Valuing the Prevention of an Infestation: The Threat of the New Zealand Mud Snail in Northern Nevada

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The Truckee/Carson/Walker River watershed in northern Nevada is under an imminent threat of infestation by the New Zealand mud snail, an aquatic nuisance species with the potential to harm recreational fisheries. We combine a utility-theoretic system-demand model of recreational angling with a Bayesian econometric framework to provide estimates of trip and welfare losses under different types of regulatory control policies. We find that such losses can be substantial, warranting immediate investments in preemptive strategies via public outreach and awareness campaigns.

Key Words: Bayesian simulation, hierarchical modeling, incomplete demand system, New Zealand mud snail

In recent decades, problems and damages related to aquatic nuisance species (ANS) have triggered increasing research efforts by physical scientists and economists alike. However, as synthesized in Lowell, Stone, and Fernandez (2006), published economic studies with reference to ANS have to date primarily concentrated on broader issues related to trade and international economic policy (e.g., Costello and McAusland 2004, Margolis, Shogren, and Fischer 2005, Costello et al. 2007) or use ANS as an example to calibrate broader bio-economic models of invasive species management (e.g., Leung et al. 2002, Moore, Macpherson, and Provencher 2006, Finoff et al. 2006).

In contrast, a few studies exist that examine ANS management policies from an empirical perspective based on primary data of economic activities and choices. Notable exceptions are Lupi, Hoehn, and Christie (2003), who use a random utility model of recreational fishing to estimate the benefits of sea lamprey control to Michigan anglers; Nunes and Bergh (2004), who apply a travel cost model of beach visitation in Holland to estimate the welfare losses due to beach closures related to harmful algal blooms; and Timar and Phaneuf (2008), who examine the role of humans in the spread of the zebra mussel, using a recreation demand framework. This study contributes to this sparse empirical literature by providing estimates of economic welfare losses to anglers from a variety of management scenarios to combat the New Zealand mud snail (NZMS).

The NZMS (*Potamopyrgus antipodarum*), while present in the United States since the 1980s, has enjoyed much less media and research coverage than other more prominent ANS, such as the zebra mussel (*Dreissena polymorpha)* and its close relative, the quagga mussel (*Dreissena rostriformis bugensis*). This is likely due to the fact that the detrimental economic impacts of the latter two species have become evident relatively quickly since their introduction to the United States, while the effects of the NZMS on human economic production or activities have to date been less obvious and less pronounced. In fact,

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there still exists much uncertainty surrounding the NZMS in all stages of typical ANS research, from the identification of pathways and vectors, to ecological impacts and methods of prevention, detection, and control (Proctor et al. 2007). As a result, agencies are still far from converging towards optimal management strategies.

However, experts agree that the NZMS has the potential to severely impact freshwater fisheries (e.g., Cada 2004, Proctor et al. 2007), and that recreational access restrictions might be considered as a management strategy to avoid a further spread of the snail (Proctor et al. 2007). In fact, temporary site closures have already been implemented in some cases to quarantine infested waters (California Department of Fish and Game 2004).

Economists can contribute to the development of informed management strategies by shedding light on the economic impact of potential changes in fishery regulations and access. Specifically, given adequate underlying data of consumer behavior, economists can provide estimates of expected welfare losses to recreationists and expenditure losses to the local economies from reduced visitation due to restrictions on site use or access. At the very least, this allows agencies to rank sites and prioritize interventions based on economic sensitivity, ceteris paribus. In a climate of pronounced scientific uncertainty, this is—at the margin—a very valuable degree of freedom. In addition, a better knowledge of possible economic losses enables agencies to more accurately assess the expected net benefits from public outreach and education campaigns, widely considered the most viable—and perhaps only—option to curb the spread of the snail (Proctor et al. 2007).

This study focuses on the Truckee/Carson/Walker (TCW) watershed along the northern Nevada-California border in the Lake Tahoe region. This is an ideal research area with respect to the NZMS for several reasons: (i) It is an important recreational fishery to locals and visitors alike; (ii) There are to date no documented occurrences of the NZMS in the TCW system, and resource managers still have the option to invest in *preemptive* strategies; and (iii) Several nearby creeks and angling destinations are already infested, thus there is an imminent threat to the system of a near-future infestation. As a result, local managing agencies are under considerable pressure to decide on budget allocations for public outreach and awareness campaigns.

We use visitation data for 2004 Nevada fishing license holders to estimate a multisite demand model of trip counts to 12 segments of the TCW system. We cast our analysis in a hierarchical Bayesian econometric framework to circumvent the need to approximate multidimensional integrals, and to allow for variation in angler preferences related to fishing regulations and access restrictions. We examine the economic impact of stricter fishing regulations, winter closures, and seasonal closures at some or all segments. We find that such intervention can lead to system-wide welfare losses of \$10 million to \$30 million per year, depending on the policy scenario. In addition, there may be annual losses of angler expenditures to the local economy in the amount of \$5 million to \$10 million. These figures clearly justify considerable preemptive expenditures by agencies on public education and outreach. To our knowledge, this is the first economic study with specific focus on the NZMS.

The remainder of this manuscript is structured as follows: The next section describes the NZMS threat to the western United States, the TCW river system, and the current state of feasible management strategies. The third section outlines the utility-theoretic and econometric modeling framework. The fourth section describes the data set and presents estimation results and predicted economic impacts. Concluding remarks are given in the final section.

Background Information

The NZMS in the Western United States

The New Zealand mud snail is an invasive freshwater species with tremendous reproductive potential. It can overtake and degrade entire ecosystems through its competition with native invertebrates for habitat and food sources. It was first discovered in the mid-Snake River in Idaho in the 1980s and has since rapidly spread to other watersheds in ten western states, including three National Parks.[1] NZMS colonies have been

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[1] The exact pathway or mode of introduction is unknown.

reported to reach densities as high as 750,000 square meters in suitable habitats comprising over 95 percent of the invertebrate biomass in a water body (Department of Ecology, Montana State University 2005). These impressive rates of proliferation are largely attributable to the absence of specific parasites that curb the snail's spread in its native New Zealand waters. Furthermore, the snail is largely indigestible to potential predators.

Given the snail's documented competitive edge for habitat and food to the detriment of traditional food sources for trout and other game fish, and its own poor nutritional value to these fish populations, the arrival of the NZMS has naturally triggered strong concerns regarding the future health of affected fisheries. While more research is needed to gain clarity regarding the impacts of NZMS infestations on the vertebrate fauna, preliminary scientific findings indicate that large densities of mud snails can lead to a reduced fish growth (Cada 2004). As stated in Richards (2002) and in various agency outlets (e.g., Colorado Division of Wildlife 2005, Proctor et al. 2007), it is the general consensus amongst scientists and water managers that the NZMS, if left unchecked, will have a significant and potentially permanent negative impact on western fisheries.

The NZMS threat is aggravated by the fact that these invaders are very small (generally less than one-eighth inch) and can survive for long periods of time in moist environments. These characteristics facilitate the spread of the snail across watersheds through human activities, as the snail can become an undetected "hitchhiker" on watercraft and fishing gear. NZMS distribution through human vectors is now widely considered the main reason for the snail's rapid inter-shed spread in recent years (National Park Service 2003, Proctor et al. 2007).

As is evident from Figure 1, the snail has arrived in the San Francisco Bay Area, in aquatic systems near the northeastern and southeastern corners of Nevada, and near Nevada's southwestern border with California. These infected waters include primary recreation destinations, such as the American River between Lake Tahoe and Sacramento, the Owens River along Nevada's western border with California, and Lake Mead near the city of Las Vegas. All of these destinations are located within driving distance from the TCW watershed.

