




CONTRIBUTED PAPER

A dynamic simulation model to support reduction in illegal trade within legal wildlife markets

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Article impact statement: Simulation models that explicitly consider traders' roles in wildlife markets can help support reduction in illegal wildlife trade.

Abstract

Sustainable wildlife trade is critical for biodiversity conservation, livelihoods, and food security. Regulatory frameworks are needed to secure these diverse benefits of sustainable wildlife trade. However, regulations limiting trade can backfire, sparking illegal trade if demand is not met by legal trade alone. Assessing how regulations affect wildlife market participants' incentives is key to controlling illegal trade. Although much research has assessed how incentives at both the harvester and consumer ends of markets are affected by regulations, little has been done to understand the incentives of traders (i.e., intermediaries). We built a dynamic simulation model to support reduction in illegal wildlife trade within legal markets by focusing on incentives traders face to trade legal or illegal products. We used an Approximate Bayesian Computation approach to infer illegal trading dynamics and parameters that might be unknown (e.g., price of illegal products). We showcased the utility of the approach with a small-scale fishery case study in Chile, where we disentangled within-year dynamics of legal and illegal trading and found that the majority (~77%) of traded fish is illegal. We utilized the model to assess the effect of policy interventions to improve the fishery's sustainability and explore the trade-offs between ecological, economic, and social goals. Scenario simulations showed that even significant increases (over 200%) in parameters proxying for policy interventions enabled only moderate improvements in ecological and social sustainability of the fishery at substantial economic cost. These results expose how unbalanced trader incentives are toward trading illegal over legal products in this fishery. Our model provides a novel tool for promoting sustainable wildlife trade in data-limited settings, which explicitly considers traders as critical players in wildlife markets. Sustainable wildlife trade requires incentivizing legal over illegal wildlife trade and consideration of the social, ecological, and economic impacts of interventions.

KEYWORDS

Bayesian approach, enforcement, fisheries, intermediaries, predictive modeling, supply-driven markets, sustainability

Un Modelo Dinámico de Simulación para Asistir en la Reducción del Comercio Ilegal dentro de Mercados Legales de Vida Silvestre

Resumen: El comercio sustentable de vida silvestre es crítico para la conservación de la biodiversidad, los medios de subsistencia y la seguridad alimentaria. Son necesarios marcos regulatorios para asegurar estos diversos beneficios del comercio sustentable de vida silvestre. Sin embargo, las regulaciones que limitan el comercio pueden ser contraproducentes, generando un mercado ilegal si la demanda no se suple solamente con el comercio legal. El análisis de cómo las regulaciones afectan a los incentivos de los participantes del comercio de vida silvestre es de suma importancia para controlar el comercio ilegal.

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Mientras que muchas investigaciones se han centrado en analizar cómo las regulaciones afectan tanto a quienes consumen como quienes proveen vida silvestre, poco se ha hecho para entender los incentivos de los intermediarios. Construimos un modelo dinámico de simulación para asistir en la reducción del comercio ilegal de vida silvestre dentro de los mercados legales, enfocándonos en los incentivos que enfrentan los intermediarios para comercializar productos legales o ilegales. Usamos un enfoque de Computación Bayesiana Aproximada para inferir las dinámicas del comercio ilegal y los parámetros que podrían ser desconocidos (p. ej.: el precio de los productos ilegales). Demostramos la utilidad del modelo mediante el caso de estudio de una pesquería de pequeña escala en Chile, en donde desentrañamos las dinámicas del comercio legal e ilegal y estimamos que la mayor parte del pescado comercializado es ilegal. Utilizamos el modelo para analizar el efecto de intervenciones para mejorar la sustentabilidad de la pesquería y para explorar los trade-offs entre metas ecológicas, económicas y sociales. Las simulaciones de escenarios mostraron que incluso incrementos significativos (más del 200%) de parámetros que recreaban intervenciones permitieron solamente mejoras moderadas en la sustentabilidad ecológica y social de la pesquería a un costo económico sustancial. Estos resultados exponen cuán desequilibrados están los incentivos de los intermediarios hacia el comercio de productos ilegales por encima de los legales en esta pesquería. Nuestro modelo proporciona una herramienta innovadora para la promoción del comercio sustentable de vida silvestre en entornos con datos limitados, y considera explícitamente a los intermediarios como actores críticos dentro del comercio de vida silvestre. El comercio sustentable de vida silvestre requiere incentivar el comercio legal sobre el ilegal y la consideración del impacto social, ecológico y económico de las intervenciones.

