Measuring the Bioeconomic Impacts of Prolonged Drought on a Lake Ecosystem: The Case of the Great Salt Lake, Utah

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Abstract

We present a general-equilibrium (GE) bioeconomic model of Utah's Great Salt Lake (GSL) ecosystem that tightly links the lake's ecosystem with its regional economy and attendant international trading partners, thereby enabling full identification of dynamic feedback effects in the presence of prolonged drought. The drought modeled here mimics a drying climate's impact on the lake's nutrient pool. We demonstrate how prolonged drought affects key bioeconomic variables over time, and how the GSL bioeconomy recovers toward a new steady state. We also consider how two separate fishery-specific regulatory tools – a temporary harvest moratorium and ad valorum tax on the fishery's factors of production – alter the bioeconomy's recovery path. Our main finding is that a fishery-specific regulation can induce perverse social welfare effects in a general equilibrium context by inducing a shift of resources out of the fishery and into a sector of the economy that produces a negative externality, in our case pollution from the mining industry. These welfare effects are appraised with two different measures of equivalent variation – one based on an initial benchmark period, the other on expenditure differences that roll through time. Our model further demonstrates how these perverse welfare effects can be mitigated by imposing either an output or input tax on the mining industry.

JEL Classifications: C68, D58, F18, Q57

Keywords: Species net energy, biomass demand and supply, regional economy, Great Salt Lake, harvest moratorium

Recommendations for Resource Managers

- The general-equilibrium bioeconomic model developed here for Utah's Great Salt Lake demonstrates how key bioeconomic variables can be tracked over time in response to an economic or ecological shock, such as prolonged drought.
- This numerical modeling tool provides an integrated perspective on the bioeconomic impacts of public policies that can be adopted to counteract these shocks.
- Estimates of the social net benefits associated with the public policies are provided.
- The context for assessing the net benefits of alternative fishery regulations is therefore broadened to account for a multi-species, multi-sector bioeconomy.

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1 Introduction

Effective management of a bioeconomy (i.e., joint ecological-economic system) requires knowledge rooted in two perspectives.[1] One perspective is micro-orientated, whereby on-going findings from laboratory and field studies of the foraging and reproductive behaviors of individual plant and animal species comprising the ecosystem's trophic structure (or food web) continually inform species-specific management plans. The other is more macro-orientated in scope, whereby species interactions (i.e., predator-prey relationships) and population dynamics within the food web are formally modeled. General-equilibrium (GE) bioeconomic analysis links these two perspectives and extends them by explicitly accounting for the anthropocentric feedback effects within the bioeconomy that occur as a consequence of regional economic activities and natural phenomena; phenomena such as prolonged drought and climate change that in turn are precipitated and exasperated by these activities.

In this paper, we develop a GE bioeconomic model of Utah's Great Salt Lake (GSL) watershed with the twofold objective of demonstrating how (1) the onset of prolonged drought conditions can affect the GSL bioeconomy over time, and (2) various regulatory regimes can potentially serve as management tools to mollify these effects. Figure 1 in Appendix C displays the GSL, its freshwater river sources, and geographic boundaries of the counties surrounding the lake. Of particular note is the railroad causeway bisecting the lake into two separate bays. Because the freshwater rivers feeding the lake all empty into southern Gilbert Bay (Bear, Weber, Ogden, and Jordan Rivers), only this bay's salinity conditions are amenable to supporting a fishery comprised of the GSL's focal species, brine shrimp (*Artemia franciscana*).

We investigate two alternative regulatory regimes, both targeting maintenance of the brine shrimp population over time. A quantity regime – temporary moratorium imposed on brine-shrimp cyst harvesting once the adult shrimp population has fallen beneath a predetermined threshold concentration (henceforth "harvest moratorium") – mimics the current approach used by the GSL's regulatory authority. A price regime – ad valorum taxation of labor and capital employed in the brine shrimp fishery (henceforth "input taxation") – serves as a benchmark to which the efficacy of the harvest moratorium is compared.[2]

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[1] Strictly speaking, "bioeconomy" refers to an interconnected ecosystem and regional economy. An ecosystem may be located within a widely or narrowly demarcated watershed or ecoregion (whichever the case may be Omernik and Robert (1997)), and the regional economy may likewise span a wide or narrow zone encompassing the ecosystem.

[2] The use of a harvest moratorium as an overt form of regulation is similar to the total allowable catch (TAC) regulatory approach investigated by Finnoff and Tschirhart (2003a,b). TAC regulation was originally introduced by Homans and Wilen (1997) in the context of an open-access fishery model. The key difference between the two approaches is that a TAC is an aggregate harvest limit set prior to the onset of the harvesting season. This limit is then allocated as individual transferable harvest quotas (ITQs) across individual firms. In contrast, a harvest moratorium is a lower-bound population threshold that once crossed on the downside (during

The GSL is representative of a multitude of ecosystems worldwide under persistent threat from prolonged drought. Solomon (2010) provides several examples of these ecosystems, from the Aral Sea watershed in Central Asia to sub-Saharan Africa's Lake Chad to the wide expanses of the Middle East and the world's industrial democracies. Closer to our particular study area in the US Great Basin, ecosystems such as Lake Albert located in southern Oregon (Rosner, 2016) and Mono Lake in northern California (Hart, 1996) have historically been prone to severe drought conditions.

We adopt Belovsky et al. (2011)'s ecological framework for the GSL, depicted as the pelagic and benthic food webs in Figure 2. As indicated in this schematic, brine shrimp prey upon cyanobacteria (*Streptococcus*) and waterbirds in turn prey upon brine shrimp. Brine shrimp cysts (i.e., eggs) are ultimately harvested commercially and waterbirds provide wildlife viewing opportunities to households. We also model the broad impacts of changes in the lake's salinity level on its nutrient pool (in particular, on the variable respiration efficiencies of the bacteria existing within the pool) as well as on the lake's brine shrimp population. As indicated in Figure 2, the salinity level is determined primarily by the extent of endogenously determined agricultural- and mining-sector diversions of the ecosystem's water supply for production purposes, as well as exogenously determined weather conditions such as prolonged drought.[3] As Figure 2 makes clear, the GSL regional economy consists of four primary production sectors – agriculture, mining, brine shrimp fishery, and wildlife viewing/recreation.[4] By explicitly accounting for international trade in brine shrimp and minerals, our model of the regional economy extends the small-country, international trade framework developed in Gilbert and Tower (2012) to more than two sectors and two input markets.

In a broad sense the main objective of this paper is thus to demonstrate how a relatively simple GE bioeconomic model can be extended to incorporate international trade and alternative regulatory regimes aimed at protecting an ecosystem's food web in the face of external shocks to the ecosystem and/or its associated regional economy. We consider the model to be a first step in this direction. Our contribution to the bioeconomic literature is thus the development of analytical and computational frameworks that, as the computational model is continually re-calibrated with updated ecological and economic data, can subsequently be used to guide management of the GSL bioeconomy in the face of both environmental and economic shocks. The particular shock modeled in this paper is prolonged drought, which has been an

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the harvest season) triggers an industry-wide shutdown of the harvest until the population later crosses the threshold on the upside.

[3] A full discussion of the GSL ecosystem is presented in Section 3.

[4] As in Finnoff and Caplan (2004), we also include a composite-good import sector in order to balance trade between the regional economy and the international markets for brine shrimp and minerals.

on-going concern of the GSL regulatory authority for the past several years (UDNR, 2013; Wurtsbaugh et al. 2016). The GE bioeconomic framework we develop here is flexible enough to conceivably handle any number of different possible shocks, such as sustained climate change and increasing residential and commercial development that encroaches upon the ecosystem's resource base.

Our numerical simulations of the model suggest that the onset of prolonged drought can lead to relatively severe short-term responses in the GSL bioeconomy, which nevertheless revert back to the bioeconomy's steady state gradually over time. In particular, both brine shrimp and waterbird populations decrease in response to the drought, while the corresponding equilibrium biomass-market energy price paid by waterbirds for brine shrimp initially increases and then undershoots its steady-state level on its return to equilibrium. These ecological adjustments accompany decreased shrimp harvests and exports, corresponding reductions in recreation/wildlife viewing, reduced imports of the composite good, and economy-wide shifts in factors of production that lead to increases in mineral extraction and its attendant pollution levels over the short term. Regional gross domestic product (GDP) and household welfare both fall in response to the prolonged drought. As expected, the harvest-moratorium and input-taxation regulations separately imposed on the brine shrimp fishery each cause the ecosystem's full set of ecological variables to recover more quickly from the drought shock to their respective steady-state levels than would otherwise be the case. Interestingly, our main finding is that the fishery-specific regulations induce perverse social welfare effects akin to the classic general-equilibrium welfare effects associated with environmental regulation found in Hazilla and Kopp (1990), Jorgenson et al. (1992), Pizer and Kopp (2003), and U.S. Environmental Protection Agency (USEPA) (2015). These welfare effects are appraised with two different measures of equivalent variation (EV) – one based on an initial benchmark period, the other on expenditure differences that roll through time.

What drives the perverse-welfare result is an exacerbated shift of production factors out of the brine shrimp fishery and into the mining sector in response to each of the two regulations. This shift ultimately leads to a decline in GDP and an increase in the emissions of pollutants, both of which negatively affect social welfare. Based on our two EV measures, we show that mining-sector taxation can mitigate this perverse social welfare effect, thus demonstrating that speeding the recovery of an ecosystem in the face of prolonged drought (e.g., by initially regulating the sector of the economy that directly impacts the ecosystem's focal species) may require offsetting regulations imposed on the sectors toward which resources flow in response to initial regulation of the focal species.

The next section provides a brief review of the bioeconomic literature to which our paper contributes. Section 3 describes the salient features of the GSL ecosystem. Section 4 then derives the two welfare measures used to value the bioeconomy-wide effects of prolonged drought, as well as the fishery-specific and mining regulations imposed to mitigate the drought's effects (specific details of the regional economy are coalesced in Appendix A). Section 5 presents results from a series of numerical simulations of the GE bioeconomic model. Section 6 concludes with a summary of the simulation results and a discussion of possible avenues for future research.

2 Literature Review

Our bioeconomic analysis of the GSL extends a literature that has, for the most part, adopted a partial equilibrium (PE) approach to modeling multi-species ecosystems in the sense that (1) the regional economy is represented solely by a fishery (i.e., linkages with other sectors of the regional economy are ignored), and consequently (2) dynamic feedback effects occurring between sectors of the economy and between the economy and the ecosystem are likewise neglected.[5,6] With respect to the relatively few GE bioeconomic models of multi-species ecosystems that do exist, our approach is firmly rooted in the theoretical framework pioneered by Tschirhart (2000) and Tschirhart (2012) and later applied to the Alaskan marine and North Carolina estuary ecosystems in Finnoff and Tschirhart (2003a,b) and Finnoff and Tschirhart (2011).

Similar to how our model integrates the GSL ecology with the region's economy to inform the ecosystem's management in the face of prolonged drought, Finnoff and Tschirhart (2003a,b) (henceforth FTA) develop an Alaskan marine bioeconomy to inform endangered species policies, where the trade-offs between

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[5] Our analysis also extends the literature concerned with the social-welfare impacts of environmental regulation in the context of a GE setting. This literature originates with (Hazilla and Kopp, 1990)'s estimates of the social costs associated with environmental regulations mandated by the US Clean Air and Water Acts promulgated in the 1970s and 1980s and extends to Nordhaus and Boyer (2000)'s estimate of the potential discounted, global net benefits associated with an optimally set global carbon tax to combat climate change. As the results of these particular empirical studies suggest, environmental regulation may foster negative welfare effects in a GE economy, similar to the simulated negative effect we find for the GSL bioeconomy for the case of fishery-specific regulation in the presence of prolonged drought.

[6] For an exhaustive survey of PE bioeconomic models see Nielsen (2018). Good examples of studies cited therein include Knowler (2002), Gourguet and Doyen (2014), and Macher and Bertignac (2008). For additional examples of the PE approach see Waldo and Paulrud (2017), Kasulo and Perrings (2006), Huang and Perrings (2017), Xu et al. (2018), Perrings and Walker (1997), Baggio and Perrings (2015), and Erickson et al. (2007). In an interesting application of the PE approach, Quaas and Requate (2013) extend Conrad and Adu-Asamoah (1986) by focusing on consumer preferences for diversity in private consumption of different fish species. Surprisingly, the authors find that the greater is consumer preference for variety the greater the number of commercial stocks prone to collapse, leading to less biodiversity in the oceans. This is due to the fact that when one of the preferred fish stocks declines (and thus its market price rises) consumers lack the inclination to shift demand to an alternative, more abundant fish stock. As the authors point out, this result is all the more remarkable given the lack of external dynamics in their model that typically induce collapse, such as ever-increasing demand or innovation in harvesting technology.

harvested fish (pollock) and endangered Steller sea lions are examined. Similar to our use of a harvest moratorium to mitigate declines in the GSL's brine shrimp population levels, FTA investigate the role of a recovery plan for endangered sea lions located in Alaska's Aleutian Islands and Eastern Bering Sea that limits the harvest of pollock (the sea lion's prey species) via a TAC. FTA's numerical simulations show that reducing sea lion mortality by 50 percent requires a slightly larger percentage reduction in pollock harvest (by 51.2 percent). The authors also estimate a relatively inelastic response in pollock population size to incremental tightening of the TAC limit.

The key difference between our framework and that of FTA is the extent to which the regional economy is represented in the two models. FTA adopt the PE approach by isolating the pollock fishery as the sole sector affecting (and therefore affected by) the Alaskan marine bioeconomy, while our model explicitly accounts for the feedback effects to and from multiple economic sectors simultaneously, including international trade in the harvested focal species. Finnoff and Tschirhart (2011)'s (henceforth FTE's) bioeconomic model of agricultural runoff in North Carolina's Neuse Estuary is more closely aligned with our GSL model in this respect, i.e., in terms of accounting for multi-sectoral impacts within the regional economy. The authors develop a model that accounts for the effects of hypoxia and associated oxygen depletion on multiple species populations across both space (shallow vs. deep channels) and time, and assesses the impact of reduced agricultural runoff on the region's ecology and economic welfare. As expected, FTE find that as runoff is reduced total blue crab populations increase, ultimately leading to increased crab harvests and reduced crab prices in the product market. Discounted social welfare is impacted negatively in scenarios where agricultural costs associated with runoff reductions have increased (by 1 percent and 10 percent).