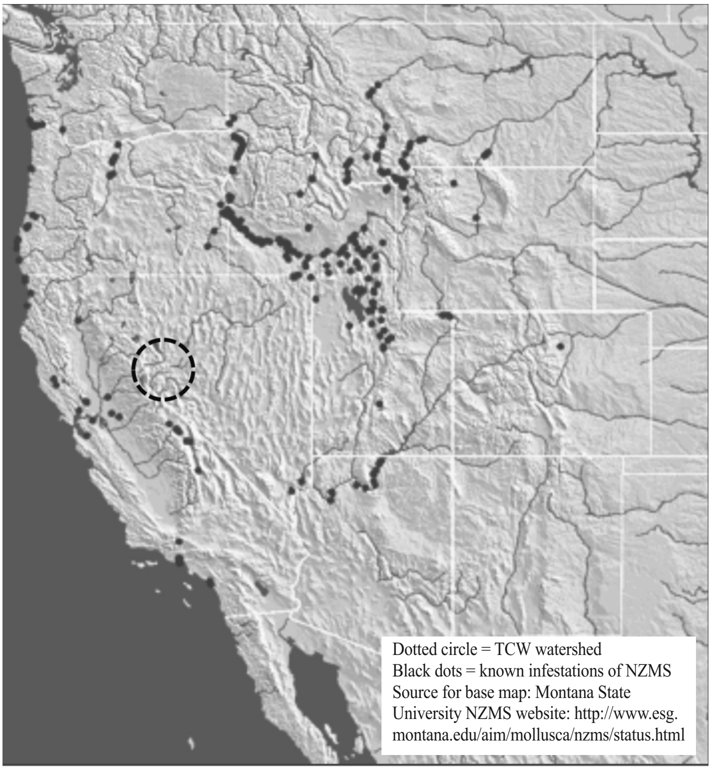

Dotted circle = TCW watershed
Black dots = known infestations of NZMS
Source for base map: Montana State University NZMS website: http://www.esg.montana.edu/aim/mollusca/nzms/status.html

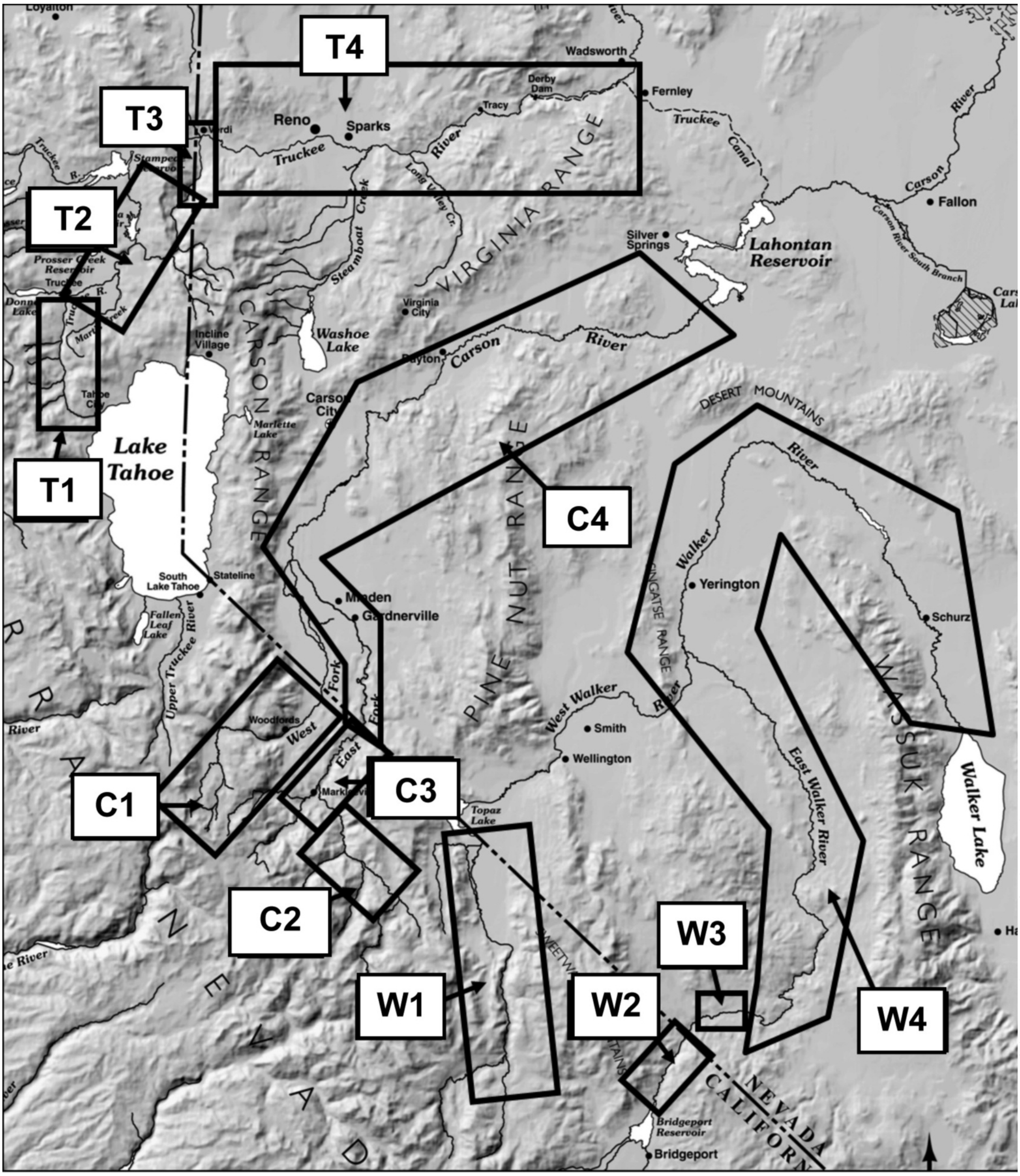
Figure 1. The TCW Watershed and Known Infestations of the NZMS in the West

The Truckee/Carson/Walker River Watershed

The TCW system is shown in Figure 2. As is evident from the figure, the Truckee River, labeled by the letter "*T,*" emerges from Lake Tahoe's eastern shore in California and empties into Pyramid Lake in the Great Basin for a total length of 140 miles. It traverses the Reno/Sparks urban area, which has a population of approximately 350,000 residents.

The Carson River's East and West forks both originate in the California Sierra Nevada, south of Lake Tahoe. The two forks of the river join in Nevada, run through the state's capital of Carson City (pop. 55,000), and feed into Lake Lahontan, a reservoir for irrigation and hydroelectricity and a popular summer destination for campers and boaters. The total length of the Carson River is approximately 150 miles. The Carson River carries the letter "*C*" in Figure 2.

The 50-mile-long Walker River, labeled as "*W*" in the figure, is located just south of the Carson system. It also originates in two forks. The West Walker River emerges from the California Sierra Nevada, while the East Walker River constitutes the outflow of Bridgeport Reservoir, also located in California. The West Walker feeds into Topaz



Map courtesy of the Nevada Bureau of Mines and Geology

Figure 2. The TCW Watershed and the 12 Fishing Segments

Lake at the California-Nevada border, then joins its eastern counterpart to continue to Walker Lake, another terminal lake in the Great Basin.

Over the last 15-20 years, the TCW watershed has received an annual average of over 16,000 visitors for a total of over 150,000 fishing days per year (Moeltner 2006). Considering average per-day expenditures of $50-$60 for the prototypical visitor, the total annual revenue to the local economy from TCW anglers amounts to $7.5 million to $9 million (Moeltner 2006). Thus, based on expenditures alone, the TCW fishery constitutes an important economic resource to the region. To date, as mentioned previously, no occurrence of the NZMS has been reported for the TCW watershed.

For the purpose of this study we divide each river into four segments, as shown in the figure. The segments were primarily chosen based on differences in current fishing regulations. As captured in Table 1, this provides for an interesting mix of winter closures and bag/size/lure restrictions across segments.

Policy Options

Ecologists generally distinguish between two types of managerial interventions with respect to invasive species: *prevention* and *control* (e.g., Finoff et al. 2007). Preventative measures are those that aim to block the arrival of a nuisance species at an as yet noninfested ecosystem, while control measures are geared towards curbing population growth or reducing the population of an invasive species after its arrival. There are several theoretical economic contributions that address the issue of how scarce agency resources should be divided between these two strategies (e.g., Leung et al. 2002, Olson and Roy 2003, Finoff et al. 2007). Not surprisingly, the identification of an optimal course of actions hinges both on the knowledge of the economic costs and on the probabilities of success or occurrence associated with prevention, detection, control, and damages.

As mentioned previously, in the case of the NZMS there still exists much uncertainty for virtually all of these components (Proctor et al.