PALABRAS CLAVE:

aplicación, enfoque Bayesiano, intermediarios, mercados impulsados por la oferta, modelo predictivo, pesquerías, sustentabilidad

摘要

可持续野生动物贸易对生物多样性保护、生计和粮食安全至关重要, 这些相关利益需要监管框架来保障。然而, 如果限制野生动物贸易的法规导致合法贸易无法满足需求, 则可能会适得其反地引发非法贸易。评估监管如何影响野生动物市场参与者的激励水平是控制非法贸易的关键。虽然许多研究已经评估了监管如何影响市场中野生动物捕获者和消费者获得的激励水平, 但对于交易者(如中间商)获得的激励水平却鲜有研究。我们建立了一个动态模拟模型, 通过关注交易者在交易合法及非法产品时面临的激励水平, 来支持在合法市场内减少非法野生动物交易。本研究使用近似贝叶斯计算方法推断了非法交易动态和可能未知的参数(如非法产品的价格), 并利用智利一个小规模渔场的案例研究展示了该方法的有效性。我们在该渔场理清了合法和非法交易的年内动态, 并发现大多数的鱼类交易都是非法的。我们还应用该模型评估了通过政策干预提高渔业可持续性的效果, 并探索了生态、经济和社会目标之间的利弊权衡。情景模拟表明, 即使代表政策干预水平的参数显著增加(超过200%), 仍只能花费高昂的经济成本对渔业的生态和社会可持续性稍加改善。以上结果揭示了该渔场中交易者对非法产品的交易相对于合法产品有高度不平衡的激励水平。我们的模型可以明确地将交易者视为野生动物市场中的关键参与者, 从而为在数据有限的背景下促进可持续野生动物贸易提供了一种新的工具。可持续的野生动物贸易需要确保合法贸易相对于非法贸易获得更高的激励水平, 还需要考虑干预带来的社会、生态和经济影响。【翻译:胡怡思;审校:聂永刚】

关键词: 执行, 贝叶斯方法, 渔业, 预测建模, 中间商, 供应驱动的市场, 可持续性

INTRODUCTION

Sustainable management of wildlife use is critical for biodiversity conservation, livelihoods, and food security (Challender & MacMillan, 2014; Costello et al., 2020; Fukushima et al., 2020;

Milner-Gulland et al., 2003). Accordingly, governments and multilateral organizations aim to promote legal and sustainable use of wildlife so that the broad range of benefits from the activity can be derived (t Sas-Rolfes et al., 2019). This requires regulations and policies at the local, national, and international levels

to reduce unsustainable and illegal use (Andersson et al., 2021; Challender & MacMillan, 2014). However, regulatory interventions can have unintended consequences because restrictions on wildlife use can create illegal trade to meet demand that is not satisfied by legal trade alone. This is an important feature of many wildlife markets, especially when legal supply is limited or distinguishing legal and illegal products is challenging (e.g., Bennett et al., 2021; Moyle, 2017).

Understanding the effect of restrictions on wildlife trade is necessary in order to move toward regulations that effectively reduce the level of illegal trade and promote sustainability. There have been important advances in understanding how restrictions affect wildlife harvesters' incentives at one end of the commodity chain and end markets and consumers' incentives at the other (Bulte & Van Kooten, 1999; Burton, 1999; Milner-Gulland, 1993). For instance, small-scale fishers who are overly restricted by quota regulations might turn to illegal fishing to complement their income (Oyanedel et al., 2020a). At the other end, sellers in end markets may use diverse laundering techniques to sell illegal products as legal products where trade is poorly regulated (Moyle, 2017). However, research on how restrictions affect traders' (sometimes referred to as intermediaries) incentives is limited (Jones et al., 2019; Phelps et al., 2016; Purcell et al., 2017). Traders connect end markets and consumers with wildlife harvesters, ultimately influencing how wildlife is used (Crona et al., 2010; González-Mon et al., 2019). Therefore, understanding how restrictions affect traders' incentives and the dynamics of legal and illegal wildlife markets is critical to promoting sustainable use.

Assessing how restrictions affect traders' incentives requires understanding the overarching dynamics of the market in which they operate. Wildlife markets can be broadly categorized into 2 types. In supply-driven markets, suppliers participate in the market independently of price signals; therefore, in these markets supply is constrained. As such, overall quantities entering the commodity chain are determined by natural variability and harvester effort, so traders can only access a fixed supply. In demand-driven markets, suppliers' participation responds to price signals, so demand is filled at the available price (McNamara et al., 2016). Most classic models of illegal wildlife trade are based on the assumption that markets are demand driven (e.g., Bowen-Jones & Pendry, 1999; Brashares et al., 2004; Hall et al., 2008; Holden & Lockyer, 2021; McNamara et al., 2016; Milner-Gulland & Clayton, 2002; Milner-Gulland & Leader-Williams, 1992). However, if restrictions on the quantity that can be legally traded exist (e.g., as a result of a quota), decisions by the trader are made under a fixed supply (e.g., supply-driven market). As such, traders can play a crucial role in determining the proportion of legal and illegal product traded (Oyanedel et al., 2021). This proportion depends on traders' economic incentives, such as the difference in prices between legal and illegal products and the probability of illegal trade being detected by enforcement authorities. Ultimately, linking demand-driven and the less explored supply-driven market theories will provide a clearer picture of how markets in which illegality is present operate and the role of traders in them.