In addition to the inclusion of multiple sectors in the regional economy model, our GSL bioeconomic model shares several simplifying assumptions with the FTE model. Both models assume myopic economic agents, and savings and investment behavior is omitted from the household sector's decision problem. The dynamics of both models therefore emanate solely from species population adjustments that directly affect the brine shrimp fishery and wildlife-viewing sectors.[7,8] Further, in both models government involvement

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[7] Myopia is a common assumption in PE and GE bioeconomic models, particularly those, like ours, that explicitly model inter-species interactions, or 'ecosystem externalities'. As in any externality model, the equilibrium outcome occurring as a result of myopic behavior on the part of economic agents serves as the customary benchmark to which regulatory intervention is compared. Assuming otherwise, i.e., assuming farsighted behavior in what is necessarily a noncooperative setting, is at best heuristically tenuous. At worst the assumption of farsightedness is theoretically inconsistent with the existence of an externality to begin with. This inconsistency extends to agents that might otherwise be endowed with forward-looking expectations, since to accurately form these expectations agents would need to at least partially internalize the externality, which again is heuristically and theoretically unappealing.

[8] Omitting household savings and investment behavior in the context of PE and GE bioeconomic models is the norm in the

in the economy occurs solely through its regulatory practices, and cumulative aggregate welfare (equivalent variation) measures corresponding to these practices are calculated for each respective policy intervention.

There are also several differences between the two models. FTE model a closed economy, while we assume a small open-economy framework. FTE ignore potential non-market linkages between households and the bioeconomy, while we explicitly model the impacts of pollution from mining and the periodicity of recreation/wildlife viewing opportunities on household welfare. Nutrient flows are exogeneously determined in FTE, while in our model salinity flows are determined endogenously as a consequence of upstream water usage by the agriculture and mining sectors.

Several of these differences also extend to a comparison between our model and that of Finnoff and Caplan (2004) (henceforth FC). In particular, FC depict regulation of the brine shrimp fishery as occurring through an industry-wide quota (or upper bound) on total harvest at the outset of each season. In contrast, the harvest moratorium depicted in our model is imposed seasonally once the shrimp population falls beneath a certain threshold level, i.e., the moratorium is effectively a lower-bound regulatory instrument that better reflects both the extent to which and immediacy with which the regulatory authority is capable of managing the fishery. As in our model, FC's simulation exercises are demonstrative. However, the shock occurring in our model mimics a particular natural occurrence – prolonged drought – rather than an arbitrary shock occurring randomly to lake salinity levels and the brine shrimp population. We nevertheless share with FC the overriding goal of simulating dynamic welfare effects associated with different regulatory regimes.

3 The GSL Ecosystem

The GSL bioeconomy depicted in Figure 2, which is an adaptation of Belovsky et al. (2011), describes how the ecosystem interacts with human and environmental factors comprising the surrounding watershed. As mentioned in Section 1, the ecosystem is restricted to the GSL's south bay (Figure 1), where the lake's

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literature. To our knowledge only FTE have endowed households with this capability – in the end the authors do not identify savings and investment as playing any notable role in determining the overall trajectory of their bioeconomy in response to exogenous shocks to the ecosystem. It appears, therefore, that the bioeconomic literature has evolved in accordance with Nielsen (2018)'s observation that "...increased complexity within each dimension and greater integration of the dimensions, for example including economic dynamics in ecosystem models, may also increase the difficulty of parameterizing the models and understanding and communicating the results" (page 3). It is well-known that household savings and investment are crucial components of economic growth models (c.f., **?**). Incorporating this dynamic into a bioeconomic framework would essentially endogenize what is currently a fixed capital stock. Doing so would potentially exasperate shock-induced changes in the allocation of capital across economic sectors (and thus corresponding relative allocations). To the extent that the biomass demand-and-supply functions and species population dynamics are sensitive to relative capital allocation, this may induce more pronounced adjustments in the ecosystem in response to the initial shock, which nevertheless would be reflective of the shock's longer-term impacts on the bioeconomy. Comparison of bioeconomic models with and without the inclusion of potential economic growth remains an area of future inquiry.

salinity level has historically supported a viable brine shrimp fishery.[9] The GSL ecology is comprised of two food webs. One is the benthic food web, where algae (*Phytoplankton*) located in the nutrient pool are preyed upon exclusively by brine flies (*Ephydra Larvae*), which in turn are preyed upon by Adult Ephydras-feeding waterbirds. The other grouping is the pelagic food web, where cyanobacteria (*Streptococcus*) from the nutrient pool are exclusively preyed upon by brine shrimp (*Artemia franciscana*), which in turn produce hard-cased eggs, or cysts. The shrimp cysts are preyed upon by insects (*Trichocorixa*) and waterbirds, and are commercially harvested and exported to Asian and South American aquaculture markets as feed for prawns and table shrimp (Lavens and Sorgeloos 2000; UDNR, 2013). Lastly, the lake's salinity level – a critical factor determining the survival of algae, bacteria, shrimp, and fly species – is governed by net water inflow, which in turn is determined by both endogenous (e.g., mineral extraction, agricultural production, residential and commercial development, etc.) and exogenous (e.g., drought, climate change, etc.) factors. As mentioned in Section 1, mineral extraction also leads to loadings of pollutants (mercury and selenium) which negatively impact the ecosystem's health.

To simplify our ensuing numerical analysis while retaining the essential features of the ecosystem, we focus on the predator-prey relationships existing between waterbirds (predator species) and the brine shrimp and (adult and larvae) flies (respective prey species), and thus ignore the relatively minor predation role played by *Trichocorixa* on shrimp (Belovsky et al., 2011). We also assume that pollution emitted from mineral extraction impacts households directly, rather than indirectly via negative effects introduced into the ecosystem. Thus, our focus is retained on the role that the lake's salinity level plays in determining the ecosystem's sustainability. For future reference identification numbers are assigned to each respective species according to Table 1 in Appendix B.

Species' Net-Energy Maximization Problem

Following Finnoff and Caplan (2004), we represent the net-energy maximization problem for each predator species' $i = \{s1, f1, 2, ..., 4\}$ as predator i's optimal choice of prey species j's biomass in any given time period.[10] For example, consider the interrelated net-energy maximization problems of (representative members of) the bacteria, brine shrimp and waterbird species (i.e., the Pelagic food web in Figure 2),

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[9] The north and south bays of the lake were physically separated in 1959 when the original Southern-Pacific Railroad causeway was in-filled, thus preventing mixing of water flows between the two (GSLEP, 2017). Because freshwater inflow into the north bay is much less than that flowing into the south bay, the north's salinity level exceeds the maximum concentration permissible for shrimp survival.

[10] For expository clarity we henceforth drop the time-period subscript $t = 1, ..., T$ from the model's variables except where needed.

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\begin{aligned}
&\underset{x_{s10}}{\text{Max}} \quad R_{s1} = \left[e_0 - e_{s10}\right]x_{s10} - e_{s1}\left[1 + t_{12}e_{21}\right]y_{12}(x_{s10}) - f_{s1}(x_{s10}; SA_{s1}) - \beta_{s1} \\
&\underset{x_{21}}{\text{Max}} \quad R_2 = \left[e_{s1} - e_{21}\right]x_{21} - e_2\left[1 + t_{24}e_{42}\right]y_{24}(x_{21}) - f_2(x_{21}; SA_2) - \beta_2 \qquad (1) \\
&\underset{x_{42}}{\text{Max}} \quad R_4 = \left[e_2 - e_{42}\right]x_{42} + \left[e_3 - e_{43}\right]x_{43} - f_4(x_{42}, x_{43}) - \beta_4,
\end{aligned}
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where net energy R_i is measured in power units (e.g., watts or kilocalories/time). The first terms on the right-hand sides (RHSs) of each problem in (1) represent inflows of energy from the nutrient pool and respective prey species. For instance, the term $\left[e_0 - e_{s10}\right]x_{s10}$ for R_{s1} represents the energy inflow from the nutrient pool to bacteria. Constant e_0 is measured in power units (kilocalories/kilogram) and represents the amount of energy embodied in a unit of biomass from the nutrient pool. Embodied energy e_{s10} represents the energy expended by bacteria per unit of predation on the nutrient pool (e.g., to locate, capture, and handle a unit of biomass from the pool), i.e., it is the equilibrium "energy price" (also measured in power units), established in the bacteria - nutrient pool "biomass market", which a member of the bacteria species pays to capture a unit of biomass from the nutrient pool.[11] The choice variable in bacteria's maximization problem, x_{s10}, is biomass (kilograms/time) transferred to, or demanded by, bacteria from the nutrient pool. Similar interpretations are made for the initial RHS terms in the brine shrimp and waterbird problems. Note that two energy inflow terms exist for waterbirds, one representing inflow from brine shrimp, $\left[e_2 - e_{42}\right]x_{42}$, the other inflow from brine flies, $\left[e_3 - e_{43}\right]x_{43}$, both measured in kilocalories/time.

The second terms in (1) represent energy outflow (kilocalories/time) via predation. The term $e_{s1}\left[1 + t_{12}e_{21}\right]y_{12}(x_{s10})$ in R_{s1}, for instance, is the energy lost by bacteria to brine shrimp through predation, and the term $e_2\left[1 + t_{24}e_{42}\right]y_{24}(x_{21})$ in R_2 is similarly the energy lost by brine shrimp to waterbirds. There is no energy lost through predation for waterbirds since waterbirds are the top predator species in the GSL ecosystem. The second bracketed terms in R_{s1} and R_2, $\left[1 + t_{ik}e_{ki}\right]$ for $k > i$, represent "taxes" (measured in power units) on the energy expended by species i to avoid predation by species k, with constant t_{ik} representing the associated tax rate. The total tax paid by a member of species i is assumed to increase with the energy price paid by members of predator species k, e_{ki}, which introduces a "convex damages" predation effect on species i's net energy level.[12] Variable y_{ik} represents the biomass transferred from, or supplied by, a member of prey species i to predator species k. This supply is assumed to be a strictly

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[11] Assuming energy prices $e_{ij} > 0, \forall i > j$ represent equilibrium prices implies that both the predator and prey species populations are constrained in size in any given time period.

[12] In other words, the rate at which the marginal damages associated with predation increase is proportional to the rate at which the energy price paid by the predator species increases with predation.

increasing, concave function of x_{ij}. For example, y_{24} is the biomass supplied by brine shrimp to waterbirds, which is an increasing function of shrimp's biomass demand for bacteria, x_{21}. Similarly, y_{12} is the biomass supplied by bacteria to brine shrimp, which in turn is a function of bacteria's biomass demand for nutrients, x_{s10}. The specific functional forms for the set of $y_{ik}(x_{ij})$ in both food webs of the GSL ecosystem are shown on the left side of Table 2, with productivity constants $\delta_{ij} > 0$ and $0 < \alpha_{ij} < 1, \forall i, j$.

Following Finnoff and Caplan (2004), energy lost via respiration (measured in power units) occurs through variable ($f_i(x_{ij}; SA_i)$) and fixed, or basal metabolic (β_i) capacities $\forall i, j$. Variable respiration, which accounts for energy lost in reproduction, defecation, defense of territory, etc., is assumed to be strictly increasing and concave in species i's biomass demand for its prey, x_{ij}, and increasing in salinity level, SA_i, which in turn is determined via natural fluctuations in water availability and the amount of water diverted for use in the agriculture and mining sectors. As described in the lower half of Table 2 in Appendix B, SA_i equals the summation of species-specific salinity effects occurring through agricultural (s_{ia}) and mining (s_{im}) production. These effects are calculated as constant multiples of the proportions of water used in agricultural (W_a) and mining (W_m) production, respectively, where proportionality factors σ_{ia} and σ_{im} are each assumed greater than zero, $\forall i$. We define $f_i(\cdot)$ according to the expressions listed on the right-hand side (RHS) of Table 2, with respiration-productivity constants r_i and γ_i both greater than zero, $\forall i$.[13] Lastly, basal metabolism for each species, β_i, is assumed to be independent of energy intake since it represents the minimum amount of energy necessary for a species to maintain respiration, circulation, and other vital body functions while at rest. First-order optimality conditions (FOCs) corresponding to the net-energy maximization problems expressed in equation (1) for the Pelagic food web result in,[14]

$$\begin{aligned}
e_0 &= e_{s10} + e_{s1}\left[1 + t_{12}e_{21}\right]y'_{12}(x_{s10}) + f'_{s1}(x_{s10}; SA_{s1}),\\
e_{s1} &= e_{21} + e_2\left[1 + t_{24}e_{42}\right]y'_{24}(x_{21}) + f'_2(x_{21}; SA_2),\\
e_2 &= e_{42} + f'_{42}(x_{42}, x_{43}),\\
e_3 &= e_{43} + f'_{43}(x_{42}, x_{43}),
\end{aligned} \tag{2}$$

where $y'_{ik}(x_{ij}) > 0$ and $f'_{ij}(\cdot) > 0$ are the partial derivatives of $y_{ik}(x_{ij})$ and $f_i(\cdot)$ with respect to x_{ij}, respectively, $i, j, k \in \{0, s1, 2, 3, 4\}$. The expressions in equations (2) are standard optimality conditions, which in our case

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[13] As in Finnoff and Caplan (2004), we express the top predator's (waterbird's) variable respiration as a flexible translog function, which accounts in a relatively unrestrictive way for the dual effects that a waterbird's brine-shrimp and brine-fly biomass demands have on its variable respiration.

[14] Similar FOC expressions are calculated for the benthic food web in Figure 2.

indicates that at any given point in time the biomass demand of each species occurs up to the point where the marginal benefit from energy inflow is equated to the marginal cost of energy outflow. Marginal benefit equals the energy per-unit of prey biomass, e_i, on each equation's left-hand side (LHS). The marginal cost of energy outflow on the RHS is the summation of (i) energy price paid per unit of biomass demanded, e_{ij}, (ii) energy lost to predator k per unit of biomass demanded , $e_i\left[1+t_{ik}e_{ki}\right]y'_{ik}(x_{ij})$, and (iii) energy lost via respiration per unit of biomass demanded, $f'_{ij}(\cdot)$. We note that the last two expressions in equations (2) represent the waterbird's optimality conditions, the first with respect to its demand for brine shrimp, the second with respect to its demand for brine flies. Neither of these two expressions include energy lost due to predation in the calculation of marginal cost because waterbirds are the ecosystem's top predator species. The specific functional forms used in our ensuing numerical analysis for the full set of species' net-energy equations and corresponding FOCs are presented in Table 3 in Appendix B.