Table 1. Basic Site Characteristics

River	Section	State	Season	Regulations
Truckee	T1	CA	All year	General
	T2	CA	All year	Special*
	T3	NV	All year	Special*
	T4	NV	All year	General
Carson	C1	CA	April 21–Nov. 15	General
	C2	CA	April 21–Nov. 15	General
	C3	CA	All year	Special**
	C4	NV	All year	General
Walker	W1	CA	April 21–Nov. 15	General
	W2	CA	All year	Special*
	W3	NV	All year	Special**
	W4	NV	All year	General

All *special regulations* = artificial lures *Bag and size limits **Catch & release

In 2004, general regulations in Nevada were “any hour of the day or night,” and “5 trout/day” without size or lure restrictions. In California, general regulations implied “one hour before sunrise to one hour after sunset,” and “5 trout/day, with no more than 10 trout in possession” without size or lure restrictions.

2007). However, there appears to be an emerging consensus amongst scientists that there may not exist any effective and environmentally safe control options to combat the snail *after* an infestation (Department of Ecology, Montana State University 2005, Proctor et al. 2007). Therefore, researchers are largely advocating investments in preemptive measures, especially via public outreach and education. A recent report by the NZMS Management and Control Plan Working Group, prepared for the interagency Aquatic Nuisance Species Task Force (ANSTF), suggests several such measures. These include the fostering of grassroots movements to educate recreationists on-site, awareness-raising via public announcements along identified pathways, and the integration of NZMS-related topics into school programs (Proctor et al. 2007).

If preemptive measures fail to protect a given ecosystem against the NZMS, available post-infestation management efforts may be limited to controlling human behavior to avoid a further spread, e.g., via vessel and gear inspections (currently implemented at Lake Tahoe, albeit with the main focus on the zebra and quagga mussels); enforced post-visit gear cleaning (the state of Montana has started to set up washing stations at infested fishing spots); and access restrictions (the state of California closed Putah Creek for several months in 2004 to study snail behavior and to raise public awareness (California Department of Fish and Game 2004). For the purpose of this study, we will label such post-infestation interventions as pertaining to the "control" category, even though they are not directly aimed at a physical reduction of existing snail populations.

For this study we consider the following control strategies: (i) Size/lure/bag restrictions; (ii) Winter closures; (iii) Both (i) and (ii); and (iv) Complete year-round closure to access. The first three measures are envisioned as strategies to alleviate human pressure on mud snail-stressed fish populations, while the fourth could be implemented to hamper a further spread of the snail to other waters. As shown below, each intervention generates pronouncedly different welfare effects for the underlying population of anglers.

Modeling Framework

Utility-Theoretic Framework

We aim to model trip demand for our 12-segment system of fishing destinations, allowing for demand changes at the extensive margin in reaction to policy interventions. This renders a generic random utility framework (RUM), which implicitly conditions on a fixed total number of seasonal trips, unsuitable for our purpose. A multi-season RUM could circumvent this problem but is incompatible with our available data.

We thus choose a complete demand system with a Hicksian composite commodity as our utility-theoretic framework. We stipulate that angler i derives aggregate utility during a single fishing season from taking trips to the $j = 1, \ldots, J$-site recreation system, collected in vector $\mathbf{y}_i$, and from consuming a numeraire composite commodity b. Specifically,

$$U_i = U\left(\mathbf{y_i}, \mathbf{q_j}, \mathbf{s_i}, b\right) \tag{1}$$

where $\mathbf{q_j}$ denotes site attributes, and $\mathbf{s_i}$ is a vector of person or household characteristics. Utility maximization subject to a (assumed binding) budget constraint yields the Marshallian quasi-demand system

$$\mathbf{y_i} = \mathbf{y}\left(\mathbf{p_i}, \mathbf{q_j}, \mathbf{s_i}, m_i\right) \tag{2}$$

where $\mathbf{p_i}$ is a vector of prices associated with the destinations included in the system, and m_i denotes annual income.

We follow Hagerty and Moeltner (2005) and Shonkwiler and Englin (2005) and apply a Log I demand specification. In other words,

$$y_{ij} = \exp\left(\mathbf{a_{ij}} + \sum_{k=1}^{J} \beta_{p,jk}\, p_{ik} + \beta_{m,j}\, m_i\right) \tag{3}$$

which has performed well in similar applications and leads to tractable expressions for welfare measures. To assure symmetry of the Slutsky substitution matrix, a permissible set of parameter restrictions is given by $\beta_{m,j} = \beta_m,\ \forall_j$, and $\beta_{p,jk} = 0$,

$k \neq j$ (von Haefen 2002 , p. 304). Shifting vector $\mathbf{a}_{ij}$ comprises all site and respondent characteristics multiplied by their respective coefficients. While these restrictions explicitly rule out cross-price effects in the uncompensated site-specific demand equations, they still allow for substitution effects between sites through compensated demands (Englin, Boxall, and Watson 1998, Shonkwiler 1999).

In addition to these restrictions, the utility-theoretic properties of our demand system approach rest on the standard assumption that prices and quality attributes for other commodities (including other recreation sites) remain constant throughout the study period (Hanemann and Morey 1992).

Econometric Framework

As shown in Shonkwiler (1999) and Moeltner (2003), the Log I demand specification can be embedded in a count data model of recreation trips by letting the right-hand side of (3) be the parameterized expected value of a Poisson probability mass function, i.e.,

$$\lambda_{ij} = E\left(y_{ij}\right) = \exp\left(\mathbf{a}_{\mathbf{ij}} + \beta_{p,j} p_{ij} + \beta_{m} m_{i}\right). \tag{4}$$

In addition, anglers' trip demand to the 12 river segments likely also includes unobserved factors. We need to accommodate this unobserved heterogeneity in our model to avoid misleading inferences with respect to policy interventions. A common strategy taken in existing contributions in the context of count data modeling is to combine the link function for the Poisson distribution in (4) with a multiplicative error term, and to specify a *J*-dimensional multivariate density for the *J*-vector of site-specific errors (e.g., Egan and Herriges 2006, Moeltner and Shonkwiler, Forthcoming).

In this study we take a slightly different approach and model unobserved heterogeneity via a second-layer density for some of the parameters in the link function. This has two main advantages over the multiplicative-error method: (i) It couples preference heterogeneity directly with specific site attributes, which is better aligned with our research focus; and (ii) It avoids the proliferation of parameters in the error variance matrix when *J* is large (as is the case in our application).

Specifically, we employ a hierarchical Poisson model with mixed effects, in which some of the parameters in the link function remain fixed over all individuals, and others are allowed to vary randomly across anglers. Collecting all fixed and random effects in parameter vectors β and γ_i, respectively, and corresponding regressors in vectors $\mathbf{x}_{ij}$ and $\mathbf{h}_{ij}$, respectively, the model can be formally described as follows:

$$f\left(y_{ij} \mid \lambda_{ij}\right) = \frac{\exp\left(-\lambda_{ij}\right) \lambda_{ij}^{y_{ij}}}{y_{ij}!} \qquad \text{where} \tag{5}$$

$$\lambda_{ij} = \exp\left(\mathbf{x}'_{\mathbf{ij}} \boldsymbol{\beta} + \mathbf{h}'_{\mathbf{ij}} \gamma_{\mathrm{i}}\right) \text{ and } \gamma_{\mathrm{i}} \sim mvn\left(\gamma, \boldsymbol{\Sigma}\right).$$

Thus, we stipulate that the vector of individual random effects, γ_i, is drawn from a common multivariate normal density with expectation γ and variance matrix Σ. Labeling the number of random effects as k_r, this matrix will have $k_r(k_r+1)/2$ unrestricted parameters. However, in our application k_r is considerably smaller than *J*, which supports our argument of parameter parsimony from above.