Understanding trading dynamics is complicated when illegal trade is present because, usually, only legal data are available (Gavin et al., 2009; Oyanedel et al., 2018). Assessing illegal behaviors is challenging because those involved are generally reluctant to participate in research elucidating the extent and characteristics of their activities (Hinsley et al., 2019). Understanding trading dynamics is further complicated in data-limited settings, where even legal data might be challenging to obtain. In these settings, simulation models can be powerful tools for assessing the economic incentives to trade legal or illegal products (or a mix of both), helping to elucidate overall legal and illegal trading dynamics. As such, simulation models can provide quantitative insights to assist managers in deciding on approaches to reduce the level of illegal trade in legal markets.

We devised a generic dynamic simulation model to assess the economic incentives that affect traders' decisions to trade in wildlife legally or illegally, thereby shedding light on the potential effectiveness of approaches to reducing illegal trade in legal markets. The model can be adapted to a broad range of wildlife-use contexts in which supply-driven dynamics dominate. It can be used to estimate the amounts of legal and illegal wildlife traded, explore the sensitivity of trade dynamics to market characteristics, and predict the effects of policy interventions, including the synergies and trade-offs among ecological, economic, and social sustainability goals. To show the model's utility, we applied it to a small-scale fishery, where we sought to provide management-relevant insights into the legal and illegal trading dynamics of the fishery. Reducing the unsustainable use of wildlife requires a better understanding of trade dynamics and novel tools to support management decisions. By assessing illegal wildlife use dynamics through a focus on traders' incentives, we aimed to provide a novel approach to understanding the hidden illegal dynamics of wildlife use, thereby advancing the theory and practice of conservation research.

METHODS

Stationary general form of the model

The model's general, stationary form solved a profit maximization problem by calculating the optimal quantity of legal and illegal units to trade in 1 period (Figure 1). Units are generic and adaptable to any wildlife product. We considered supply at the harvest level, and trading occurred in 1 step in which the trader (focal agent in our model) links harvesters and end markets. We defined costs (for the trader) at the harvest level and prices (for the trader) at end market. Enforcement was targeted at the trader rather than the harvester or the end market.

In the model, traders faced a profit maximization problem in which they chose the quantities of legal and illegal units to trade. This is a generic profit function that considers the costs and benefits associated with legal and illegal units (Milner-Gulland & Leader-Williams, 1992):

$$\Pi = f(x_l, x_i), \quad (1)$$

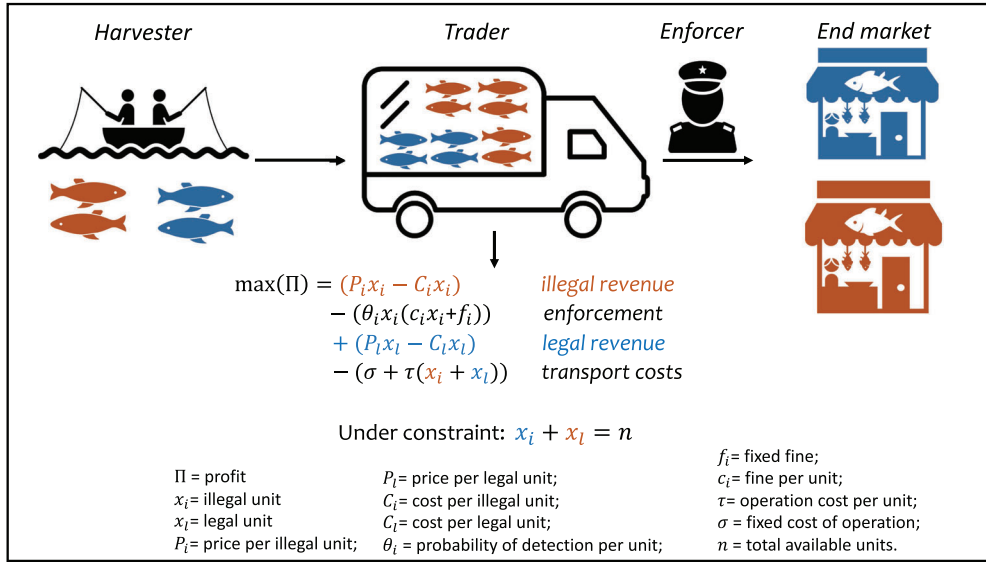


FIGURE 1 Schematic representation of the general, stationary form of the model built to support reduction in illegal wildlife trade within legal markets (brown, elements associated with illegal trade; blue, elements of legal trade)