As in Finnoff and Caplan (2004), the resulting ecosystem FOCs can be solved each period for a set of six optimal (short-run equilibrium) biomass demands, $x_{ij}\left(e_i, e_j, e_{ij_{i,j}}, e_{kii,k}, t_{iki,k}, SA_j\right)\forall i, j, k$, and, via the corresponding functions $y_{ik}(x_{ij})$, four optimal biomass supplies (recall that waterbirds do not exhibit biomass supplies). For example, a brine shrimp's optimal biomass demand for bacteria in any given period is expressed as $x_{21}\left(e_{s1}, e_2, e_{21}, e_{42}, t_{24}, SA_2\right)$, resulting in optimal biomass supply $y_{24}\left(e_{s1}, e_2, e_{21}, e_{42}, t_{24}, SA_2\right)$.

Short-Run Ecosystem Equilibrium

Similar to how equilibrium commodity and factor prices are determined in a competitive economy, energy prices play a central role in the determination of an ecosystem equilibrium in both the short- and long-runs. In particular, a species' choice of prey depends upon the prey's relative energy price determined in any given biomass market. Each predator species is assumed to be an energy price-taker in the market. However, an equilibrium energy price is determined endogenously within the market via the forces of aggregate predator demand and prey supply. In a short-run equilibrium each species population level is fixed, analogous to the fixed-number-of-firms condition that distinguishes a market economy's short-run competitive equilibrium. A short-run, ecosystem-wide equilibrium is attained when all biomass markets reach equilibrium simultaneously, irrespective of whether any given species' population will subsequently adjust along the path to a long-run ecosystem equilibrium.

For example, short-run equilibrium in the brine shrimp-bacteria biomass market occurs when brine-shrimp demand for bacteria biomass equals the bacteria population's biomass supply. Notationally speaking, equilibrium in this biomass market satisfies the clearing condition $N_2 x_{21}(e_{s1}, e_2, e_{21}, e_{42}, t_{24}, SA_2) = N_{s1} y_{12}(e_0, e_{s1}, e_{s10}, e_{21}, t_{12}, SA_{s1})$, where the LHS of the condition corresponds to brine-shrimp market demand and the RHS corresponds to bacteria market supply. Variables N_2 and N_{s1} represent the given brine-shrimp and bacteria population units, respectively, which in the short-run are assumed constant. As in an economy's market equilibrium, where the price of what is demanded must equal the price of what is supplied, a unique equilibrium energy price determined in the brine-shrimp-bacteria biomass market is e_{21}, i.e., the price paid by shrimp for a unit of bacteria biomass. Short-run equilibrium conditions for the full set of biomass markets in the GSL ecosystem are provided in Appendix Table 3.

Population Adjustment and Long-Run Equilibrium

Given its fixed population size in the short run, a species may exhibit negative, positive, or zero net energy in a short-run equilibrium. The adjustment from short-run to long-run (steady-state) equilibrium in the ecosystem is therefore driven by the simultaneous movement of species' net-energy levels toward zero, which in turn governs associated changes in species population sizes. In effect, natural variations in species population sizes drive, and are driven by, the transition from short-run to long-run equilibrium. The relationship between a species' net-energy and population levels is characterized by what is known as a population-updating equation.[15] The ecosystem is in long-run equilibrium when every species' net-energy levels are driven to zero and thus each species' population level is stationary.

Following Finnoff and Caplan (2004), we begin by constructing the population-updating equation for the top predator species in the GSL ecosystem – waterbirds – and note again that in a long-run steady-state equilibrium there is by definition no change in the waterbird population, i.e., births equal deaths. Denote the lifespan of a representative waterbird as s_4 and the size of the waterbird population at time t as N_4^t. The total number of waterbird births and deaths is then calculated as N_4^t/s_4, where $1/s_4$ equals both the per-capita waterbird steady-state birth and death rates. Given a representative waterbird's maximized net energy in period t, denoted as $R_4^{t^*} = R_4^t(x_{42}^t, x_{43}^t)$, where x_{42}^t and x_{42}^t represent the waterbird's optimal biomass demands for brine shrimp and brine flies, respectively, a long-run ecosystem equilibrium is consistent with the waterbird exhibiting zero net energy, i.e., $R_4^{t^*} = 0$.[16]

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[15] A similar updating process occurs in a competitive market economy with respect to the relationship between the different "population sizes" of firms and their respective profitability levels – positive profitability in the short run leads to more firms in a long-run equilibrium (via free entry), while negative profitability leads to fewer firms in long-run equilibrium (via free exit).

[16] $R_4^{t^*}$ may also be referred to as the waterbird's optimal-value, or "indirect net energy" function for period t. As discussed

Letting v_4^{ss} represent the waterbird's steady-state variable respiration level, and recalling that variable respiration is used partially for reproduction purposes, we denote energy required for reproduction in the steady state as ρv_4^{ss}, with constant proportionality factor $\rho > 0$. Note that the production level of waterbird offspring in the steady state (i.e., the waterbird population's steady-state birth rate) may therefore be denoted as $N_4^{ss}\left[\rho v_4^{ss}\right]$, which equals the total number of waterbird deaths, N_4^{ss}/s_4, in an ecosystem steady state. This in turn yields the result $\rho = 1/\left[v_4^{ss}s_4\right]$. When the waterbird species is instead in a non-steady state, i.e., $R_4^{t^*} \neq 0$, its variable respiration level is (henceforth) denoted simply as v_4^t. It therefore follows that in general (i.e., for any period t, regardless of whether a steady state has been attained), the waterbird species' per-capita birth rate can be defined as $[R_4^{t^*} + v_4^t]/[v_4^{ss}s_4]$.[17]

Assuming the waterbird species' death rate is independent of energy available for reproduction, the waterbird population adjustment equation can therefore be written as,

$$N_4^{t+1} = N_4^t + \frac{N_4^t}{s_4}\left[\frac{R_4^* + v_4^t}{v_4^{ss}} - 1\right]. \tag{3}$$

Note that in the steady state, where $R_4^{t^*} = 0$ and $v_4^t = v_4^{ss}$, equation (3) collapses to $N_4^{t+1} = N_4^t$, implying no change in the waterbird population from the current period t to the next period $t+1$. Outside of the steady state we see that changes in the waterbird population depend upon the values of a waterbird's maximized net energy, $R_4^{t^*}$, and variable respiration level, v_4^t.

The population-updating equation for brine shrimp is of special interest. Brine shrimp is the ecosystem's focal species, which is preyed upon by waterbirds and commercially harvested by the regional economy's brine shrimp fishery. As a result, the number of offspring equals the sum of natural deaths, predation mortality, and commercial harvest (which we henceforth denote H_2^t) in the steady state. Recall from equation (1) that a member of the brine shrimp species loses its biomass to waterbird predation according to supply function $y_{24}(x_{21})$. Thus, brine shrimp population loss through predation is represented as $N_2 y_{24}(x_{21})$. In the steady state, brine shrimp births equal the sum of natural deaths and predation mortality (net of natural deaths), i.e.,

$$N_2^{ss}\rho_2 v_2^{ss} = N_2^{ss}\left[y_{24}^{ss}\left(1 - \frac{1}{s_2}\right) + \frac{1}{s_2}\right],$$

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previously, optimal biomass demand exhibited by each species is itself a function of ecosystem parameters pertinent to that species. Hence $R_i^{t^*}, \forall i,t$ are also functions of those same respective parameters.

[17] Note that in a steady-state equilibrium $R_4^{t^*} = 0$ and $v_4^t = v_4^{ss}$ by definition. Thus, the waterbird birth rate expression collapses to $1/s_4$, which is the waterbird species death rate.

resulting in,

$$\rho_2 = \left[y_{24}^{ss}\left(1 - \frac{1}{s_2}\right) + \frac{1}{s_2}\right]\frac{1}{v_2^{ss}},$$

where s_2 and v_2^{ss} are a brine shrimp's lifespan and the steady-state variable respiration level, respectively, and y_{24}^{ss} is the steady-state supply of brine shrimp to waterbirds.[18]

Analogous to the waterbird population-updating equation, the population-updating equation for brine shrimp can be written as,

$$N_2^{t+1} = N_2^t + \frac{N_2^t}{v_2^{ss}}\left[y_{24}^{ss}\big(1 - \frac{1}{s_2}\big) + \frac{1}{s_2}\right]\left[v_2 + R_2^*\right] - N_2^t\left[y_{24}^t\big(1 - \frac{1}{s_2}\big) + \frac{1}{s_2}\right] - H_c^t. \tag{4}$$

Population-updating equations for each species in the ecosystem are presented in Table 4 in Appendix B.

4 Measuring Welfare Change

As mentioned in Section 1, the GLS regional economy is an extended version of the small-country trading equilibrium model (Gilbert and Tower, 2012). As in Finnoff and Caplan (2004), a "myopically dynamic" approach is adopted, whereby a sequence of short-run bioeconomic optimizations determines a dynamic equilibrium path via the evolution of species population updates in the GSL ecosystem. The model described here is of a small open-economy, where the (given) prices of the tradable commodities – brine shrimp, minerals, and a composite import good – are exogenously determined in world markets. International trade in these commodities enables the regional economy to export and import at given world prices, subject to the constraint that in any market equilibrium (short- or long-run) the aggregate values of exports and imports are equated. The conceptual framework for the regional economy's production and household sectors, along with associated market-clearing and trade-balance conditions, are provided in Appendix A. Here, we derive the measures used to assess the welfare effects associated with prolonged drought and the different regulatory polices designed to mitigate the drought's effects on the GSL bioeconomy.

We adopt equivalent variation (EV) as our basic welfare measure. Because drought imposes a negative social welfare shock on both the ecosystem and the regional economy, our EV measure represents the maximum amount of wealth the aggregate household sector would willingly sacrifice (i.e., its willingness-

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[18] Recall that y_{24}^{ss} is a function of the steady-state bacteria biomass demanded by brine shrimp. In order to change units of measure from biomass to population (which we must do for simulation purposes), the total biomass of brine shrimp is divided by a representative brine shrimp's weight, w_2. Thus, $y_{24}^{ss} = y_{24}(x_{21}^{ss})/w_2$

to-pay (WTP)) to avoid the full bioeconomic impacts of the drought. We calculate EV using two methods. One method, which mimics the approach used in Finnoff and Tschirhart (2011), calculates annualized EV as the difference between the current period's GDP and next period's minimum expenditure (evaluated at the current period's prices). We henceforth name this measure "Rolling EV". The second method calculates annualized EV as the difference between the initial period's regional GDP (i.e., GDP in period $t = 1$) and each subsequent period's minimum expenditure (evaluated at period $t = 1$'s prices). We henceforth label this measure "Base EV". Clearly, Rolling EV is a fully dynamic EV measure, in the sense that it explicitly accounts for period-by-period adjustments in GDP as the minuend in the EV equation. To the contrary, Base EV fixes GDP at its initial level in period $t = 1$ as the equation's minuend. In this sense, Base EV is not confounded by the period-to-period changes in GDP as is the Rolling EV measure.

To calculate the two welfare measures, we begin by expressing the household-sector expenditure function evaluated at current prices $\mathbf{P}^t = (P_a^t, P_m^t, P_r^t, P_c^t)$ (subscripts a, m, r, c denote the agricultural, mining, recreation/wildlife viewing, and composite import good sectors, respectively) and next period's indirect utility level V^{t+1} as,

$$E\left(\mathbf{P}^t, V^{t+1}\right) = \left[\left(\frac{P_a^t}{\beta_a}\right)^{\beta_a}\left(\frac{P_m^t}{\beta_m}\right)^{\beta_m}\left(\frac{P_r^t}{\beta_r}\right)^{\beta_r}\left(\frac{P_c^t}{\beta_c}\right)^{\beta_c}\left(\frac{V^{t+1}}{\alpha\left(G^t\right)^{\beta_G}}\right)\right]^{\frac{1}{(\beta_a+\beta_m+\beta_r+\beta_c)}} \tag{5}$$

where the $\beta_i, i = a, m, r, c$, represent household-sector utility substitution parameters, G^t is aggregate emissions from the mining sector in period t, β_G is G^t's associated utility substitution parameter, and the value of V^{t+1} is calculated using equation (11) in Appendix A and optimal household-sector demands resulting from the optimality conditions derived in Table 6 in Appendix B. In specific,

$$V^{t+1} = \alpha\left(\frac{\beta_a GDP^{t+1}}{P_a^{t+1}}\right)^{\beta_a}\left(\frac{\beta_m GDP^{t+1}}{P_m^{t+1}}\right)^{\beta_m}\left(\frac{\beta_r GDP^{t+1}}{P_r^{t+1}}\right)^{\beta_r}\left(\frac{\beta_c GDP^{t+1}}{P_c^{t+1}}\right)^{\beta_c}\left(G^{t+1}\right)^{\beta_G}. \tag{6}$$

Rolling EV in period $t + 1$ is then expressed as,

$$EV^{t+1}\left(\mathbf{P}^t, GDP^t, V^{t+1}\right) = GDP^t - E\left(\mathbf{P}^t, V^{t+1}\right) \tag{7}$$

while Base EV in period $t + 1$ is expressed as,

$$EV^{t+1}\left(\mathbf{P}^1, GDP^1, V^{t+1}\right) = GDP^1 - E\left(\mathbf{P}^1, V^{t+1}\right) \tag{8}$$

5 Numerical Results

In this section we present two sets of numerical results. The first set provides answers to this study's two main questions: how does the GSL bioeconomy respond to prolonged drought and what are the broader impacts of different regulations exclusively targeting recovery of the ecosystem's focal species, brine shrimp? Because one of the regulations investigated here – a harvest moratorium – mimics the regulatory framework currently in force in the GSL bioeconomy (Wotipka, 2014), and drought conditions also persist in the GSL region (Rosner, 2016), we can interpret this first set of results as loosely representing the bioeconomy's status quo. The second set of results answer's the following question: given that the fishery-specific regulations imposed in the status quo each generate a perverse social welfare effect (associated with an increase in the emissions of air and water pollution from the mining sector), to what extent can these effects be mitigated by an input or output tax levied on the mining industry?