By letting $\tilde{\lambda}_{ij} = \exp(x_i'\beta)$ and following the exposition of the standard Poisson-lognormal model in Egan and Herriges (2006) and Moeltner and Shonkwiler (Forthcoming), it is straightforward to derive the marginal unconditional moments of trip counts as

$$E\left(y_{ij}\right) = \tilde{\lambda}_{ij} \exp\left(\tfrac{1}{2} \mathbf{h}'_{\mathbf{ij}} \boldsymbol{\Sigma} \mathbf{h}_{\mathbf{ij}}\right) = \delta_{ij} \qquad \text{and} \tag{6}$$

$$V\left(y_{ij}\right) = \delta_{ij} + \delta_{ij}^{2}\left(\exp\left(\mathbf{h}'_{\mathbf{ij}} \boldsymbol{\Sigma} \mathbf{h}_{\mathbf{ij}}\right) - 1\right).$$

This shows clearly that our model is purged of the restrictive mean-variance equality of the basic Poisson model and can thus accommodate overdispersion in the underlying data. In addition, it induces correlation across trip counts corresponding to the same individual since

$$Cov\left(y_{ij}, y_{ik}\right) = \delta_{ij} \delta_{ik}\left(\exp\left(\mathbf{h}'_{\mathbf{ij}} \boldsymbol{\Sigma} \mathbf{h}_{\mathbf{ik}}\right) - 1\right). \tag{7}$$

Assuming independence of trip decisions across individuals, the likelihood function for the model can be written as

$$(8)\quad p\left(\mathbf{y} \mid \boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\Sigma}\right)=$$
$$\prod_{i=1}^{N}\left(\int_{\boldsymbol{\gamma}_{\mathrm{i}}}\left(\left(\prod_{j=1}^{J}\frac{\exp\left(-\lambda_{ij}\right)\lambda_{ij}^{y_{ij}}}{y_{ij}\,!}\right)f\left(\boldsymbol{\gamma}_{\mathrm{i}} \mid \boldsymbol{\gamma}, \boldsymbol{\Sigma}\right)\right)d\boldsymbol{\gamma}_{\mathrm{i}}\right)$$

where N denotes the number of individuals in the sample.

While this hierarchical Poisson-multinormal model is conceptually straightforward, its empirical implementation in a classical framework is somewhat cumbersome, as it requires the approximation of the k_r-dimensional integral over $\boldsymbol{\gamma}_{\mathrm{i}}$ in (8). This hurdle, coupled with the limited nature of the dependent variable, can make estimation via maximum likelihood techniques (MLE) quite challenging. We thus follow Chib, Greenberg, and Winkelmann (1998) and Jochmann and Léon-González (2004) and take a Bayesian estimation approach via Gibbs Sampling to implement this model. To our knowledge, this is the first application of a hierarchical Bayesian count data model to the analysis of recreation demand.[2]

A Bayesian approach requires the specification of priors for all model parameters. We choose the standard "convenience" priors that, when combined with the likelihood function, yield tractable conditional posteriors. Specifically, we choose multivariate normal priors for $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$ and an inverse Wishart (IW) prior for the elements of $\boldsymbol{\Sigma}$, i.e.,

$$(9)\quad \boldsymbol{\beta} \sim mvn\left(\boldsymbol{\mu}_{\beta}, \mathbf{V}_{\beta}\right),\ \boldsymbol{\gamma} \sim mvn\left(\boldsymbol{\mu}_{\gamma}, \mathbf{V}_{\gamma}\right),$$
$$\boldsymbol{\Sigma} \sim IW\left(v_0, \mathbf{S}_{\mathbf{0}}\right)$$

where v_0 and $\mathbf{S}_0$ are the degrees of freedom and scale matrix, respectively. The *IW* density is parameterized such that

$$E\left(\boldsymbol{\Sigma}\right)=\left(\nu_0-k_r-1\right)^{-1}\mathbf{S}_{\mathbf{0}}\,.$$

The posterior simulator (Gibbs Sampler) draws from the following conditional densities:

$$(10)\quad \boldsymbol{p}\left(\boldsymbol{\beta} \mid \mathbf{y}, \mathbf{X}, \mathbf{H}, \boldsymbol{\Sigma}, \boldsymbol{\Gamma}\right), \boldsymbol{p}\left(\boldsymbol{\gamma} \mid \mathbf{y}, \mathbf{X}, \mathbf{H}, \boldsymbol{\Sigma}, \boldsymbol{\Gamma}\right),$$
$$\boldsymbol{p}\left(\boldsymbol{\Sigma} \mid \boldsymbol{\gamma}, \boldsymbol{\Gamma}\right),\ \text{and}\ \boldsymbol{p}\left(\boldsymbol{\gamma}_{\mathrm{i}} \mid \mathbf{y}_{\mathrm{i}}, \mathbf{X}_{\mathrm{i}}, \mathbf{H}_{\mathrm{i}}, \boldsymbol{\beta}, \boldsymbol{\Sigma}, \boldsymbol{\gamma}\right),$$
$$\boldsymbol{i}=\mathbf{1}\cdots\boldsymbol{N}\quad \text{where}$$
$$\boldsymbol{\Gamma}=\left[\begin{array}{cccc}\boldsymbol{\gamma}_{\mathbf{1}}' & \boldsymbol{\gamma}_{\mathbf{2}}' & \cdots & \boldsymbol{\gamma}_{\mathbf{N}}'\end{array}\right]'.$$

The ability to draw $\boldsymbol{\beta}$, $\boldsymbol{\gamma}$, and $\boldsymbol{\Sigma}$ conditional on the N sets of $\boldsymbol{\gamma}_{\mathrm{i}}$ preempts the need to approximate the integral in the likelihood function. The draws of $\boldsymbol{\beta} \mid \mathbf{y}, \mathbf{X}, \mathbf{H}, \boldsymbol{\Sigma}, \boldsymbol{\Gamma}$ and $\boldsymbol{\gamma}_{\mathrm{i}} \mid \mathbf{y}_{\mathrm{i}}, \mathbf{X}_{\mathrm{i}}, \mathbf{H}_{\mathrm{i}}, \boldsymbol{\beta}, \boldsymbol{\Sigma}, \boldsymbol{\Gamma}$ require Metropolis-Hastings (MH) sub-routines within the Gibbs Sampler. Posterior inference is based on the marginals of the joint posterior distribution $p(\boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\Sigma} \mid \mathbf{y}, \mathbf{X}, \mathbf{H})$. The detailed steps of the posterior simulator for this model are given in Chib, Greenberg, and Winkelmann (1998). The Matlab code to implement this model is available from the authors upon request.

Posterior Predictions

The posterior sampler generates $r = 1, \ldots, R$ draws of parameters. To derive posterior predictive distributions (PPDs) of trip counts and welfare measures, these draws need to be combined with specific settings for individual characteristics and site attributes. Let $g(\mathbf{x}_{\mathrm{ij}}, \mathbf{h}_{\mathrm{ij}} \mid \boldsymbol{\theta}, \boldsymbol{\gamma}_{\mathrm{i}})$ be some posterior measure of interest for some settings of regressors $\mathbf{x}_{\mathrm{ij}}$ and $\mathbf{h}_{\mathrm{ij}}$, conditional on model parameters $\boldsymbol{\theta}$ and random effects $\boldsymbol{\gamma}_{\mathrm{i}}$. To properly average this measure over all combinations of $\mathbf{x}_{\mathrm{ij}}$ and $\mathbf{h}_{\mathrm{ij}}$ observed in our sample (and presumably present in the underlying population in similar proportions), we compute

$$\tfrac{1}{N}\sum_{i=1}^{N} g\left(\mathbf{x}_{\mathbf{ij}}, \mathbf{h}_{\mathbf{ij}} \mid \boldsymbol{\theta}, \boldsymbol{\gamma}_{\mathbf{i}}\right)$$

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[2] Two recent contributions use related Bayesian modeling: Von Haefen (2007) estimates a Bayesian Kuhn-Tucker continuous demand system model using a Bayesian estimation algorithm. Herriges, Phaneuf, and Tobias (2008) estimate a Bayesian multi-site recreation demand model with correlated counts but without a hierarchical structure.

for each draw of $\boldsymbol{\theta}$ and $\boldsymbol{\gamma}_{\mathrm{i}}$. The unconditional posterior predictive density for this sample-weighted measure of interest can then be expressed as

(11)
$$p\left(g\left(\mathbf{x},\mathbf{h}\right)\right)=\int_{\boldsymbol{\theta}}\left(\int_{\boldsymbol{\gamma}_{\mathrm{i}}}\left(\frac{1}{N}\sum_{i=1}^{N}g\left(\mathbf{x}_{\mathrm{ij}},\mathbf{h}_{\mathrm{ij}}\mid\boldsymbol{\theta},\boldsymbol{\gamma}_{\mathrm{i}}\right)\right)f\left(\boldsymbol{\gamma}_{\mathrm{i}}\mid\boldsymbol{\gamma},\boldsymbol{\Sigma}\right)d\boldsymbol{\gamma}_{\mathrm{i}}\right)p\left(\boldsymbol{\theta}\mid\mathbf{y},\mathbf{X},\mathbf{H}\right)d\boldsymbol{\theta}$$

In practice, draws from this PPD are obtained in straightforward fashion as follows:

1) For a given draw of $\boldsymbol{\theta}$, obtain several, say r_2, draws of random vector $\boldsymbol{\gamma}_{\mathrm{i}}$. For each draw of γ_{i}, compute the sample-averaged measure of interest, i.e.,

$$\frac{1}{N}\sum_{i=1}^{N}g\left(\mathbf{x}_{\mathrm{ij}},\mathbf{h}_{\mathrm{ij}}\mid\boldsymbol{\theta},\gamma_{\mathrm{i}}\right)$$

2) Repeat step (1) for all R draws of θ from the original Gibbs Sampler.