where x_i is the number of illegal units and x_l is the number of legal units. Legal and illegal revenue was calculated simply by the number of legal or illegal units and their cost and price:

$$\Pi_i = (P_i x_i - C_i x_i) \quad \text{and} \quad (2)$$

$$P_l = (P_l x_l - C_l x_l), \quad (3)$$

where P_i and P_l are the price paid to the trader at the market per illegal (i) and legal (l) unit, respectively, and C_i and C_l are the cost for the trader to purchase, from the harvester, an illegal and legal unit, respectively. When there was trading of illegal units, there was a cost to the trader associated with the probability of enforcement and the fine level, which was a linear function of the number of illegal units and the probability of detection per illegal unit. Moreover, we assumed all illegal units were discovered once the trader was caught. The enforcement cost function was composed of a variable component, for which we calculated the fine by multiplying the number of illegal units by a per-unit fine constant and adding a fixed fine component. Thus, the costs associated with enforcement were as follows:

$$c_e = [\theta_i x_i (c_i x_i + f_i)], \quad (4)$$

where θ_i is the probability of detection per unit; c_i is the fine per illegal unit constant, and f_i is the fixed fine if detected. Finally, the trader's profit function included a cost associated with the operation, calculated with a fixed and a variable component (we assumed the operational costs of illegal and legal units were the same):

$$c_o = [\sigma + \tau (x_i + x_l)], \quad (5)$$

where τ is the operation cost per unit and σ is the fixed cost of operation. Then, the profit maximization function was as follows:

$$\begin{aligned} \max_{x_i} (\Pi) &= (P_i x_i - C_i x_i) - [\theta_i x_i (c_i x_i + f_i)] + (P_l x_l - C_l x_l) \\ &\quad - [\sigma + \tau (x_i + x_l)] \\ &= (P_i x_i - C_i x_i) - c_e + (P_l x_l - C_l x_l) - c_o \end{aligned} \quad (6)$$

under the constraints that $x_i \geq 0$, $x_l \geq 0$, and $(x_i + x_l) = T_a$, where T_a is the total available units from the harvester (or supplier further down the supply chain). The Karush–Kuhn–Tucker (KKT) conditions were necessary and sufficient for this constrained optimization problem, and the solution was unique due to the strong concavity of the objective function. It is given by $x_i = \max_{x_i} \{0, \min[T_a, \arg(\Pi)]\}$.

This profit-maximization function can be solved analytically, given the condition (Equation 7)

$$x_l = T_a - x_i \quad \text{and} \quad (7)$$

$$0 = P_i - C_i - 2\theta_i c_i x_i - f_i \theta_i - P_l + C_l, \quad (8)$$

which rearranges to

$$x_i = \frac{(P_i - C_i - f_i \theta_i - P_l + C_l)}{2\theta_i c_i}. \quad (9)$$

Dynamic general form of the model

For the time-dynamic model, cost and price parameters change each time step (t), depending on the amount of product

supplied (product availability). Other parameters can also change over time (e.g., enforcement activity) to represent management, cultural, or market variability within a year. Product availability at each time step was taken from random draws from a prior distribution, so supply was exogenously determined. We assumed that the quantity of traded wildlife is determined by harvest effort and natural fluctuations, a feature of supply-driven markets, where harvesters participate in the market independently of price signals (McNamara et al., 2016; Oyanedel et al., 2021). As such, traders were recipients of supply and could not determine the total quantities being traded (only the proportion of legal and illegal units):

$$n_t = \text{rand}(\delta)/T, \quad (10)$$

where n_t is units of wildlife products at time t , δ is prior distribution of total units traded, and T is time horizon.

Next we calculated C_i, C_l, P_i , and P_l . Price and costs for illegal and legal units had separate elasticity terms that represented the change in prices and costs depending on product availability at time t compared with a reference quantity, cost, and price. We introduced this elasticity term to account for how market dynamics at the consumer end, and harvester and trader bargaining power dynamics, determine prices and costs depending on availability. Moreover, different elasticity values for legal and illegal products reflected cases in which different processes determined the price and cost of legal and illegal units. This elasticity of price and costs is a feature observed, for instance, in fisheries (Loannides & Whitmarsh, 1987; Oyanedel et al., 2021) and bushmeat hunting contexts (McNamara et al., 2016, 2019). We also differentiated the price and cost of legal and illegal units by including a fixed permit fee paid by traders to harvesters (V_l) and a per unit price premium received by traders on the end market for legal products (β_l):