Prolonged Drought and Fishery-Specific Regulation

As mentioned previously, here we perform numerical simulations of the GSL bioeconomy in order to demonstrate (i) the effects of prolonged drought on the ecosystem and regional economy, and (ii) the extents to which two separate regulatory policies – brine-shrimp harvest moratorium and fishery input taxation – might speed the bioeconomy's recovery from this environmental shock.[19] We model the drought as an exogenous 25-percent decrease in the lake's nutrient pool, in particular a 25-percent decrease in bacteria and algae biomass, that recurs for the first five consecutive periods of the simulation.[20] To account for a potential lag in the regulatory response we assume regulations take effect three periods after the onset of the drought and continue for four consecutive periods.[21]

The full set of initial and calibrated parameter and variable values for the ecosystem and regional economy are provided in Tables 5 and 7 in Appendix B, respectively. The ecosystem values contained in Table

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[19] GAMS version 24.7.4 r58773WEX-WEI x86 64bit/MS Windows was used for the simulation exercises.

[20] While it is possible to model any size shock for any length of time (consecutive or otherwise), we chose 25 percent strictly for demonstrative purposes. As mentioned previously, drought is at least partially an endogenous occurrence, whereby dry weather conditions coincide with what are already relatively high water-use conditions to push water availability beneath an implicit threshold. For simplicity, we impose the drought shock on the bioeconomy during the first five periods, thus avoiding the need to account for any endogenous factors that would potentially precede and ultimately compound the drought's impacts. Lastly, we ran the simulations with both smaller and larger decreases in the lake's nutrient pool for longer and shorter lengths of time. In all cases the results obtained are qualitatively similar to those discussed in the paper.

[21] For simulation purposes we compare the harvest moratorium with 50-percent ad valorum taxes levied on both wages (for labor) and the market interest rate (for capital) employed in the brine shrimp fishery. It is assumed that the revenues obtained by the government from imposition of the taxes are redistributed lump-sum to the household sector each period.

5 are taken from Finnoff and Caplan (2004), which in turn are derived from an extensive review of the pertinent GSL ecological and mircobiological literatures. As identified with asterisks ($*$) in Table 5, species i's basal metabolism rate (β_i), biomass-supply factors (δ_{ij}), respiratory productivity factor (r_i), equilibrium energy prices (e_{ij}), and bacteria and algae nutrient constraints ($Aress$) and ($Aresf$), respectively, are calibrated within the model. To our knowledge both the assumed and calibrated parameter values for the ecosystem reflect the current state of knowledge regarding the GSL's ecology. The economic component of the bioeconomic model is calibrated based on what is currently known about the relative sizes (values of production) of each sector in the regional economy. As identified by $*$ in Table 7, sector i's productivity factor (γ_i), factor shares for capital (δ_{Ki}), labor (δ_{Li}), agricultural and mining water resources (δ_{Wa} and δ_{Wm}, respectively), brine shrimp and waterbird resources (δ_{2f} and δ_{4r}, respectively) are calibrated within the model, along with household sector taste and shift parameters (β_i and α, respectively), and a host of initial values.[22]

We begin by exploring the drought's impacts on species populations in Figure 3 in Appendix C, along with the respective impacts that the fishery harvest moratorium and input taxes have on mitigating the drought and speeding species population recoveries to their original steady-state levels over time (recall that these two regulatory instruments are imposed separately, not jointly, with the latter serving as a benchmark for comparison with the former). The figure's first column depicts the steady-state species population paths when the GSL ecosystem remains in its natural state (sans harvest) versus with harvest, respectively. As expected, harvesting brine shrimp reduces the shrimp population along with its predator species, waterbirds. The brine fly population also decreases as the declining waterbird population substitutes predation on brine flies for predation on brine shrimp. Further, bacteria and algae populations increase due to the falling populations of their respective predator species, brine shrimp and brine flies. One of the concerns with increased base-species populations in the ecosystem is that as the brine shrimp and fly populations decrease due to harvest, a significant increase in the bacteria and algae populations may result in the lake's eutrophication, potentially leading to hypoxic conditions (Bedford, 2005). Although the detailed relationship between bacteria and algae populations and the lake's water quality is beyond the scope of this paper, the relationship between brine shrimp harvest and those species' populations is readily estimated via our numerical simulations.

The second and third columns of Figure 3 show the effects of the drought on species populations, along with the countervailing effects of the harvest moratorium and input tax regulations, respectively. We see in

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[22] A goal of future research is to more firmly calibrate the regional-economy model with disaggregated sector-specific data.

column two that drought reduces the population size of each species, and that the harvest moratorium has a relatively pronounced countervailing effect on the brine shrimp population recovery path, but relatively small effects on the population recovery paths of the remaining species. Results are similar for the input tax in column three. Both sets of results demonstrate (in a relative sense) the shrimp-specific effects of the harvest moratorium and input tax regulations.

To more carefully assess the effects of the respective regulations on the brine shrimp and waterbird populations we must compare the actual numbers behind the graphs. Table 8 in Appendix B presents the population sizes for periods 3 - 15 under drought (with neither regulation imposed) and with each regulation separately imposed during periods 3 - 6.[23] As the table indicates, the moratorium has slightly stronger recovery effects on both brine shrimp and waterbird populations than does the input tax.

To save space, figures depicting corresponding results for species energy prices have been omitted.[24] We find that the equilibrium energy prices paid by brine shrimp and brine flies for bacteria and algae, respectively, decrease to lower steady-state levels in the presence of harvesting, reflecting the relatively larger population sizes of these two prey species as a result of shrimp harvest and waterbirds substituting brine flies for brine shrimp in their predation decisions. Energy prices paid by waterbirds for shrimp and flies each rise initially (tracking the reduced shrimp and fly populations) and then decrease to lower steady-state levels (tracking the reduced waterbird population itself in the new steady state). Drought has relatively large, short-term impacts on the equilibrium energy prices paid by each species; impacts that attenuate as prices return to their respective steady-state levels. It is interesting to note that the prices paid by each predator species (i.e., shrimp for bacteria, fly for algae, and waterbird for shrimp and fly) experience periods of relatively marked over- or under-shooting (i.e., high volatility) along their return paths.[25]

Similar to their effects on species population adjustments, the harvest moratorium and input tax each reduce this volatility, most notably with respect to the price brine shrimp pay for bacteria. In the case of equilibrium prices paid by waterbirds for shrimp and flies, the initial price increases track the strength of the drops in the shrimp and fly populations relative to the reduction in waterbird population. The overshooting effects suggest that these relative population adjustments are later reversed, causing energy prices to temporarily fall beneath their corresponding steady-state levels. The price paths for shrimp and flies indi-

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[23] The table's assessment begins with imposition of the respective regulations in period three. Reversion back to the species' respective steady-state levels occurs at roughly the 15th period for each regulation.

[24] These figures, along with those for the economic sectors' input levels, are available upon request from the authors.

[25] Price volatility of this nature is a common artifact of general-equilibrium models (c.f., Petri and Hahn (2003)). Although anticipated, the provenance of this volatility in the GSL ecosystem is nevertheless difficult to pin down.

cate that the initial, drought-induced reductions in bacteria and algae populations cause a sharp yet brief spike in prices, the paths of which then track the consequent falls in shrimp and fly populations downward. Overshooting later occurs as the effect of lower bacteria and algae populations outweigh the effect of lower shrimp and fly populations.

Figure 4 in Appendix C contains our corresponding results for the regional economy. To begin, we note the drought-induced shifts in production from the lower-valued fishery and recreation/wildlife viewing sectors to the higher-valued agriculture and mineral extraction sectors.[26] Corresponding changes in output prices lead to a decrease in GDP during the drought, which in concert with the increase in pollution associated with increased mining activity leads to a relatively pronounced decline in the household sector's welfare level. To save space, figures depicting corresponding results for the sector's respective input levels lying behind these adjustments in production have been omitted. We find that increases in labor and capital employed in agriculture effectively outweigh the reduction in water usage, leading to an increase in production. The mining sector increases its use of each factor. Capital and labor shift out of the fishery, and despite increases in capital and labor employed in the recreation/wildlife viewing sector, the drought-induced reduction in the waterbird population ultimately leads to a fall in that sector's production level.

Unlike their respective, countervailing effects on the drought's impacts on the ecosystem itself, the two fishery-specific regulations for the most part exasperate the drought's effects on the regional economy, with the harvest moratorium inducing the more pronounced effects than the input tax. As indicated in Figure 4, the regulations each offset the initial decline in the recreation/wildlife viewing sector and mitigate the amplitude of the sector's return path to its steady state. These effects on the recreation/wildlife viewing sector are a direct consequence of each regulation's negative impact on the brine shrimp harvest. Corresponding positive impacts on the shrimp population transfer directly to its predator species, waterbirds, and via the sector's production function to recreation/wildlife viewing services available to the household sector. With respect to the remaining sectors of the regional economy, the exasperated declines in the respective shrimp harvests due to each regulation in turn exasperate the drought's original impacts. These 'exasperated' effects are uniform across the sectors' respective factor demands and the markets' equilibrium prices for both the harvest moratorium and input tax.

The corresponding paths of Rolling and Base EV values associated with the drought and each fishery-

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[26] Recalling that the waterbird population, i.e., waterbird stock, appears as an input in the recreation/wildlife production function, the fall in this stock in response to drought is what leads to the sector's noticeable production decline.

specific regulation are provided in Figure 5 in Appendix C. As expected, by fixing GDP at $t = 1$ Base EV essentially tracks the path of the household sector's welfare level, rising as welfare declines over the five consecutive periods of drought. Except for brief time periods occurring near the conclusion of the drought, each specific fishery-specific regulation exacerbates this increase in Base EV, reflecting the perverse welfare effects associated with each regulation (similar in nature to Hazilla and Kopp (1990), Pizer and Kopp (2003), and Jorgenson et al. (1992), which report perverse social welfare effects associated with environmental regulation in a general-equilibrium setting).

Because Rolling EV simultaneously accounts for reduced household welfare levels and the economy's reduced GDP levels over time as a consequence of the drought, its time paths naturally deviate from those representing Base EV. Specifically, while it initially reflects the negative welfare effects associated with the drought, Rolling EV's path suggests that these welfare effects are eventually outweighed by the drought's negative impact on regional GDP, causing it to drop beneath its benchmark path beginning in period seven. Thus, the efficacy of Rolling EV as a theoretically consistent measure of welfare loss associated with the drought is drawn into question. It suggests an eventual increase in monetized welfare in the face of what are clearly negative impacts of the drought on social welfare itself and regional GDP. As expected, the respective fishery-specific regulations each exasperate the Rolling EV measure of the drought on both its upside (in reference to the spike occurring from roughly periods 2 – 4) and downside (periods 5 – 8).

Table 9 in Appendix B presents the corresponding discounted sums of both EV measures, where we assume a constant discount rate of 2.9% over a 15-period time frame.[27] We note that both measures increase in response to the drought, and then increase again in response to the imposition of each fishery-specific regulations. Larger EV values are associated with the harvest moratorium as opposed to the input tax, indicating that on average the household sector is willing to pay the most to avoid the combination of the prolonged drought and the moratorium.

Mining Regulations

As discussed in Section 1, the perverse social welfare effects associated with each fishery-specific regulation begs the question of how we might subsequently boost welfare through additional regulation, e.g., via the imposition of multiple, sector-specific regulations. The natural sector to target in our case is the mining industry, since the increased mineral extraction induced by the fishery-specific regulations ultimately causes

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[27] The 2.9% discount rate used in this study reflects Utah's historical rate of inflation (The Salt Lake Tribune, 2013).

a welfare-reducing increase in pollution. In this section we investigate two separate forms of mining regulations – ad valorem input and output taxation – each levied separately at 30 percent for the same four consecutive periods (periods 3 – 6) as were the two fishery regulations.[28] For ease of reference, the full set of regulations considered in the paper are now summarized in Table 10 in Appendix B. We focus the ensuing discussion on results for the Moratorium and Mining Output Tax scenario.[29]

Figure 6 in Appendix C depicts the effects of the mining output tax (in concert with the harvest moratorium) on species population levels. This figure demonstrates that relative to the moratorium's impacts on the drought alone, the imposition of the mining output tax (henceforth simply "mining tax") has no discernible, additional effects. Potential feedback effects within the ecosystem may therefore be considered second-order small at best. To the contrary, the mining tax (again, in concert with the shrimp harvest moratorium) has relatively pronounced effects on the regional economy. As shown in Figure 7 in Appendix C, these effects are in some cases countervailing and in others intensifying. For example, as expected the mining tax induces increases in agricultural and recreation/wildlife production as well as in consumption of the composite good. Mining production and net exports decline along with associated pollution emissions. Regional GDP also declines, but household welfare increases, mainly in response to the reduced pollution from mining. These output effects are driven by a reallocation of factors of production from the mining sector to the agriculture and recreation/wildlife viewing sectors.

As shown in Figure 8 in Appendix C, the increase in household welfare associated with imposition of the mining tax is mirrored in the Base and Rolling EV time paths. Base EV now tracks beneath the reference path corresponding to valuation of the drought itself, both during and shortly after the drought's occurrence. Rolling EV demonstrates similar countervailing tendencies, tracking beneath its reference drought valuation path during the bulk of the drought period, and then spiking above the reference path for 2 – 3 periods in the drought's wake. Similar to valuation results obtained for each of the fishery-specific regulations, the efficacy of Rolling EV as a theoretically consistent measure of welfare is drawn into question. In this case the eventual increase in monetized welfare in the face of what is clearly the mining tax's positive impact on social welfare itself suggests that the household sector's WTP to avoid the triumvirate of drought, harvest

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[28] Although taxation per se has heretofore not been identified by the lake's regulatory authority as a possible pollution control mechanism for the mining industry, the need for some form of control has found at least some support in the literature. See for instance Bedford (2005). As with the fishery input taxes discussed in the previous subsection, revenue obtained by the government from imposition of the mining taxes are assumed to be redistributed lump-sum to the household sector each period.

[29] Results for the other three scenarios are qualitatively similar and available from the authors upon request.

moratorium, and mining tax should fall relative to its WTP to avoid only the drought and moratorium, as is reflected in the time path of Base EV.

As Table 11 in Appendix B indicates, both discounted EV measures are nevertheless consistent with the effects of the mining tax on household welfare – the measures associated with the combination of harvest moratorium and mining tax are lower than those for the harvest moratorium alone.