The resulting PPD, based on the R^*r_2 draws of $g(\mathbf{x},\mathbf{h})$, can then be examined with respect to its statistical properties. We follow this procedure for different specifications of $g(\mathbf{x}_{\mathrm{ij}},\mathbf{h}_{\mathrm{ij}}\mid\theta,\gamma_{\mathrm{i}})$, as described below in more detail.

Empirical Application

Data

The data for this analysis stem from a combined mail/Internet survey of all 2004 annual Nevada fishing license holders residing in Nevada and California counties surrounding the TCW watershed (28,331 individuals). This target population constitutes 80 percent to 90 percent of all anglers at the three rivers (Moeltner 2006). The sampling frame was obtained from the Reno, Nevada office of the Nevada Department of Wildlife. The survey was implemented in five rounds during the period of November 2005 to February 2006, following the "best science" methodology described in Dillman (2000).

The initial round of questionnaires was mailed to 1,800 anglers, randomly chosen from the sample frame of 28,331 individuals. Each targeted respondent was given the option to complete the survey online or via mail. Small University of Nevada tokens (key chains, pens) were included in the mailings as participation incentives. The target sample count was then adjusted for rounds 2 and 3 of the survey, based on responses to previous rounds and attrition due to undeliverable addresses. Response rates in terms of targeted anglers were in the 20 percent range for the first two rounds and declined to approximately 11 percent for round 3. The total percentage of undeliverable surveys was in the expected range of 10 percent to 20 percent for a relative transient area such as Reno/Sparks/Carson City. Overall, 751 completed surveys were returned for an overall response rate of close to 50 percent. Approximately 9 percent of respondents used the Internet version of the survey.

Following a brief introduction to the NZMS infestation in the western United States, the survey was structured into four sections. The first section asked respondents about their general fishing experience and preferences, including fishing technique (fly-fishing vs. spin casting); tendency to keep or release caught fish; and the relative importance of different fishing site attributes and fishing regulations. Section 2 asked anglers about their awareness of the NZMS threat to the TCW system, as well as any preemptive actions they had taken or were planning to take to avoid an infestation, such as chemically treating or drying fishing gear after an angling trip. The third section inquired about their history for 2004 *day*-trips to each of the 12 river segments shown in Figure 2. The last section collected some basic demographic information, including education and income levels. The questionnaire is available from the authors upon request.

For this analysis we further narrowed the sample to those respondents who: (i) lived no more than 200 miles from the *nearest* river segment (given our focus on day trips); and (ii) provided all necessary socio-demographic information, most notably their annual household income. This led to a final useable sample of 551 individuals and 551 x 12 = 6,612 observations on day-trip counts.

Some salient summary statistics for this sample are given in Table 2. With respect to demographic characteristics, we observe that older, male anglers, residing in Nevada, dominate the sample. These anglers are also more affluent than the population at large; for comparison, the median household income in Nevada in 2007 was $49,288 (U.S. Census Bureau 2007). In contrast, the average years of schooling appear to be comparable to statewide levels (for comparison, in 2000, 81 percent of adult Nevadans had completed high school, and close to 20 percent had a bachelor's degree or higher).

The fact that recreational fishing has traditionally been a popular sport in this region is highlighted by the close-to-40-years of fishing experience for the average angler in our sample. The majority of anglers use both spin casting and fly-fishing techniques. Approximately a third also held a California fishing license in 2004. Importantly for our policy focus, a considerable segment of anglers prefer sites with no bag or lure restrictions.

With respect to the NZMS threat, only slightly more than a fourth of anglers were aware of the snail at the time of the survey. Close to a fifth of the sample had also fished waters with known infestations of the NZMS in 2004, and over half of the respondents stated that they generally use wading as a fishing strategy. Together, these findings stress the imminence of the NZMS threat to the TCW system, and the pressing need to enhance public awareness.

As is evident from the table, the average angler in our sample spends approximately $65 on a day-long fishing trip, on items such as gasoline, food and beverages, and fishing supplies. As stated earlier in the text, this underlines the importance of the TCW fishery to the local economy.

Table 3 provides a summary of travel distances and trip counts. Distances were computed for the shortest possible travel route from a respondent's ZIP code centroid to the nearest road access point for each river section, using geographic information system (GIS) techniques. The details of this process are available from the authors upon request. For the three longest river segments (*T4*, *C4*, and *W4*), distances were computed to four separate access points per segment. For a given

Table 2. Sample Statistics

Attribute	Mean/Percent	Median	Std.
Female	16.15%	-	-
Age	52.31	53	13.98
Years of schooling	14.3	14	2.4
Income	$81,800	$70,000	$58,715
HH with children	35.39%	-	-
CA resident	1.63%	-	-
CA fishing license holder in 2004	33.76%	-	-
Fishing experience (years)	37.97	40	16.58
Fly fish only	13.79%	-	-
Spin cast only	43.74%	-	-
No bait restrictions is important	31.58%	-	-
Keeping fish is important	46.46%	-	-
Per-day trip expenditures	$65.41	$55.00	$49.87
Knows NZMS	27.52%	-	-
Wades in water	56.62%	-	-
Fished an infected river in 2004	13.97%	-	-

N = 551

Table 3. Distances and Trips

Distances*					Trips per individual				Trips: all individuals		
Section	Mean	Min.	Max.	Std.	Mean	Min.	Max.	Std.	visits	% of river	% system
T1	71.3	5.1	237.9	39.4	0.19	0	30	1.62	107	5.4%	3.2%
T2	66.7	13.2	242.0	37.5	0.22	0	20	1.25	119	6.0%	3.5%
T3	50.9	5.1	254.6	40.0	0.83	0	40	2.80	458	23.0%	13.6%
T4	45.9	2.3	264.9	36.1	2.38	0	250	13.08	1311	65.7%	39.0%
Truckee	-	-	-	-	3.62	0	250	13.92	1995	100.0%	59.3%
C1	70.1	8.5	257.0	38.1	0.22	0	10	1.00	123	20.2%	3.7%
C2	73.5	11.3	264.4	37.1	0.14	0	10	0.85	79	13.0%	2.3%
C3	69.5	3.7	256.8	38.6	0.14	0	20	1.06	78	12.8%	2.3%
C4	57.4	6.0	231.7	27.0	0.60	0	40	2.89	329	54.0%	9.8%
Carson	-	-	-	-	1.11	0	40	3.68	609	100.0%	18.1%
W1	80.7	29.7	265.6	30.0	0.31	0	23	1.79	172	22.7%	5.1%
W2	100.9	33.5	276.0	30.6	0.21	0	50	2.30	115	15.2%	3.4%
W3	94.1	26.0	268.5	30.4	0.32	0	20	1.52	176	23.2%	5.2%
W4	82.1	24.7	252.3	27.3	0.54	0	20	1.74	296	39.0%	8.8%
Walker	-	-	-	-	1.38	0	85	5.10	759	100.0%	22.6%
System	-	-	-	-	6.10	0	250	15.65	3363	-	100.0%

*One way, miles

respondent, we then used that person's preferred access point (elicited in the survey) or, if no preference was given, an average of the four distances for further analysis.

As captured in the first four columns of the table, the prototypical angler travelled approximately 50-70 miles to reach a specific segment on the Truckee or Carson, and 80-100 miles to fish at the Walker River. The longer distances to the Walker River are expected, given the relative remoteness of this destination from the Reno/Sparks population hub.