$$C_{i,t} = C_R \left(1 + \frac{\epsilon_{c,i}(n_R - n_t)}{n_R} \right) \quad \text{and} \quad (11)$$

$$C_{l,t} = C_R \left(1 + \frac{\epsilon_{c,l}(n_R - n_t)}{n_R} \right) + V_l, \quad (12)$$

where C_R is the cost reference, n_R is the reference quantity, $\epsilon_{c,i}$ is the cost elasticity for illegal units, and $\epsilon_{c,l}$ is the cost elasticity for legal units. Similarly, $P_{i,t}$ and $P_{l,t}$ are calculated as

$$P_{i,t} = P_R \left(1 + \frac{\epsilon_{p,i}(n_R - n_t)}{n_R} \right) \quad \text{and} \quad (13)$$

$$P_{l,t} = P_R \left(1 + \frac{\epsilon_{p,l}(n_R - n_t)}{n_R} \right) + \beta_l, \quad (14)$$

where P_R is the price reference, $\epsilon_{p,i}$ is the price elasticity for illegal units, and $\epsilon_{p,l}$ is the price elasticity for legal units.

Then, in each time step, these cost and price values were used to calculate $x_{i,t}$ and $x_{l,t}$, following the analytical solution in Equation 9. Finally, total quantities of illegal and legal prod-

uct traded over the whole period (x_i and x_l) were calculated as follows:

$$x_i = \sum_{t=1}^T x_{i,t} \quad \text{and} \quad (15)$$

$$x_l = \sum_{t=1}^T x_{l,t}. \quad (16)$$

Approximate Bayesian computation for parameter estimation and model results

We used an Approximate Bayesian Computation (ABC) rejection algorithm for estimating unknown parameter distributions and calculating legal and illegal units traded (Beaumont, 2010; Figure 2). This approach helps when only some of the data needed to describe a process are available. The ABC approach models how the available data are generated from some partially unobserved (latent) variables. It then helps find the latent variable values, or their distributions in a probabilistic setting, that would approximately generate the observed data.

For the ABC approach, we constructed priors for unknown parameters (which might vary depending on the context, but are usually those associated with illegal trade). Ranges for priors can be obtained from previous knowledge, surveys, or key informant interviews. Then, we ran several thousand simulations ($\sim 10,000$ – $100,000$) in which random values were drawn from the priors and combined with known parameters in the dynamic model presented above to calculate legal and illegal units traded. We compared model results for legal units (x_l) with available data and rejected simulation runs that did not match predefined criteria. Samples from parameter priors associated with simulations that were not rejected, then composed the posterior distribution. The criterion we used for selection or rejection of simulations was that the Mahalanobis distance between the calculation of total number of legal units traded (x_l) and the official legal data was not higher than a prespecified threshold. The Mahalanobis distance is a measure of the distance between a vector and a distribution summarized by its mean and covariance. We computed the prespecified threshold so that the simulation was accepted if it could have been generated with probability 0.95 by a Gaussian distribution with mean and covariance computed from that empirical data distribution. The 0.95 threshold can be updated depending on the context. The R code for the model is provided in Appendix S6.

Common-hake fishery case study

The common hake (*Merluccius gayi gayi*) small-scale fishery in Chile employs more than 3000 fishers directly, making it one of Chile's most important fisheries (SUBPESCA, 2016). The fishery comprises vessels usually less than 12 m in length (Arancibia & Neira, 2008). It is subject to extensive trade in illegal fish that

