to be avoided, those who catalyze persistent associations of that kind will lead us there.

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[41] The aphorism has been variously attributed. Everyone to whom it has been attributed is correct on both counts.

[42] Stella™ is a dynamical-systems modeling environment developed by isee systems, Inc., Lebanon, NH. Mention of that particular trade name should not be construed as a product endorsement by Texas A&M AgriLife Research or the Texas A&M University System to the exclusion of other, similar products that may also be suitable for the purposes noted herein.

marveling at all the insights that modeling software makes possible, I was learning to privilege sociology, psychology, and politics over my native language of engineering.

Finally, the late Nobel Prize laureate and political economist, Dr. Elinor Ostrom, left us far too soon (2012). I'm indebted to her for generously daring to see and articulate a "third way" between statism and anarchy. Rest in peace, Dr. Ostrom, and may your tribe increase.