The remainder of the table depicts trip counts to the 12 segments at both individual and total levels. Clearly, the Truckee section *T4*, flowing directly through the Reno/Sparks urban area, receives by far the highest visitation counts (66 percent of all trips to the Truckee, and 39 percent of all trips to the system). Similarly, the longer downstream sections with general regulations were also the most popular in 2004 for the Carson and Walker Rivers, with 54 percent and 39 percent of river-specific visits, respectively. Overall, the Truckee River received close to 60 percent of all visits to the system, with the remaining 40 percent divided approximately equally between the other two waterways.

The average angler took slightly over six trips to the system, with some individuals visiting certain segments over 200 times during the season. While this may seem excessive, it should be noted that for many residents in the Reno/Sparks or Carson City communities, accessing one of the TCW rivers implies little more than a walk across their backyard, and daily angling outings are not uncommon for our target population.

In general, we observe considerable variability in trip counts within and across sites, which aids in the identification of our model parameters.

Estimation Results

We implement our hierarchical mixed-effects Poisson model using the following demographic regressors: gender (1=female); age; age squared; household income (in \$1,000s); and an indicator set to one if the respondent's household includes children, and set to zero otherwise. The remaining respondent-specific explanatory variables are indicators for "fly-fishing only" and "spin casting only," respectively, plus fishing experience, in years. Site-specific information enters the model via indicators for "special regulations" and "winter closure," respectively, as discussed above and captured in Table 1. Together, these regressors, plus a common constant term, comprise the elements of the shifting vector $\mathbf{a}_{\mathrm{ij}}$ in our Log 1 specification in (3).

The demand system specification is completed by adding separate price terms for each of the 12 segments. These prices are computed in standard fashion (e.g., Moeltner 2003, Hagerty and Moeltner 2005) by multiplying the round-trip distance in miles by an automotive cost factor (we follow Hagerty and Moeltner 2005, and Moeltner and Shonkwiler 2005, and choose 3 cents) and adding a time-cost component, derived as driving time in hours (we assume an average speed of 45 mph) times 1/3 * hourly wage. For anglers who did not hold an annual fishing license for California, and who visited segments located in California, we add that state's daily fishing fee in 2004 of \$10 to their travel cost.

We allow for unobserved heterogeneity of anglers' reactions to special regulations and winter closures and pair these two regressors with random coefficients. Thus, these two variables form the contents of vector $\mathbf{h}_{\mathrm{ij}}$ in (5). The remaining regressors are collected in the vector of fixed effects, $\mathbf{x}_{\mathrm{ij}}$.

We estimate all models using the following vague but proper[3] parameter settings for our priors:

$$\boldsymbol{\mu}_{\beta} = \boldsymbol{\mu}_{\gamma} = 0, \mathbf{V}_{\beta} = \mathbf{V}_{\gamma} = 10,\ v_0 = k_r = 2, \text{ and } \mathbf{S}_{\mathbf{0}} = \mathbf{I}_{\mathbf{k}_r}.^{4}$$

We use multivariate *t*-distributions as tailored proposal densities in our MH algorithms for draws of β and γ_{i} (Chib, Greenberg, and Winkelmann 1998). The tuner elements for these *t*-distributions are the degrees of freedom, and a scalar for the variance matrix. For draws of β we set the degrees of freedom to 8, and the variance scalar to 1.5. For draws of γ_{i} we choose 8 and 2, respectively, for these two tuning elements. These settings led to acceptance rates of approximately 47 percent for β and 58 percent for γ_{i}, and to desirable efficiency measures. The model is estimated using 10,000 burn-in draws and 10,000 retained draws in the Gibbs Sampler. The decision on the appropriate amount of burn-ins was guided by Geweke's convergence diagnostics (Geweke 1992).

Estimation results are captured in Table 4. The first two columns depict the posterior mean and standard deviation for each parameter. The third column provides the numerical standard error (*nse*), a measure of simulation noise surrounding the posterior mean. If the Gibbs Sampler generates perfectly independent draws for a given parameter, the *nse* is computed as

$$std / \sqrt{(R)}$$

where *std* is the standard deviation of the posterior distribution and *R* is the number of draws in the Gibbs Sampler. We use an autocorrelation-adjusted *nse* following Geweke (1992). The Bayesian analog of a numerical 95 percent confidence interval for the posterior mean can be obtained as posterior mean $\pm 1.96 \cdot nse$. For further details on the *nse* measure and its derivation, see Moeltner, Boyle, and Patterson (2007) and Moeltner and Woodward (2009, footnote 12). The fourth column in Table 4 depicts the proportion of Gibbs Sampler draws exceeding zero for a given parameter, i.e., the proportion of the posterior

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[3] "Proper" prior distributions are those that integrate to one over their entire range. "Vague" refers to the fact that the distribution has a relatively large variance, which preempts substantial prior density mass for any specific segment of the distribution range.

[4] Given our relatively large sample size of over 6,000 observations, the exact choice of prior *moments* is relatively unimportant as most of the posterior weight will rest on the actual data. However, the *type* of prior distribution matters for the structure of the posterior simulator. Our choices of prior densities allow for relatively straightforward simulation steps, as outlined in Chib, Greenberg, and Winkelmann (1998).

Table 4. Estimation Results

Variable	Mean	Std.	nse	pr(>0)
Fixed effects				
Constant	3.1659	0.2842	0.0132	1.0000
Price T1	-0.0721	0.0025	0.0000	0.0000
Price T2	-0.0190	0.0014	0.0001	0.0000
Price T3	-0.0090	0.0009	0.0001	0.0000
Price T4	-0.0113	0.0005	0.0000	0.0000
Price T5	-0.0059	0.0013	0.0002	0.0000
Price T6	-0.0059	0.0010	0.0001	0.0000
Price T7	-0.0066	0.0004	0.0000	0.0000
Price T8	-0.0081	0.0003	0.0000	0.0000
Price T9	-0.0021	0.0005	0.0001	0.0000
Price T10	-0.0024	0.0002	0.0000	0.0000
Price T11	-0.0020	0.0001	0.0000	0.0000
Price T12	-0.0035	0.0001	0.0000	0.0000
Gender	-0.7718	0.0907	0.0021	0.0000
Age	-0.0253	0.0129	0.0006	0.0247
Age^2	-0.0001	0.0001	0.0000	0.1780
Fly-fishing only	0.2091	0.0748	0.0022	0.9975
Spin casting only	-0.0206	0.0519	0.0013	0.3434
HH income	-0.0016	0.0005	0.0000	0.0017
Years of fishing	0.0189	0.0024	0.0001	1.0000
Children in HH	-0.2116	0.0525	0.0013	0.0000
Special regulations	-	-	-	
Winter closure	-	-	-	
RE means				
Special regulations	-3.9384	0.2424	0.0129	0.0000
Winter closure	-5.8331	0.6124	0.0813	0.0000
RE var/cov				
var(special)	7.4605	1.0360	0.0488	1.0000
cov	5.8944	1.1240	0.0587	1.0000
var(winter)	11.3287	2.3445	0.2007	1.0000

nse = numerical standard error / RE = random effects

density that is located in the positive domain.

We can immediately note from the table that all posterior densities for the price coefficients are located virtually entirely in the negative domain, as expected and required by the utility-theoretic framework. The posterior mean for the income coefficient is also negative and close to zero. This hints at an "inferior good" effect and suggests perhaps that more affluent anglers are less likely to fish the local waters and instead travel to more exotic "blue ribbon" destinations for their angling pursuits. Similarly, the remaining demographic regressors (gender = female, age, and presence of children) have a negative fractional effect on trip demand, as judged by their respective posterior means.

Interestingly, exclusive fly fishers exhibit a pronouncedly stronger visitation demand than anglers with hybrid techniques (our implicit baseline category). Since fly-fishing is generally associated with wading, this raises further concerns regarding a possible introduction of the NZMS to the TCW watershed. This demand effect is reversed for exclusive spin casters, although considerable posterior noise exists surrounding this parameter.