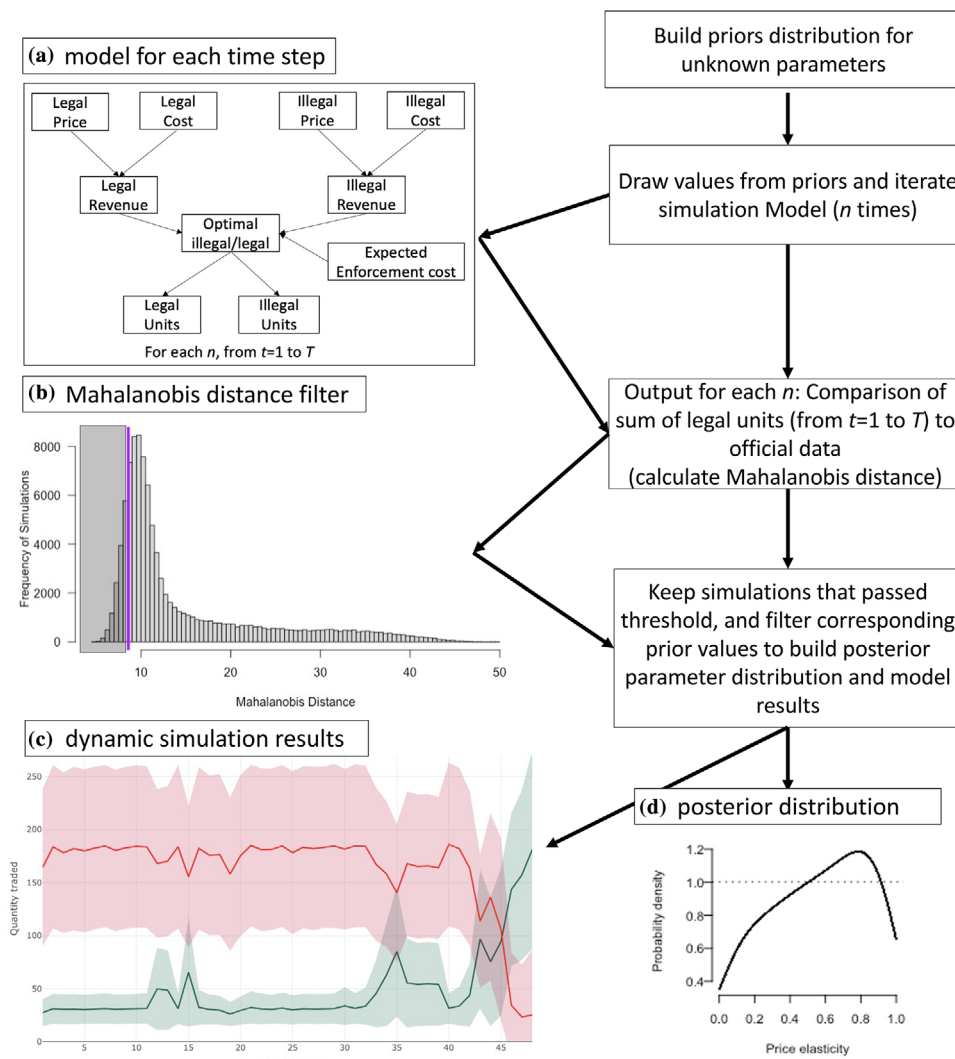


FIGURE 2 Schematic representation of the simulation model showing the Approximate Bayesian Computation (ABC) approach and the model steps: (a) known and unknown input and output variables (which ones are unknown depends on context), (b) Mahalanobis distance histogram with the distribution of simulations generated in an ABC run (purple vertical line, threshold computed from the mean and covariance computed from empirical data distribution; shaded area, accepted simulations), (c) mean (SD) of simulations of legal (green) and illegal (red) units traded over time, and (d) example of a posterior parameter distribution (price elasticity) constructed for each of the previously unknown parameters

infiltrates the legal market (Oyanedel et al., 2021). This sustainability challenge is especially severe in the country's VII region, where most of the fish traded does not comply with official regulations. The market for this fishery is primarily domestic. The trade goes from different ports along the coast of Chile to a central fishing terminal in Santiago (Chile's capital) (Oyanedel et al., 2020a). This is a single-species fishery, so fishers only target common hake when fishing this species. However, traders may occasionally engage in trading other fish species when trading hake, following the same route.

We used mixed methods to obtain the input data for the model. First, we used open-ended key informant interviews to understand the fishery's operation and market. We focused on the most critical factors affecting trade dynamics and the decision to trade legal or illegal units (interview methods in Appendix S1). The interview methodology complied with Oxford University's ethical requirements (approval num-

ber R68516/RE001). We gathered primary data from government sources, including legal units sold from fishers to traders per day from 2015 to 2019 in the VII region; stage-specific and overall quota available for 2014–2019 (the government gives the quota to the fishery in 3 stages within the year) in the VII region; the number of enforcement activities per week for 2015–2019 in the VII region; and size of fines for the same period. Because we had valuable data on enforcement activities in the region, we adapted the probability of detection θ_i to be a function of enforcement effort (number of activities, θ_a) and efficiency of enforcement (θ_e , unknown parameter, prior) so that $\theta_i = \theta_e \theta_a$. Using these enforcement data (number of enforcement activities in the region) improved the model's predictive capacity substantially. An evaluation of model simulations with and without incorporating these data is in Appendix S2, and Appendix S3 contains the data sets used.