6 Summary and Conclusion

We have developed a general-equilibrium bioeconomic model of Utah's Great Salt Lake (GSL) ecosystem that tightly links the lake's ecosystem with its regional economy and attendant international trading partners. The bioeconomic model initially developed in Finnoff and Caplan (2004) has been updated to reflect new information regarding mutually exclusive species interaction in the ecosystem's food web. The ecosystem has been linked with an extended version of the small-country trading equilibrium model developed by Gilbert and Tower (2012) in order to identify the dynamic feedback effects of prolonged drought on the GSL bioeconomy. The drought modeled here mimics a temporally drying climate's impact on the lake's nutrient pool, which consists of the food web's base species, algae and bacteria. The base species are preyed upon by brine shrimp (the ecosystem's focal species) and brine flies, which in turn are preyed upon by waterbirds. In this framework we have demonstrated numerically (1) how the effects of prolonged drought change key bioeconomic variables over time, and (2) how these variables eventually recover from the drought toward a new steady state. We have also considered how two separate fishery-specific regulatory tools – a temporary brine-shrimp harvest moratorium (i.e., quantity regulation) and an ad valorum tax on the fishery's factors of production (price regulation) – might be used independently of one another to alter the bioeconomy's recovery path. By explicitly accounting for dynamic feedback effects between the GSL ecosystem and regional economy, our GE bioeconomic model extends to a inland lake setting the models similarly developed by Finnoff and Tschirhart (2003a) and Finnoff and Tschirhart (2003b) for an Alaskan marine fishery and Finnoff and Tschirhart (2011) for a North Carolina estuary.

Numerical simulation exercises have generated four key findings. First, the fishery-specific regulatory instruments have relatively strong recovery effects on the brine shrimp population, but noticeably weaker effects on the ecosystem's other species populations, suggesting that multi-species recovery in an ecosystem suffering from prolonged drought likely requires the imposition of multiple species-specific regulatory instruments, similar to how the control of multiple pollutants require pollutant-specific regulation (Lence et al., 1988; Montgomery, 1972; Caplan and Silva, 2005; Caplan, 2006; Ambec and Coria, 2013; Michaelis, 2017). In other words, if society's goal is to simultaneously speed recovery from an environmental shock of both a focal prey species and a predator species, additional species-specific regulatory policies may be necessary – one directed toward the recovery of the prey species, the other toward recovery of the predator species. Second, the reallocation of production in the regional economy wrought by these regulations affects social welfare perversely, as a consequence of an increase in pollution damage accompanying the reallocation of production resources from the shrimp fishery to the mining sector. This result extends to a bioeconomic setting the classic general-equilibrium literature (e.g., Hazilla and Kopp (1990); Pizer and Kopp (2003); Jorgenson et al. (1992)) on welfare effects associated with environmental regulation.

Third, we show that these perverse welfare effects associated with fishery-specific regulations can be offset via imposition of either an input or an output tax on mineral extraction. This suggests that, in addition to multiple species-specific regulations imposed within the ecosystem itself, multi-sector regulation within the regional economy is also likely necessary to maintain, or perhaps improve, social welfare. Fourth, we have evaluated the efficacy of two different dynamic measures of equivalent variation in measuring the welfare effects associated with prolonged drought, the shrimp harvest moratorium, and a mining output tax. What we have named Base EV calculates annualized EV as the difference between the initial period's GDP (GDP in period $t = 1$) and each subsequent period's minimum expenditure (evaluated at period $t = 1$'s prices). In contrast Rolling EV calculates annualized EV as the difference between the current period's GDP and next period's minimum expenditure (evaluated at the current period's prices). With respect to each EV measure's time path, we find that the efficacy of Rolling EV as a theoretically consistent measure of welfare loss associated with the drought is drawn into question. However, summary (i.e., discounted) measures of EV are theoretically consistent for both Base and Rolling EV.

The path(s) for future research are clear, each relating to a series of updates to the numerical model presented here as more scientific information about the effects of prolonged drought on the bioeconomy come to light. For instance, the specific effects of drought on agricultural productivity and water allocation in general in the GSL regional economy have not been fully explored in this particular version of the model (Coppock, 2011; Elias et al., 2016). Neither have the effects of pollution from mining and nutrient loading from agriculture on the GSL ecosystem. Indeed, the array of possible adjustments to the model, as new information about the bioeconomy becomes available, seems almost limitless. Ultimately, the usefulness of this type of bioeconomic model is measured by the extent to which it can be utilized to inform management policy. As it evolves with new data and better understanding of the bioeconomy, the model can provide a holistic framework (that captures both direct and dynamic feedback effects) within which to assess the joint effects of drought and climate change on the ecology of the GSL, as well as on the region's economy and social welfare.

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Figure Legends

Figure 1: The Great Salt Lake (GSL) Map

Figure 2: The Great Salt Lake (GSL) Bioeconomy

Figure 3: Species Populations

Figure 4: Output Markets

Figure 5: Rolling and Base Equivalent Variation (EV) Paths

Figure 6: Species Populations: Moratorium and Output Tax on Mining

Figure 7: Output Markets: Moratorium and Output Tax on Mining

Figure 8: Rolling and Base EV Paths: Moratorium and Output Tax on Mining

Appendix A: The GSL Regional Economy

Production

The GSL regional economy consists of four main production sectors: agriculture (a), mineral extraction (m), brine shrimp fishery (f), and recreation/wildlife-viewing (r). Following Gilbert and Tower (2012), each sector is endowed with constant elasticity of substitution (CES) production technology. Specifically,

$$\begin{aligned} Q_a(K_a,L_a,W_a) &= \gamma_a[\delta_{Ka}K_a^{\rho_a}+\delta_{La}L_a^{\rho_a}+\delta_{Wa}W_a^{\rho_a}]^{1/\rho_a} && \text{(9a)}\\ Q_m(K_m,L_m,W_m) &= \gamma_m[\delta_{Km}K_m^{\rho_m}+\delta_{Lm}L_m^{\rho_m}+\delta_{Wm}W_m^{\rho_m}]^{1/\rho_m} && \text{(9b)}\\ Q_f(K_f,L_f,N_2) &= \gamma_f[\delta_{Kf}K_f^{\rho_f}+\delta_{Lf}L_f^{\rho_f}+\delta_{2f}(cyst_2N_2)^{\rho_f}]^{1/\rho_f} && \text{(9c)}\\ Q_r(K_r,L_r,N_4) &= \gamma_r[\delta_{Kr}K_r^{\rho_r}+\delta_{Lr}L_r^{\rho_r}+\delta_{4r}N_4^{\rho_r}]^{1/\rho_r}, && \text{(9d)} \end{aligned}$$

where Q_i represents sector i's output level, $i \in a,m,f,r$, γ_i represents sector i's productivity scale factor, δ_{ji} input j's share factor in the production of sector i's output, $j \in K,L,W,2,4$, and ρ_i the degree of input substitutability in sector i (time subscript t is again dropped for expository convenience). Variables K and L are mobile factors of production – labor and capital, respectively – while W represents water input, which is mobile across the agriculture and mining sectors. The term $cyst_2N_2$ in the expression for Q_f accounts for the input role that the brine-shrimp population plays in the quantity of cysts ultimately harvested in any given period[30] Here, proportionality factor $cyst_2$ converts the adult brine-shrimp population to its corresponding cyst population, which, as explained below, is ultimately exported. Similarly, waterbird population, N_4, serves as an input in the production of recreation and wildlife-viewing, Q_r, but without the need for any attendant conversion factor per se.

Lastly, it is assumed that homogeneous and perfectly mobile inputs capital, labor, and water satisfy their respective finite full-employment conditions each period, expressed as,

$$\bar{K} = K_a + K_m + K_f + K_r, \tag{10a}$$

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[30] As mentioned earlier, precedent for the inclusion of a commercial species' population level as an input in its associated production function can be found in Gordon (1954) and Smith (1969).

$$\bar{L} = L_a + L_m + L_f + L_r, \tag{10b}$$

$$\bar{W} = W_a + W_m, \tag{10c}$$

where $\bar{K}, \bar{L}$ and $\bar{W}$ represent period-specific, total available levels of capital, labor, and water, respectively.

The Household Sector

Following Gilbert and Tower (2012), we assume the regional economy's preferences (i.e., the household sector's aggregate preferences), are represented by a standard Cobb-Douglas utility function (U). Specifically,

$$U(C_a, C_m, C_r, C_c, G) = \alpha C_a^{\beta_a} C_m^{\beta_m} C_r^{\beta_r} C_c^{\beta_c} G^{\beta_G}, \tag{11}$$

where the set $\{C_a, C_m, C_r, C_c\}$ represents domestic consumption levels of the agricultural, mineral, recreation/wildlife viewing, and composite import goods, respectively. Parameter $\alpha > 0$ is the utility function's shift parameter and the β_i's represent the function's set of taste parameters, $i \in \{a, m, r, c, G\}$. Variable G represents the composite air and water pollution level resulting from mineral extraction, which is assumed proportional to the mining sector's production level Q_m, specifically $G = \phi Q_m$, $\phi > 0$.[31] While β parameters, β_a, β_m, β_r, and β_c, are each greater than zero, β_G is less than zero, reflecting the fact that pollution damages the environment and thus reduces social welfare. For simplicity we assume β_G is the (negative) average of the other (positive) taste parameters, i.e., $\beta_G = -(\beta_a + \beta_m + \beta_r + \beta_c)/4$.

Market-Clearing and Trade Balance Conditions

Following Issacson and Robson (2002), U.S. Department of the Interior, Fish and Wildlife Service and U.S. Department of Commerce, U.S Census Bureau (2001), and UNDR (2013), we model the agriculture and recreation sectors as producing solely for the domestic regional market. Brine shrimp cysts are produced solely for export and the mineral extraction industry produces partially for the domestic regional market and partially for export to the world market. Households import the composite good. As a result, the regional

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[31] See Henetz (2005) and Farrell (2005) for evidence on the link between GSL mercury pollution and regional mining activities.

economy's per-period market-clearing and trade-balance equations may be expressed as,

$$Q_a = C_a, Q_r = C_r, \tag{12a}$$

$$Q_m = C_m + X_m, Q_f = X_f, C_c + X_c = 0, \tag{12b}$$

$$\hat{P}_m X_m + \hat{P}_f X_f + \hat{P}_c X_c = 0, \tag{12c}$$

where equations (12a) and (12b) represent the respective market-clearing conditions and equation (12c) the trade balance. Here, X_m, X_f, and X_c are net exports of the mining products, brine-shrimp cysts, and composite good, respectively. Their respective values are negative (imports) or positive (exports), whichever the case may be. Given our small open-economy assumption, output prices for the traded goods ($\hat{P}_m$, $\hat{P}_f$, and $\hat{P}_c$) are exogeneously determined in their respective world markets. As the corresponding trade balance equation (12c) shows, the total value of net exports sums to zero.

Formal Problem

We can now represent the regional economy's per-period optimization problem in the form of a Lagrangian function, where the objective is to maximize the household sector's welfare function (11) subject to full-employment conditions (10), production functions (9), and market-clearing and trade-balance conditions (12) period-by-period, i.e., myopically. Because the agricultural and recreation/wildlife-viewing goods are non-traded, market-clearing conditions associated with these two goods endogenously determine their associated output prices. World prices for minerals, brine shrimp, and the composite import good are determined exogenously and taken as given in the problem. The detailed optimization problem with corresponding first order conditions (FOCs) is presented in Table 6 in Appendix B. Here we present a compact form of the problem's per-period Lagrangian function,

$$\mathscr{L} = U(\mathbf{C}, G) + \Lambda[\mathbf{Q}, \mathbf{C}, \mathbf{X}] + \mathbf{M}[\bar{\mathbf{R}}, \mathbf{R_K}, \mathbf{R_L}, \mathbf{R_W}] + \phi[\mathbf{P}\cdot\mathbf{X}],$$

where consumption vector $\mathbf{C} = (C_a, C_m, C_r, C_c)$, $\Lambda = (\lambda_a, \lambda_m, \lambda_f, \lambda_r, \lambda_c)$ is the multiplier vector corresponding to the set of market-clearing and trade-balance conditions included in equation (8) (which also represent the equilibrium output prices under competitive market conditions), $\mathbf{Q} = (Q_a, Q_m, Q_f, Q_r)$, $\mathbf{X} = (X_m, X_f, X_c)$, and $\mathbf{M} = (\mu_K, \mu_L, \mu_W)$ is the multiplier vector corresponding to the full-employment conditions, with $\bar{\mathbf{R}} =$

$(\bar{\mathbf{K}}, \bar{\mathbf{L}}, \bar{\mathbf{W}})$, $\mathbf{R_K} = (K_a, K_m, K_f, K_r)$, $\mathbf{R_L} = (L_a, L_m, L_f, L_r)$, and $\mathbf{R_W} = (W_a, W_m)$. Further, $\mathbf{P} = (\hat{P_m}, \hat{P_f}, \hat{P_c})$, where ϕ is the shadow price of foreign exchange normalized to unity.