Perhaps the most important finding captured in the table are the pronounced negative posterior means coupled with relatively small posterior standard deviations for the mean effects of the two site characteristics "special regulations" and "winter closure." Clearly, the *prototypical* angler strongly prefers sites with more relaxed fishing regulations and year-round access. However, there also exists pronounced heterogeneity with respect to these preferences, as evidenced by the large posterior means for the variance components of these random effects (last three rows in the table). This indicates that to a non-negligible share of anglers, approximately 15 percent to 20 percent, tighter fishing regulations actually constitute a desirable site feature. This segment might represent catch-and-release anglers that care mainly about fish abundance, and environmentally aware anglers with relatively stronger concerns for the well-being of the overall fishery. It would be interesting to further examine this strong heterogeneity in preferences for access and fishing restrictions in subsequent research.

Predictions

Our predictive measures of interest, captured in abstract form by $g(\mathbf{x}_{ij}, \mathbf{h}_{ij} | \boldsymbol{\theta}, \gamma_i)$ in (11), are "expected season trips per angler" and "seasonal welfare effects per angler," for the status quo and for the following policy scenarios: (i) Special regulations at all sites; (ii) Winter closure at all sites; and (iii) Both (i) and (ii). The derivation of seasonal predictions for the status quo implicitly allows for the examination of an additional policy intervention (iv): Closure of all sites. For each scenario, we derive trip and welfare predictions per river segment and for the total system.[5]

Although our demand system framework allows for the computation of utility-theoretic welfare measures such as compensating variation and compensating surplus (see Moeltner 2003), we follow Hagerty and Moeltner (2005) and Shonkwiler and Englin (2005) and choose the simpler measure of consumer surplus (CS), given the negligible magnitude of income effects in our estimated model.

Thus, we are interested in deriving PPDs for expected trips per site and for the entire system, averaged over all individuals in our sample, i.e.,

$$p\left(E\left(y_j \mid \mathbf{x}, \mathbf{h}_s\right)\right) = \int_{\boldsymbol{\theta}} \left[\int_{\gamma_i} \left(\frac{1}{N} \sum_{i=1}^{N} \lambda_{ij}^{s} \right) f\left(\gamma_i \mid \gamma, \boldsymbol{\Sigma}\right) d\gamma_i \right] p\left(\boldsymbol{\theta} \mid \mathbf{y}, \mathbf{X}, \mathbf{H}\right) d\boldsymbol{\theta} \tag{12}$$

$$p\left(E\left(y \mid \mathbf{x}, \mathbf{h}_s\right)\right) = \int_{\boldsymbol{\theta}} \left[\int_{\gamma_i} \left(\frac{1}{N} \sum_{i=1}^{N} \left(\sum_{j=1}^{J} \lambda_{ij}^{s} \right) \right) f\left(\gamma_i \mid \gamma, \boldsymbol{\Sigma}\right) d\gamma_i \right] p\left(\boldsymbol{\theta} \mid \mathbf{y}, \mathbf{X}, \mathbf{H}\right) d\boldsymbol{\theta} \quad \text{where}$$

$$\lambda_{ij}^{s} = \exp\left(\mathbf{x}_{ij}'\beta + \mathbf{h}_s' \gamma_i\right),$$

and consumer surplus per site and for the system at large, i.e.,

$$p\left(CS_j\left(\mathbf{x}, \mathbf{h}_s\right)\right) = \int_{\boldsymbol{\theta}} \left[\int_{\gamma_i} \left(\frac{1}{N} \sum_{i=1}^{N} -\beta_{pj}^{-1} \lambda_{ij}^{s} \right) f\left(\gamma_i \mid \gamma, \boldsymbol{\Sigma}\right) d\gamma_i \right] p\left(\boldsymbol{\theta} \mid \mathbf{y}, \mathbf{X}, \mathbf{H}\right) d\boldsymbol{\theta} \quad \text{and} \tag{13}$$

$$p\left(CS\left(\mathbf{x}, \mathbf{h}_s\right)\right) = \int_{\boldsymbol{\theta}} \left[\int_{\gamma_i} \left(\frac{1}{N} \sum_{i=1}^{N} \left(\sum_{j=1}^{J} -\beta_{pj}^{-1} \lambda_{ij}^{s} \right) \right) f\left(\gamma_i \mid \gamma, \boldsymbol{\Sigma}\right) d\gamma_i \right] p\left(\boldsymbol{\theta} \mid \mathbf{y}, \mathbf{X}, \mathbf{H}\right) d\boldsymbol{\theta}.$$

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[5] We thin our original sequences of parameter draws by a factor of 10 to lessen the degree of simulation-induced serial correlation in our posterior predictive distributions. For each retained set of parameters we draw 10 realizations of the random effects γ_i. Thus, our posterior predictive inference is based on (10,000/10) x 10 = 10,000 draws of consumer surplus per scenario.

Since the scenario settings are implemented via the $\mathbf{h}$-vector in the link function, we add an s-subscript to this vector to indicate its applicability to a specific scenario, including the status quo. For welfare effects, we also generate PPDs for *changes* in CS by replacing

$$\lambda_{ij}^{s} \quad \text{in (13) with} \quad \lambda_{ij}^{0} - \lambda_{ij}^{s}$$

where in this case the "0" superscript denotes the status quo.

The results of our predictive modeling are captured in Table 5. As can be seen from the first block of columns, the posterior means for our trip predictions to each site and the system at large are comparable in magnitude to our sample results in Table 2. We interpret this as informal support for a reasonable fit of our model with the underlying data. Under current regulatory conditions, the system generates over $1000 in seasonal welfare to the prototypical angler. The largest contributions to this total come from sections *T4*, *W3,* and *W4*. For *T4* and *W4* this is not surprising, since they traverse population hubs and are two of only four segments with no access or technology restrictions (see Table 1). Section *W3* is the "trophy section" of the Walker River—a first-class fishery with tight regulations that is especially popular amongst fly fishers. As is evident by comparing seasonal welfare to seasonal trips, this segment generates much higher *per-trip* welfare (approximately $512) than the *T4* and *W4* segments (approximately $80-$120).

The most important finding captured in the table are the dramatic welfare losses associated with *any* of the three policy scenarios. For example, an introduction of special regulations at the currently more loosely regulated segments *T1*, *T4*, *C1*, *C2*, *C4*, *W1*, and *W4* reduces system trips to 2.73 and system welfare to $590 per angler, for, respectively, a 54 percent and 43 percent reduction from the status quo. Winter closures at current year-round sites (all except for *C1*, *C2*, and *W1*) have an even more pronounced effect on system-wide visitation and welfare, with respective reductions from the status quo of 79 percent and 71 percent. A joint implementation of both measures reduces per-angler seasonal trips to less than one, and seasonal welfare to $213. This implies an 85 percent reduction in trips and a 78 percent loss in welfare compared to the status quo. Losses in trip counts and consumer surplus are similarly pronounced for most individual sites, as shown in the top twelve rows of the table.

Figure 3 depicts the PPDs for *losses* in seasonal trips and CS for the prototypical angler for all three policy scenarios. Inspection of the full PPDs allows for insights that cannot be easily conveyed in tabular form. Specifically, it is clear from the figures that while the full range of losses (i.e., the support of the PPDs) is rather large (0 to 10 for trips, and $0 to $1000 for CS), the bulk of the probability mass for these densities locates above a much tighter range, approximately 3-5 for trips and $300–$600 for CS, depending on the scenario. While the PPDs for the three scenarios