To understand the effect on sustainability of intervening in the fishery, we selected 4 of the possible policy levers presented in Oyanedel et al. (2021) and performed a sensitivity analysis. These policy levers were: increase the legal quota, certify legal products in the end market, improve or increase enforcement, and incentivize consumption of alternative products. The increase in legal quota was included in the model as an increase in the overall quota (Q) parameter. The rationale was that higher quotas are associated with more legal fishing (Oyanedel et al., 2020a). We included certify legal product in the end market in the model as an increase in the price premium parameter (β_l , Equation 14) because by certifying legal units there could be product differentiation and increased demand for legal products and a higher price premium. Improve or increase enforcement was included as an increase in enforcement efficiency (θ_e , Equation 9), which shifts trader's incentives toward trading more legal products. Incentivize consumption of alternative products was included as an increase in the price elasticity parameter (ϵ_p , Equations 13 and 14). The rationale was that if consumers have alternative products, prices will respond faster to increases in supply.

For the sensitivity analysis, each selected parameter was assessed at a time by increasing it up to 300% while using random draws from the posterior distribution of the parameters not being assessed. Then, we selected those parameters that led to a reduction in the total number of units traded (i.e., that improved ecological sustainability). Next, we iterated the simulation model with randomly generated increases in all the selected parameters simultaneously in order to construct intervention scenarios. Finally, we explored options for improving the ecological sustainability of the trade, while limiting economic costs. We evaluated the parameter ranges that would produce 3 levels of improvement in ecological sustainability (measured as a decrease in overall units traded) while limiting the associated economic cost (measured as catch value lost) below a threshold. The thresholds were a minimum 10%, 30%, and 50% improvement in ecological sustainability, accompanied by a maximum 20%, 40%, and 60% increase in economic cost, respectively. These thresholds were chosen arbitrarily, with the aim to show different sections of the simulated results space.

RESULTS

Operation of the fishery and market and model adaptation

Key informant interviews confirmed the presence of an active and extensive market for illegal hake, consistently indicating that the vast majority of trade was illegal. Moreover, interviews allowed us to understand the operation of the market (Appendix S1). Legal and illegal units of product were traded in the same trucks and sold in the same end market; the unit was a 27–30-kg box of hake. Fishers were the quota holders. By reporting their catch on a given day, they provided the trader with a legal permit for the quantity reported, which was discounted

against the fishers quota. There was product and price differentiation: traders paid a permit fee for legal units to fishers and received a price premium on the end market for those units. This permit fee was set at a fixed value (CLP (Chilean Pesos) 3000 [\sim US\$4.3]) for most of the year, except toward the end of the year when this value decreases because fishers who still had quota rushed to sell it, lowering the permit value. We could not identify, from the interviews, a value for the price premium. Key informants indicated that traders operated with a minimum legal fraction of units per truck load to justify their operation for tax and registration purposes. However, this fraction varied depending on perceived enforcement activity levels and on the end-market price. For instance, enforcement effort and end-market price increased at Easter when demand for hake and the perceived likelihood of higher levels of illegal trade increase.

We adapted the model's general form to accommodate the peculiarities of this fishery's market. To do so, we added a parameter representing a minimum fraction of legal products traded per week, a constraint that no trading occurs when there is no quota left, and a permit fee elasticity parameter to account for the devaluation of the permit fee at the end of the year. The time step unit was defined as a week because a week was the finest scale time granularity of the available data sets (enforcement). We ran the model with 48 weeks because we removed September from the analysis given that there was a fishing ban during that month, so no trading occurred. For a summary of the unknown parameters for which we built priors, see Appendix S3.

Parameter posteriors and trading dynamics results

The filtering process using Mahalanobis distance accepted around 15% of simulations (Appendix S4), which enabled us to obtain posterior distributions for unknown parameters (Figure 3). Our estimate of the total traded units over the year and its probability distribution enabled us to estimate the ratio of legal and illegal units in trade. This confirmed the information from the key informant interviews that illegal units dominated the trade because the mean ratio was around 0.77. Our estimate of the overall mean number of legal units traded was close to the mean number of legal units recorded in official data (Figure 3).

The trade was dominated by illegal units year-round, except toward the end of the year (Figure 4). Our simulations gave temporally dynamic results that captured the fishery's dynamics relatively closely (Figure 4). The similarity of our simulation results on legal landings to the official data showed the model's ability to predict the data.