Appendix B: Tables

Table 1: Species Identification Numbers

Species Numbers	Species Names
0	Nutrient Pool
$s1$	Bacteria
$f1$	Algae
2	Brine Shrimp
3	Brine Flies (larvae and adult)
4	Waterbirds

Table 2: Biomass-Supply and Variable-Respiration Functions

Biomass-Supply	Variable-Respiration
$y_{12}(x_{s10}) = \delta_{12} x_{s10}^{\alpha_{12}}$	$f_{s1}(SA_{s1}; x_{s10}) = r_{s1}[SA_{s1} + 1] x_{s10}^{\gamma_{s1}}$, where $SA_{s1} = s_{1a} + s_{1m}$
$y_{13}(x_{f10}) = \delta_{13} x_{f10}^{\alpha_{13}}$	$f_{f1}(SA_{f1}; x_{f10}) = r_{f1}[SA_{f1} + 1] x_{f10}^{\gamma_{f1}}$, where $SA_{f1} = SA_{s1}$
$y_{24}(x_{21}) = \delta_{24} x_{21}^{\alpha_{24}}$	$f_2(SA_2; x_{21}) = r_2[SA_2 + 1] x_{21}^{\gamma_2}$, where $SA_2 = s_{2a} + s_{2m}$
$y_{34}(x_{31}) = \delta_{34} x_{31}^{\alpha_{34}}$	$f_3(SA_3; x_{31}) = r_3[SA_3 + 1] x_{31}^{\gamma_3}$, where $SA_3 = s_{3a} + s_{3m}$
	$f_4(x_{42}, x_{43}) = r_4(x_{42} + x_{43}) + 0.5 r_4(r_{43} x_{42} x_{43} + x_{42}^{\gamma_4} + r_{43} x_{43}^{\gamma_4})$

$$s_{1a} = \sigma_{1a}\left[\frac{W_a}{W_a + W_m}\right] \quad \textit{and} \quad s_{1m} = \sigma_{1m}\left[\frac{W_m}{W_a + W_m}\right]$$

$$s_{2a} = \sigma_{2a}\left[\frac{W_a}{W_a + W_m}\right] \quad \textit{and} \quad s_{2m} = \sigma_{2m}\left[\frac{W_m}{W_a + W_m}\right]$$

$$s_{3a} = \sigma_{3a}\left[\frac{W_a}{W_a + W_m}\right] \quad \textit{and} \quad s_{3m} = \sigma_{3m}\left[\frac{W_m}{W_a + W_m}\right]$$

Table 3: Species' Net-Energy Functions and First-Order and Short-Run Equilibrium Conditions

Species	Net-Energy Function (Watts or Kilocalories)
Bacteria	$R_{s1} = \left[e_0 - e_{s10}\right]x_{s10} - e_{s1}\left[1 + t_{12}e_{21}\right]y_{12}(x_{s10}) - f_{s1}(SA_{s1};x_{s10}) - \beta_{s1}$
Algae	$R_{f1} = \left[e_0 - e_{f10}\right]x_{f10} - e_{f1}\left[1 + t_{13}e_{31}\right]y_{13}(x_{f10}) - f_{f1}(SA_{f1};x_{f10}) - \beta_{f1}$
Brine Shrimp	$R_2 = \left[e_{s1} - e_{21}\right]x_{21} - e_2\left[1 + t_{24}e_{42}\right]y_{24}(x_{21}) - f_2(SA_2;x_{21}) - \beta_2$
Brine Flies	$R_3 = \left[e_{f1} - e_{31}\right]x_{31} - e_3\left[1 + t_{34}e_{43}\right]y_{34}(x_{31}) - f_3(SA_3;x_{31}) - \beta_3$
Waterbirds	$R_4 = \left[e_2 - e_{42}\right]x_{42} + \left[e_3 - e_{43}\right]x_{43} - f_4(x_{42},x_{43}) - \beta_4$
Control Variables	First Order Conditions
x_{s10}	$e_0 = e_{s10} + e_{s1}\left[1 + t_{12}e_{21}\right]y'_{12}(x_{s10}) + f'_{s1}(x_{s10};SA_{s1})$
x_{f10}	$e_0 = e_{f10} + e_{f1}\left[1 + t_{13}e_{31}\right]y'_{13}(x_{f10}) + f'_{f1}(x_{f10};SA_{f1})$
x_{21}	$e_{s1} = e_{21} + e_2\left[1 + t_{24}e_{42}\right]y'_{24}(x_{21}) + f'_2(x_{21};SA_2)$
x_{31}	$e_{f1} = e_{31} + e_3\left[1 + t_{34}e_{43}\right]y'_{34}(x_{31}) + f'_3(x_{31};SA_3)$
x_{42}	$e_2 = e_{42} + f'_{42}(x_{42},x_{43})$
x_{43}	$e_3 = e_{43} + f'_{43}(x_{42},x_{43})$
Biomass Markets	Short Run Equilibrium Conditions
Nutrient Pool – Bacteria	$N_{s1}x_{s10}(e_{s10},e_{21},SA_{s1}) = Aress$
Nutrient Pool – Algae	$N_{f1}x_{f10}(e_{f10},e_{31},SA_{f1}) = Aresf$
Brine Shrimp – Bacteria	$N_2x_{21}(e_{21},e_{42},SA_2) = N_{s1}y_{12}(e_{s10},e_{21},SA_{s1})$
Brine Flies – Algae	$N_3x_{31}(e_{31},e_{43},SA_3) = N_{f1}y_{13}(e_{f10},e_{31},SA_{f1})$
Waterbirds – Brine Shrimp	$N_4x_{42}(e_{42},e_{43}) = N_2y_{24}(e_{21},e_{42},SA_2)$
Waterbirds – Brine Flies	$N_4x_{43}(e_{42},e_{43}) = N_3y_{34}(e_{31},e_{43},SA_3)$

Note: $Aress$ and $Aresf$ represent the fixed sizes of the nutrient pool for bacteria and algae, respectively. As benchmarks, $Aress$ is calibrated by $Aress = N_{s1}x_{s10}$, and $Aresf$ by $Aresf = N_{f1}x_{f10}$. The explicit functional forms of partial derivatives of $f_i(\cdot)$ and $y_{ik}(x_{ij})$ are shown as follows,

$$f'_{s1}(x_{s10};SA_{s1}) = \gamma_{s1}r_{s1}[SA_{s1}+1]x_{s10}^{\gamma_{s1}-1},\ y'_{12}(x_{s10}) = \alpha_{12}\delta_{12}x_{s10}^{\alpha_{12}-1}$$

$$f'_{f1}(x_{f10};SA_{f1}) = \gamma_{f1}r_{f1}[SA_{f1}+1]x_{f10}^{\gamma_{f1}-1},\ y'_{13}(x_{f10}) = \alpha_{13}\delta_{13}x_{f10}^{\alpha_{13}-1}$$

$$f'_2(x_{21};SA_2) = \gamma_2 r_2[SA_2+1]x_{21}^{\gamma_2-1},\ y'_{24}(x_{21}) = \alpha_{24}\delta_{24}x_{21}^{\alpha_{24}-1}$$

$$f'_3(x_{31};SA_3) = \gamma_3 r_3[SA_3+1]x_{31}^{\gamma_3-1},\ y'_{34}(x_{31}) = \alpha_{34}\delta_{34}x_{31}^{\alpha_{34}-1}$$

$$f'_{42}(x_{42};x_{43}) = r_4 + 0.5r_4[r_{43}x_{43} + \gamma_4 x_{42}^{\gamma_4-1}]$$

$$f'_{43}(x_{42};x_{43}) = r_4 + 0.5r_4[r_{43}x_{42} + \gamma_4 r_{43}x_{43}^{\gamma_4-1}].$$

Table 4: Species' Population-Updating Equations

Species	Population-Updating Equations
$s1$	$N_{s1}^{t+1} = N_{s1}^{t} + \frac{N_{s1}^{t}}{v_{s1}^{ss}} \left[y_{12}^{ss} \left(1 - \frac{1}{s_{s1}}\right) + \frac{1}{s_{s1}} \right] \left[v_{s1} + R_{s1}^{*} \right] - N_{s1}^{t} \left[y_{12}^{t} \left(1 - \frac{1}{s_{s1}}\right) + \frac{1}{s_{s1}} \right]$
$f1$	$N_{f1}^{t+1} = N_{f1}^{t} + \frac{N_{f1}^{t}}{v_{f1}^{ss}} \left[y_{13}^{ss} \left(1 - \frac{1}{s_{f1}}\right) + \frac{1}{s_{f1}} \right] \left[v_{f1} + R_{f1}^{*} \right] - N_{f1}^{t} \left[y_{13}^{t} \left(1 - \frac{1}{s_{f1}}\right) + \frac{1}{s_{f1}} \right]$
2	$N_{2}^{t+1} = N_{2}^{t} + \frac{N_{2}^{t}}{v_{2}^{ss}} \left[y_{24}^{ss} \left(1 - \frac{1}{s_{2}}\right) + \frac{1}{s_{2}} \right] \left[v_{2} + R_{2}^{*} \right] - N_{2}^{t} \left[y_{24}^{t} \left(1 - \frac{1}{s_{2}}\right) + \frac{1}{s_{2}} \right] - H_{c}^{t}$
3	$N_{3}^{t+1} = N_{3}^{t} + \frac{N_{3}^{t}}{v_{3}^{ss}} \left[y_{34}^{ss} \left(1 - \frac{1}{s_{3}}\right) + \frac{1}{s_{3}} \right] \left[v_{3} + R_{3}^{*} \right] - N_{3}^{t} \left[y_{34}^{t} \left(1 - \frac{1}{s_{3}}\right) + \frac{1}{s_{3}} \right]$
4	$N_{4}^{t+1} = N_{4}^{t} + \frac{N_{4}^{t}}{s_{4}} \left[\frac{v_{4} + R_{4}^{*}}{v_{4}^{ss}} - 1 \right]$

Note: $y_{12}^{ss} = y_{12}(x_{s10}^{ss})/w_{s1}$, $y_{13}^{ss} = y_{13}(x_{f10}^{ss})/w_{f1}$, $y_{24}^{ss} = y_{24}(x_{21}^{ss})/w_{2}$, $y_{34}^{ss} = y_{34}(x_{31}^{ss})/w_{3}$

Table 5: Values of Ecological Parameters and Initial Variables

Embodied Energy	Tax in Supply	Supply	Basal Metabolism
$e_0 = 1500$	t_{12}=0.0000688280	α_{12}^{GSL}=0.5	β_{s1}=1.4198593*
$e_{s1} = 1300$	t_{13}=0.0000130773	α_{13}^{GSL}=0.5	β_{f1}=1.88082521*
$e_{f1} = 1300$	t_{24}=0.0090030127	α_{24}^{GSL}=0.5	β_2=56.03115663*
$e_2 = 1000$	t_{34}=0.0115926425	α_{34}^{GSL}=0.5	β_3=29.21489220*
$e_3 = 500$			β_4=61,870.1
δ^{GSL} Parameters	Respiration Parameters	r^{GSL} Parameters	Life Spans
δ_{12}^{GSL}=0.01053687*	γ_{s1}^{GSL}=1.3	r_{s1}^{GSL}=2,381.249*	s_{s1}=5
δ_{13}^{GSL}=0.00233150*	γ_{f1}^{GSL}=1.3	r_{f1}^{GSL}=2,391.057*	s_{f1}=5
δ_{24}^{GSL}=0.13640192*	γ_2^{GSL}=1.3	r_2^{GSL}=514.0552*	s_2=5
δ_{34}^{GSL}=0.24634991*	γ_3^{GSL}=1.3	r_3^{GSL}=553.338*	s_3=5
	γ_4^{GSL}=1.3	r_4^{GSL}=157.5466*	s_4=15
	γ_{43}^{GSL}=1.3	r_{43}^{GSL}=0.02332145*	
Salinity Adjustment	Solar Input	Weights	Species and Energy Constraint
σ_{1a}=0.75	ps=0.09	w_{s1}=0.007	$Aress$=1,478,332*
σ_{2a}=0.75	qs=0.4	w_{f1}=0.007	$Aresf$=2,892,059*
σ_{3a}=0.75	pf=0.09	w_2=0.776154462	$etaco$=0.005
σ_{1m}=0.75	qf=0.04	w_2=0.776154462	
σ_{2m}=0.75		w_3=0.887	
σ_{3m}=0.75			

Variables	Initial Values
Biomass Demand	x_{s10}=0.007068638
	x_{f10}=0.007068638
	x_{21}=0.656089993
	x_{31}=0.401
	x_{42}=156
	x_{43}=156
Species Populations	N_{s1}=209,139,538
	N_{f1}=409,139,538
	N_2=386,392
	N_3=200,000
	N_4=200
Biomass Energy Price	e_{s10}=191.6095*
	e_{f10}=250.6058*
	e_{21}=117*
	e_{31}=195*
	e_{42}=90*
	e_{43}=45*

Table 6: Formal Optimization Problem for the GSL Regional Economy

Objective: $U = \alpha C_a^{\beta_a} C_m^{\beta_m} C_r^{\beta_r} C_c^{\beta_c} G^{\beta_G}$

Subject to,

i) $Q_a = C_a$, $Q_m = C_m + X_m$, $Q_f = X_f$, $Q_r = C_r$, $C_c + X_c = 0$ (Market-Clearing Conditions)

ii) $\bar{K} = K_a + K_m + K_f + K_r$, $\bar{L} = L_a + L_m + L_f + L_r$, $\bar{W} = W_a + W_m$ (Full-Employment Conditions)

iii) $\hat{P}_m X_m + \hat{P}_f X_f + \hat{P}_c X_c = 0$ (Trade-Balance Condition)

First Order Conditions (FOCs):

i) $\frac{\partial U}{\partial C_a} = \lambda_a$, $\frac{\partial U}{\partial C_m} = \lambda_m$ $\frac{\partial U}{\partial C_r} = \lambda_r$, $\frac{\partial U}{\partial C_c} = \lambda_c$

ii) $\lambda_m = \phi \hat{P}_m$, $\lambda_f = \phi \hat{P}_f$, $\lambda_c = \phi \hat{P}_c$, where ϕ is normalized to unity

iii) $\lambda_a \frac{\partial Q_a}{\partial K_a} = \lambda_m \frac{\partial Q_m}{\partial K_m} = \lambda_f \frac{\partial Q_f}{\partial K_f} = \lambda_r \frac{\partial Q_r}{\partial K_r} = \mu_K$

iv) $\lambda_a \frac{\partial Q_a}{\partial L_a} = \lambda_m \frac{\partial Q_m}{\partial L_m} = \lambda_f \frac{\partial Q_f}{\partial L_f} = \lambda_r \frac{\partial Q_r}{\partial L_r} = \mu_L$

v) $\lambda_a \frac{\partial Q_a}{\partial W_a} = \lambda_m \frac{\partial Q_m}{\partial W_m} = \mu_W$

vi) market-clearing, full-employment, and trade-balance conditions hold

Note that the first order conditions are derived from the following Lagrangian function,

$$\begin{aligned}
\mathscr{L} = U &+ \lambda_a(Q_a - C_a) + \lambda_m(Q_m - C_m - X_m) + \lambda_f(Q_f - X_f) + \lambda_r(Q_r - C_r) + \lambda_c(C_c - X_c) \\
&+ \mu_K(\bar{K} - K_a - K_m - K_f - K_r) + \mu_L(\bar{L} - L_a - L_m - L_f - L_r) + \mu_W(\bar{W} - W_a - W_m) \\
&+ \phi(\hat{P}_m X_m + \hat{P}_f X_f + \hat{P}_c X_c).
\end{aligned}$$