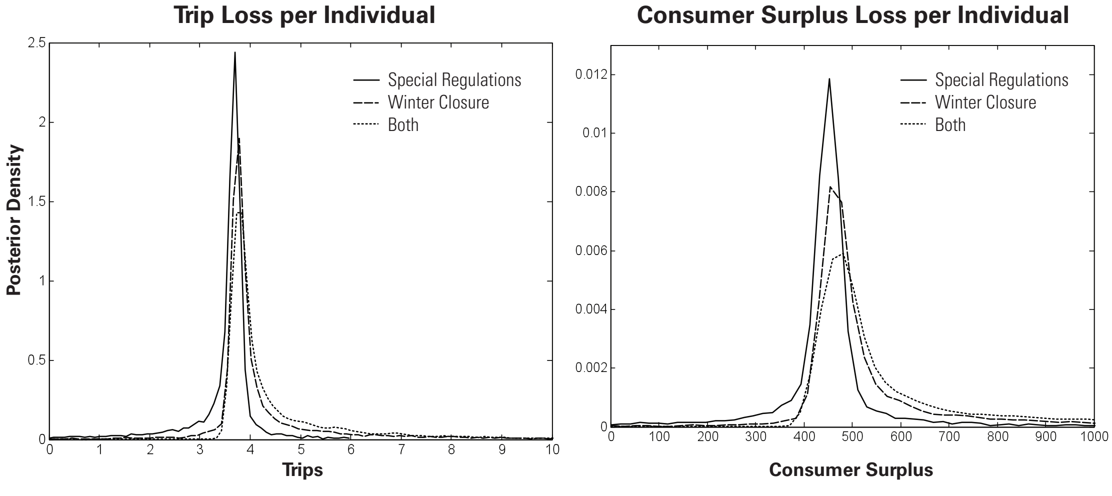

Figure 3. Posterior Distribution of Trip and Welfare Losses

Table 5. Trip and Welfare Predictions

	Status Quo				Special Regulations				Winter Closure				Both			
	Trips		CS		Trips		CS		Trips		CS		Trips		CS	
Section	mean	(nse)	mean	(nse)	mean	(nse)	mean	(nse)	mean	(nse)	mean	(nse)	mean	(nse)	mean	(nse)
T1	0.23	0.00	3.15	0.01	0.04	0.00	0.61	0.02	0.02	0.00	0.24	0.01	0.01	0.00	0.17	0.01
T2	0.21	0.01	11.10	0.30	0.21	0.01	11.10	0.30	0.06	0.00	3.12	0.16	0.06	0.00	3.12	0.16
T3	0.60	0.02	67.21	1.83	0.60	0.02	67.21	1.83	0.17	0.01	19.04	0.98	0.17	0.01	19.04	0.98
T4	2.27	0.00	200.21	0.36	0.43	0.01	38.44	1.05	0.17	0.01	15.04	0.51	0.12	0.01	10.95	0.57
C1	0.11	0.00	19.17	0.65	0.08	0.00	14.38	0.75	0.11	0.00	19.17	0.65	0.08	0.00	14.38	0.75
C2	0.08	0.00	13.85	0.46	0.06	0.00	10.26	0.53	0.08	0.00	13.85	0.46	0.06	0.00	10.26	0.53
C3	0.15	0.00	22.00	0.60	0.15	0.00	22.00	0.60	0.04	0.00	6.26	0.33	0.04	0.00	6.26	0.33
C4	0.59	0.00	72.00	0.18	0.11	0.00	13.85	0.38	0.04	0.00	5.38	0.18	0.03	0.00	3.89	0.20
W1	0.15	0.01	79.11	2.67	0.12	0.01	59.23	3.14	0.15	0.01	79.11	2.67	0.12	0.01	59.23	3.14
W2	0.20	0.01	81.74	2.24	0.20	0.01	81.74	2.24	0.06	0.00	23.13	1.21	0.06	0.00	23.13	1.21
W3	0.31	0.01	158.71	4.33	0.31	0.01	158.71	4.33	0.09	0.01	45.18	2.36	0.09	0.01	45.18	2.36
W4	0.63	0.00	177.39	0.40	0.12	0.00	33.97	0.92	0.05	0.00	13.31	0.46	0.03	0.00	9.63	0.50
System	5.95	0.06	1031.78	16.08	2.73	0.08	590.05	18.37	1.24	0.05	297.54	12.15	0.88	0.05	212.18	11.09

All values are per individual, per season
nse = numerical standard error

largely overlap, it is still evident from the figure that the density for "winter closure" is more pronouncedly skewed to the left than the PPD for "special regulations." Naturally, the PPD for the combined effect (labeled "both") in the figure has the "thickest" right-hand tail, and the "slimmest" left-hand tail of all three densities for both trips and consumer surplus.

Table 6 provides a summary of estimated *aggregate* losses in day trips, welfare, and expenditures for the entire population of anglers (i.e., the sampling frame of 28,331 individuals who held a Nevada fishing license in 2004 and resided in counties surrounding the TCW system). The figures under the "mean" columns in the table are derived by multiplying the mean of the corresponding per-angler PPD by the total number of anglers. The entries in the "low" and "up" columns represent, respectively, the 95 percent numerical confidence interval around the posterior mean, computed as the mean ± 1.96 times the numerical standard error (see Moeltner, Boyle, and Paterson 2007). As mentioned previously, this confidence interval conveys the extent of simulation noise surrounding the mean estimate. The expenditure losses have to be interpreted as upper bounds, since they are based on the underlying assumption that losses in trips translate directly into complete leaks of per-trip expenditures (using the sample average of $65/person) out of the regional economy.

The table shows that expected total losses in welfare to regional anglers can be staggering, ranging from $11 million to $20 million, if system-wide special regulations and/or winter closures are employed as a policy tool against the NZMS. A year-round closure of the fishery would lead to expected welfare losses of close to $30 million annually. Importantly, welfare losses are two to three times higher than expenditure losses, which range from $6 million to $11 million for any of the considered policy interventions. Combining both sources of economic loss, the total direct economic impact of these policy measures is estimated at $17 million to $40 million, depending on the intervention scenario. This also implies that the current economic value of the TCW fishery exceeds $40 million when recreational welfare effects are included.

Given the magnitude of these expected losses from the type of policy interventions that would most likely be used as control measures following a snail infestation, a strong argument can be made in support of outlays for preemptive strategies, most notably those that lead to enhanced public awareness. Even if only individual segments or rivers within the TCM system are targeted with changes in access or fishing regulations, associated welfare losses will likely far outweigh any reasonable outlays on preemptive measures.

Table 6. Economic Impacts

	Loss in Trips (1000s)			Loss in Welfare (millions)			Loss in Expenditures (millions)		
	mean	low	up	mean	low	up	mean	low	up
Special Regulations	84.51	82.90	86.12	$10.58	$10.32	$10.84	$5.53	$5.42	$5.63
Winter Closure	119.59	118.14	121.03	$17.14	$16.84	$17.44	$7.82	$7.73	$7.92
Both	130.97	129.75	132.20	$19.92	$19.61	$20.23	$8.57	$8.49	$8.65
Year-round Closure	168.57	165.24	171.90	$29.23	$28.34	$30.12	$11.03	$10.81	$11.24

Conclusion

This study combines a utility-theoretic system demand model of recreational angling with a Bayesian econometric framework to estimate changes in day trips and consumer surplus associated with regulatory interventions in the Truckee-Carson-Walker watershed in the eastern foothills of the central Sierra Nevada region. We cast our analysis within the threat of an infestation of this watershed by the New Zealand mud snail. The policy scenarios we examine are of the types that are currently considered as viable *control* interventions, and that have been implemented elsewhere in the past to combat a snail invasion.

The TCW system has traditionally been an important recreational fishery. Not surprisingly, our estimated losses in day trips and corresponding economic welfare are of considerable magnitude for any of the simulated policy interventions. To a somewhat minor extent, this also holds for expected losses to the regional economy in the form of foregone fishing expenditures. Overall, our results lend strong support for investments in preemptive policy measures against the NZMS, such as public awareness campaigns via grassroots operations and public outreach via all branches of the media.

It should be noted that our analysis focuses exclusively on *day trips* by *anglers* to regional *rivers*. In other words, we do not consider multi-day trips, trips by any other recreational contingent, and trips to any of the lakes connected by the three rivers. These include virtually all the large lakes of northern Nevada (some shared with California), such as Tahoe, Pyramid, Lahontan, Topaz, and Walker. A broader analysis based on more extensive recreation data (including boating and other water sports) would be required to estimate expected snail-induced losses for this wider "recreational playground," to this larger underlying population of stakeholders, and for trips of varying length. It can be safely assumed that the estimates of economic losses reported in this study would pale in comparison to welfare and expenditure losses to the regional economy if, in addition to the three rivers, any of these lakes were affected by access restrictions or other snail-induced regulatory changes.

Fortunately, TCW resource managers still have the option of taking preemptive measures to avoid a snail infestation without limiting site access. However, the snails' current geographic expansion and the wading-intensive angling techniques preferred by a considerable share of TCW anglers stress the imminence of such an infestation. Hopefully, the findings summarized in this study will lend ammunition to local managing agencies in their quest for state and federal funding to enhance public awareness on and off the water, before the window for low-cost, preemptive interventions closes—perhaps in perpetuity.

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