Table 7: Values of Economic Parameters and Initial Variables

Sectors	Factor Productivity	Factor Substitutability
Agriculture (*a*)	γ_a=2.89937061*	ρ_a=0.1
Mining (*m*)	γ_m=2.76880520*	ρ_m=0.1
Brine-Shrimp Fishery (*f*)	γ_f=0.19452063*	ρ_f=0.1
Recreation (*r*)	γ_r=0.04637760*	ρ_r=0.1
Composite (*c*)		
Share Parameter (Capital)	Share Parameter (Labor)	Share Parameter
δ_{Ka}=0.27361600*	δ_{La}=0.27361600*	δ_{Wa}=0.45276800*
δ_{Km}=0.51294360*	δ_{Lm}=0.21217673*	δ_{Wm}=0.27487967*
δ_{Kf}=0.87841463*	δ_{Lf}=0.12158537*	δ_{2f}=0.25*
δ_{Kr}=0.91491276*	δ_{Lr}=0.08508724*	δ_{4r}=0.375 *
Output Price(exogenous)	Taste Parameter	Shift Parameter in Utility
$\hat{P}_f$=1	β_a=0.23076923*	α=9.81493045*
$\hat{P}_m$=3	β_m=0.23076923*	
$\hat{P}_c$=2	β_r=0.23076923*	
	β_c=0.30769231*	
	β_{poll}=-0.25*	

Variables	Initial Values
Output, Consumption, and Net Exports	Q_a=C_a=150 Q_m=C_m=150 (X_m=0) Q_f=X_f=200 Q_r=C_r=150* C_c=$-X_c$=200*
Capital	K_a=40 K_m=80 K_f=180* K_r=140*
Labor	L_a=40 L_m=30 L_f=20 L_r=10
Specific Factor	W_a=70* W_m=40*
Factor Price	r_k=1 r_l=1 r_w=1
Output Price (endogenous)	P_a=2 P_r=2
Utility	U=650
Gross Domestic Product	GDP=650
Pollution	G=37.5*
Harvest	H_c=104,000*

Table 8: Brine Shrimp and Waterbird Populations under Drought, Moratorium, and Input Taxation

Key Periods	Brine Shrimp			Waterbirds		
	Drought	Moratorium	Input Tax	Drought	Moratorium	Input Tax
3	257,590	257,590	257,590	194.32	194.32	194.32
4	236,116	255,794	250,816	189.61	189.61	189.61
5	222,623	252,195	244,485	184.51	185.01	184.89
6	214,660	248,850	239,709	179.42	180.63	180.33
7	230,108	265,267	255,664	175.95	178.03	177.49
8	249,291	265,840	261,187	174.34	177.25	176.49
9	264,395	272,023	269,844	174.22	177.29	176.48
10	274,927	278,213	277,257	175.06	177.97	177.20
11	281,804	282,944	282,597	176.44	179.04	178.35
12	286,048	286,136	286,089	178.05	180.30	179.70
13	288,499	288,100	288,193	179.68	181.59	181.08
14	289,782	289,191	289,341	181.24	182.84	182.41
15	290,337	289,706	289,870	182.65	183.97	183.62

Table 9: Present Values of Rolling and Base EV

Scenario	Rolling EV	Base EV
With Harvest	4.78	43.98
Drought	9.07	119.23
Moratorium	10.03	161.02
Fishery Input Tax	9.47	141.73

Table 10: Multi-Sector Regulatory Scenarios

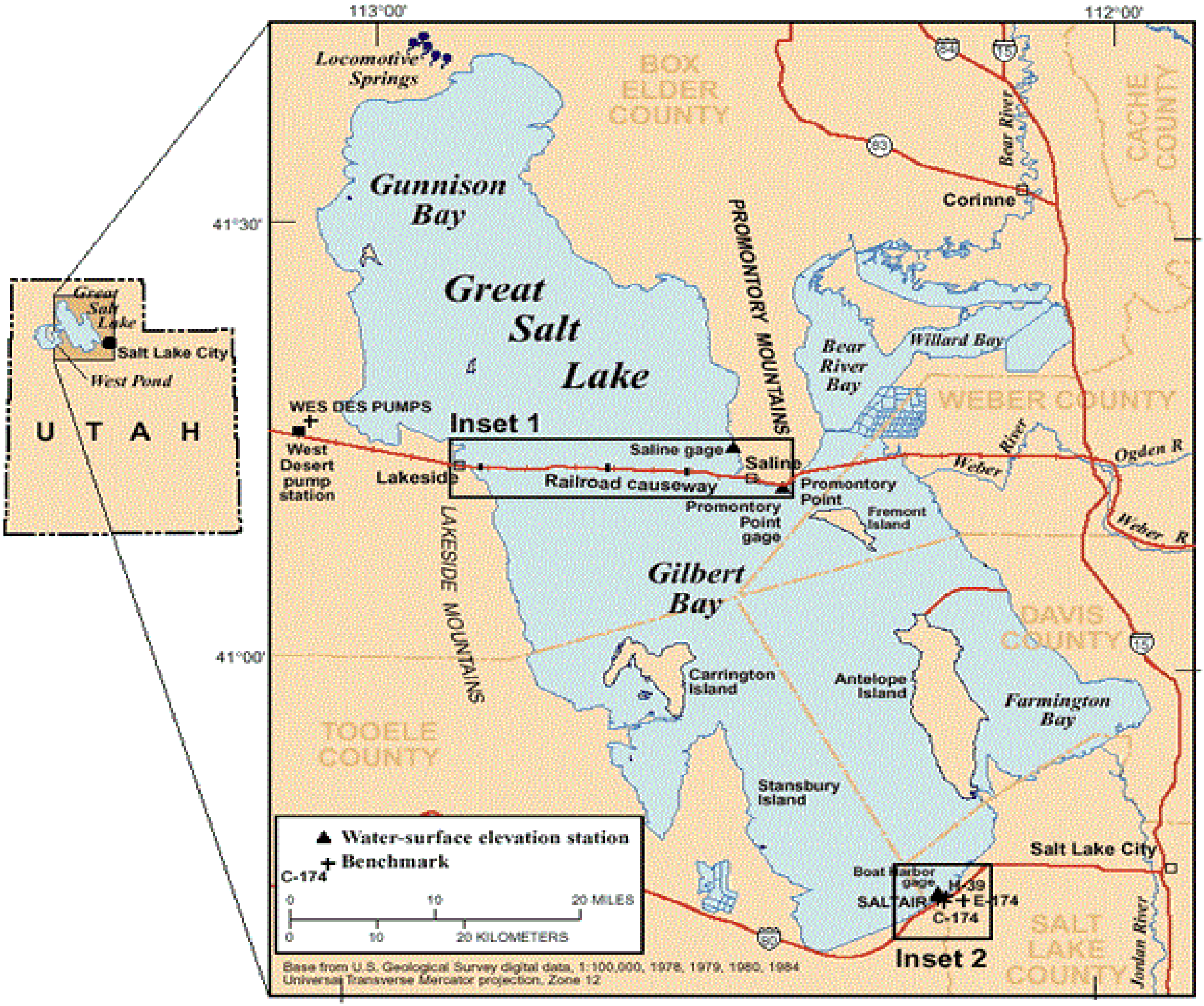
Scenarios
Moratorium and Mining Input Tax (30%)
Moratorium and Mining Output Tax (30%)
Fishery Input Tax (50%) and Mining Input Tax (30%)
Fishery Input Tax (50%) and Mining Output Tax (30%)

Table 11: Present Values of Rolling and Base EV

Single/Multiple Sector Regulations	Rolling EV	Base EV
Drought	9.07	119.23
Moratorium	10.03	161.02
Moratorium and Output Tax on Mining	6.78	74.33

Appendix C: Figures

Figure 1: The Great Salt Lake (GSL) Map



Source: U.S. Geological Survey (USGS)
`http://ut.water.usgs.gov/greatsaltlake/elevations/gslcorrection.html`

Figure 2: The Great Salt Lake (GSL) Bioeconomy

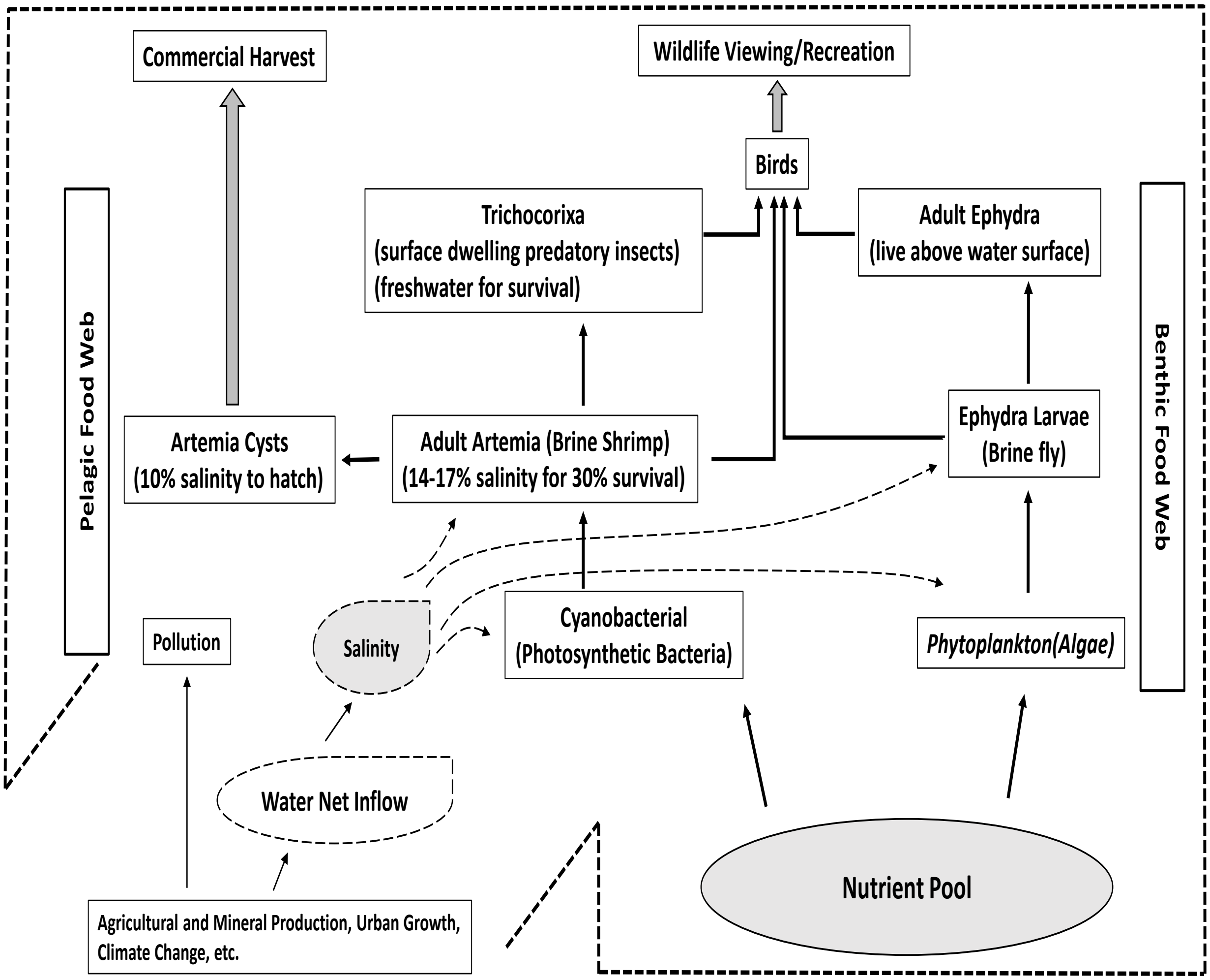


Figure 3: Species Populations

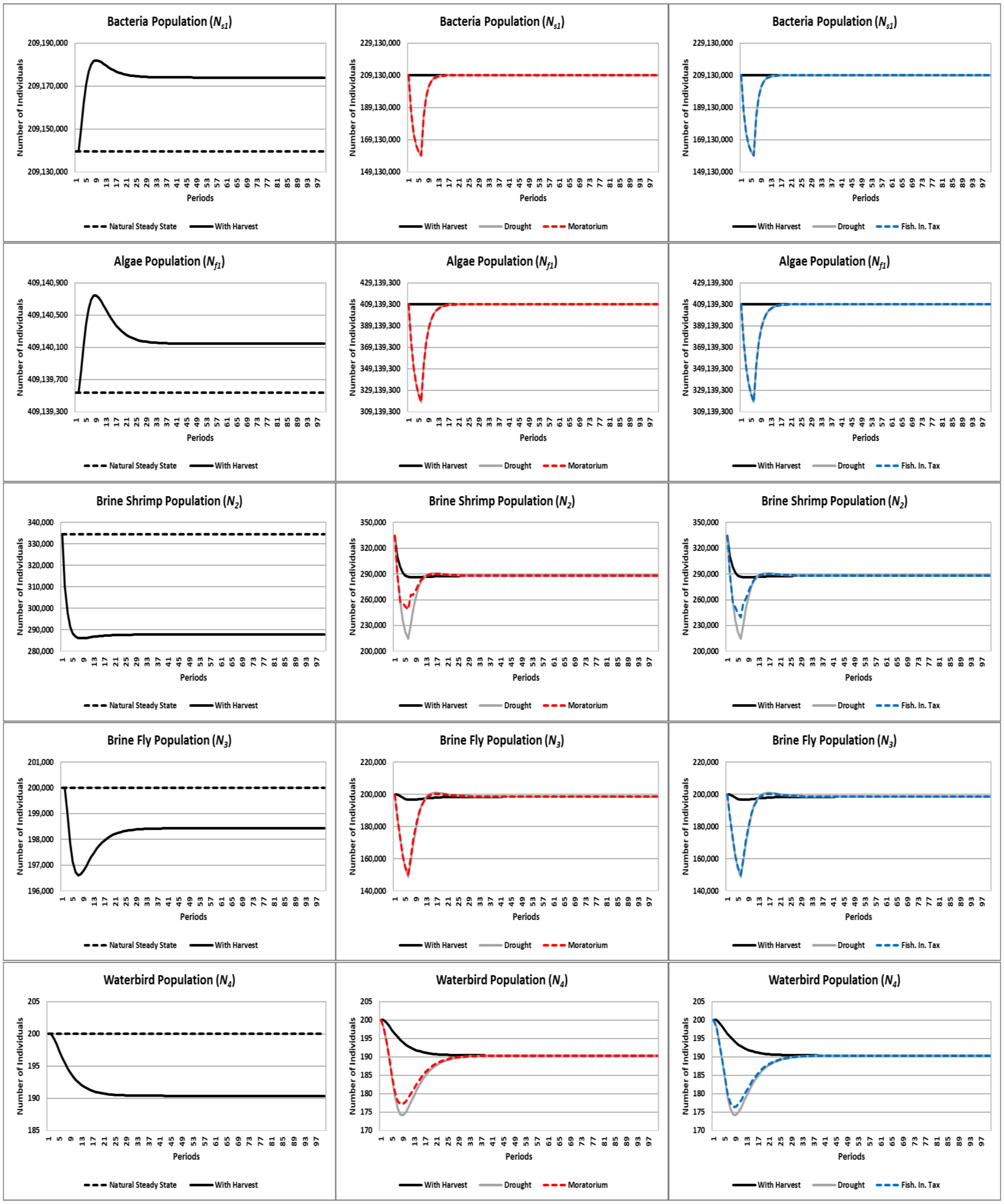


Figure 4: Output Markets

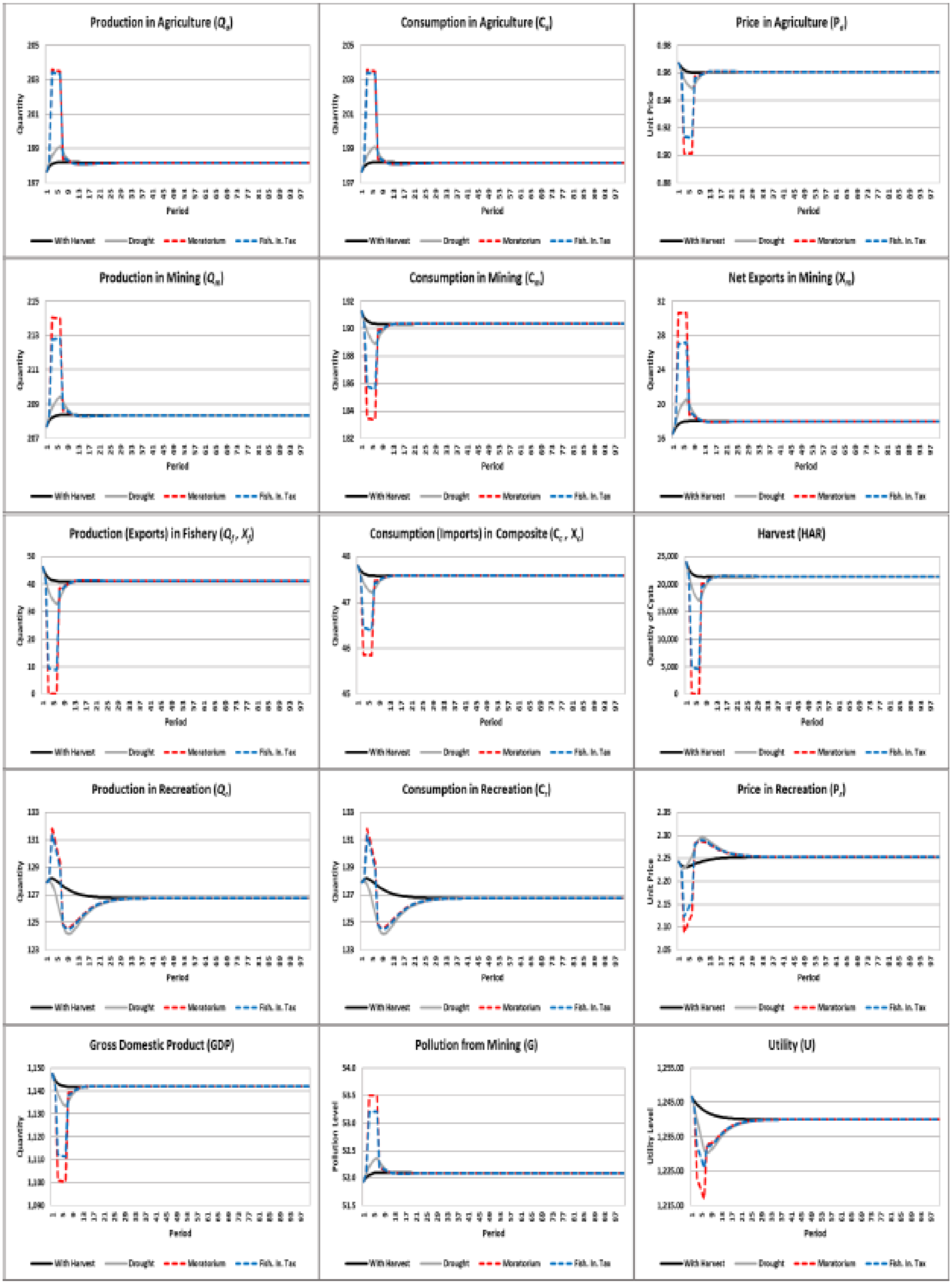


Figure 5: Rolling and Base Equivalent Variation (EV) Paths

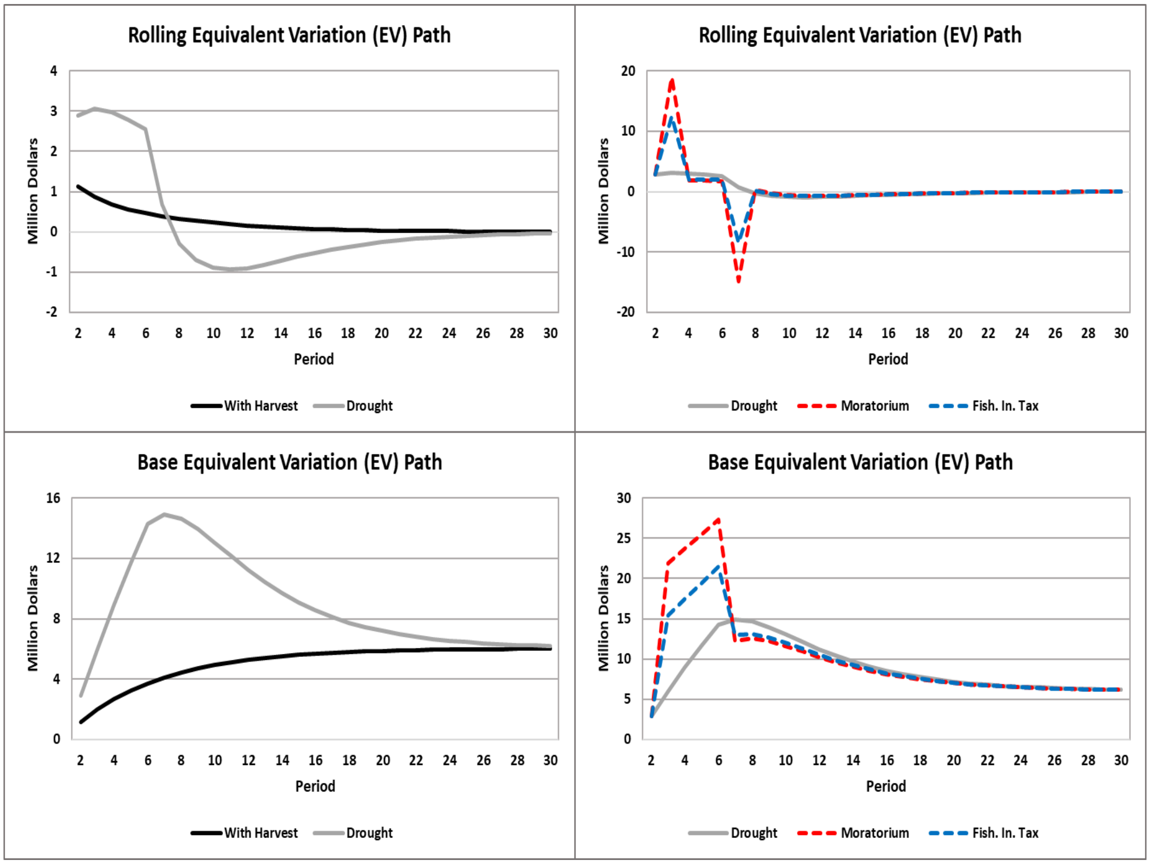


Figure 6: Species Populations: Moratorium and Output Tax on Mining

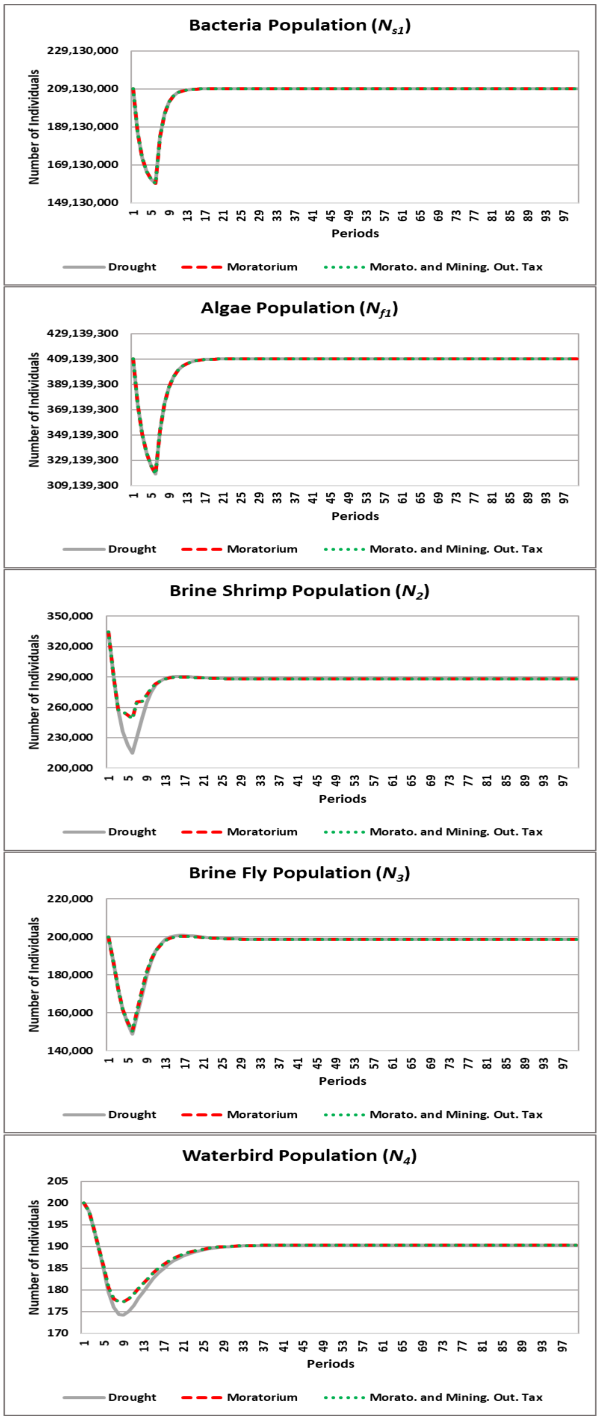


Figure 7: Output Markets: Moratorium and Output Tax on Mining

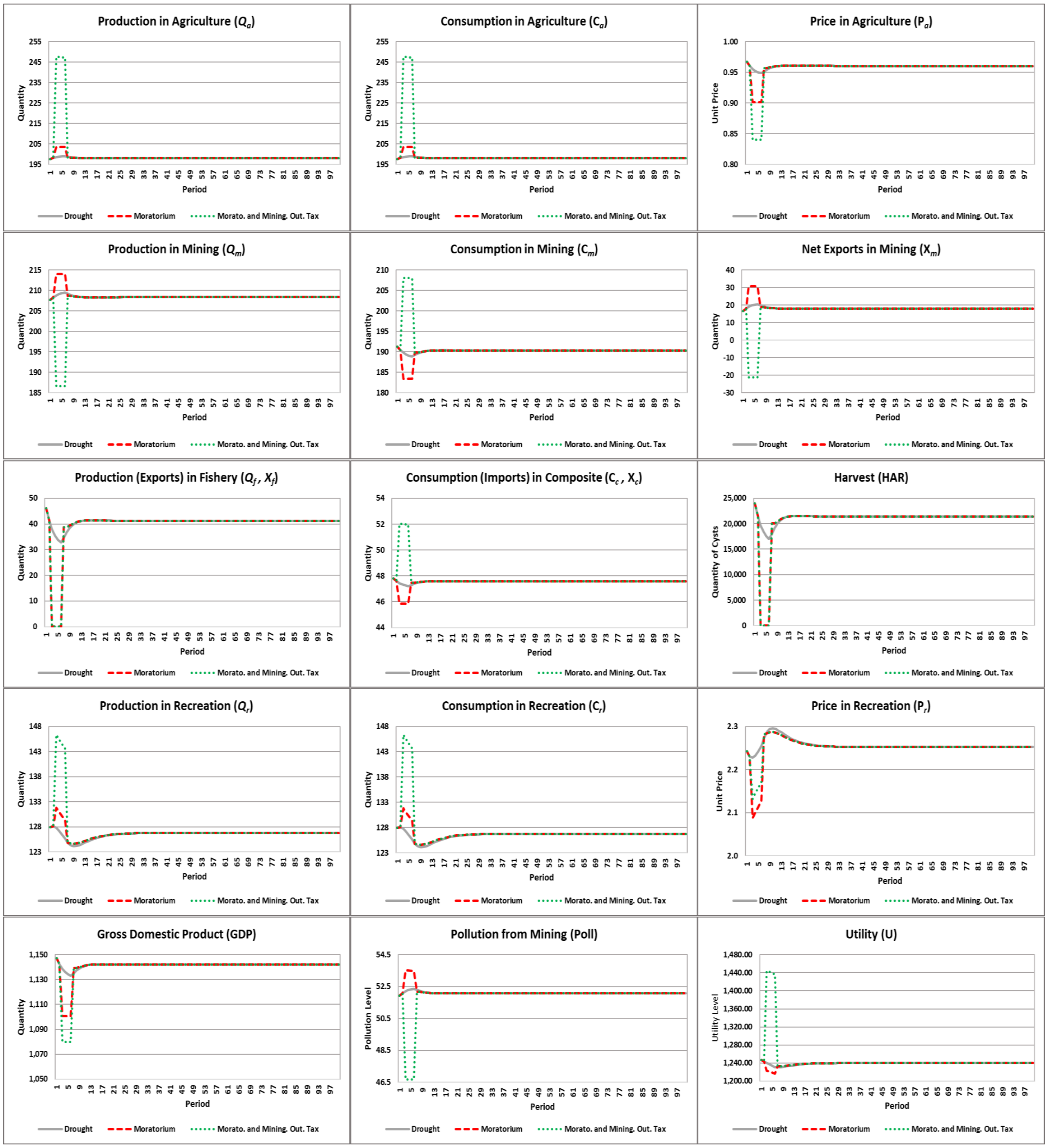


Figure 8: Rolling and Base EV Paths: Moratorium and Output Tax on Mining