Intervening for improving sustainability

Our sensitivity analysis showed that reductions in the total number of units traded were obtained when we increased beta (the

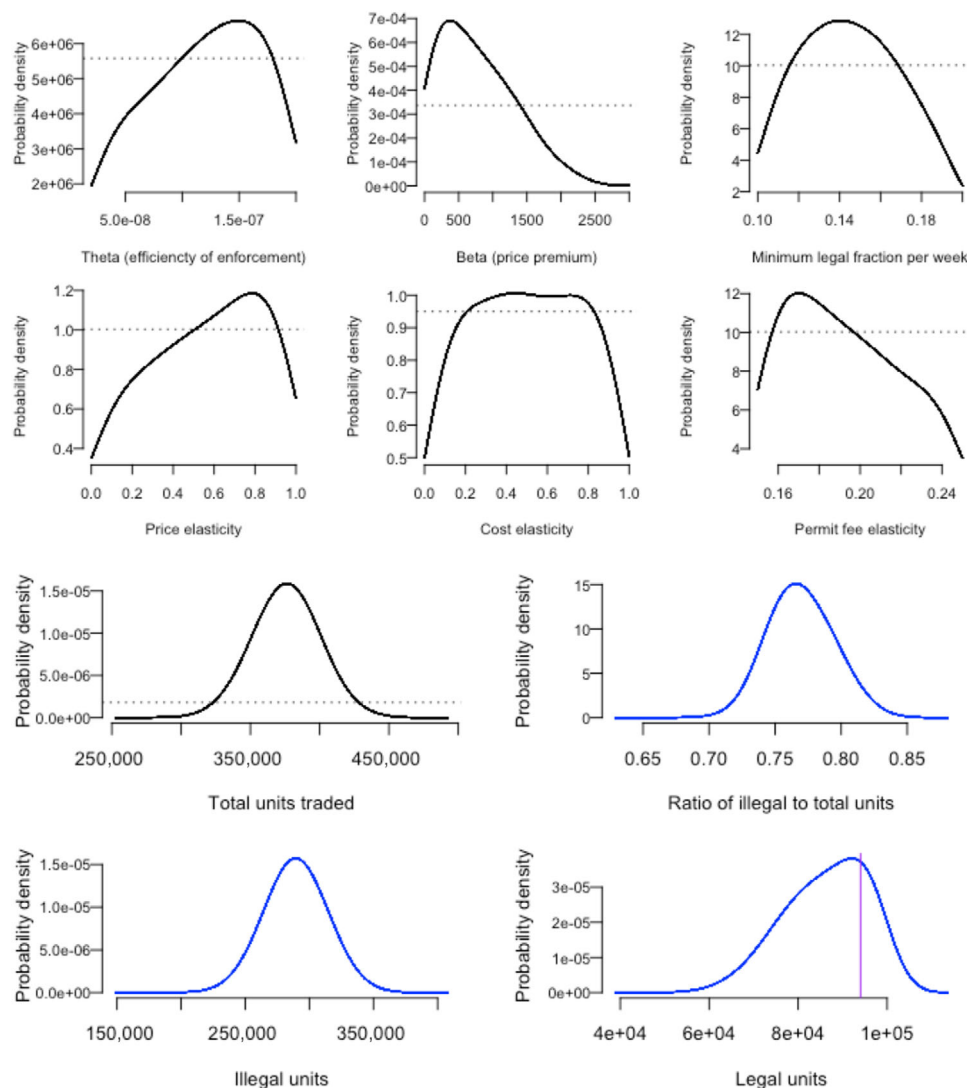


FIGURE 3 Prior (dotted lines, uniform distribution) and posterior distribution (black lines) for unknown parameters and model-aggregated results (blue) for the case study application of the model (purple line in the legal units plot is overall legal landings mean from the data)

price premium) by 100–300% (Appendix S5). Reductions in units traded were obtained for all levels of increase in theta (efficiency of enforcement). Reductions in units traded were obtained with an increase in price elasticity of at least 150%. We observed no change in units traded when quota was increased alone. Therefore, the sensitivity analysis suggested that only theta, beta, and price elasticity were effective at reducing the number of units traded (therefore holding promise as levers for improving ecological sustainability).

Our scenario assessment showed a negative linear relationship between the fishery's economic and ecological goals (Figure 5a). The highest reductions in illegality (social goal) were obtained at higher values of the ecological goal (i.e., more catch reduction) but lower values of the economic goal (i.e., less value derived from catch). To meet our minimum level of ecological sustainability improvement (10%) and economic cost (20%), the increases required in beta and theta were <200%, whereas price elasticity varied across its whole range (Figure 5b). To reach a

30% improvement in ecological sustainability for up to a 40% increase in economic cost, there was an expansion of the parameter space, concentrating on increases in beta and theta values >200% and 0–300% increases in price elasticity (Figure 5c). In the most extreme scenario (>50% reduction in overall catch, up to 60% increase in cost), the parameter space moved further toward higher levels of increase in beta and theta values, concentrating above 250% (Figure 5d).

DISCUSSION

Assessing how to reduce illegality in legal markets is necessary to promote sustainable use and derive the diversity of benefits from wildlife trade (t Sas-Rolfes et al., 2019). Our model presents a novel tool for understanding trade dynamics in cases where legal and illegal products are traded in the same market, but only partial information on the dynamics of that trade is

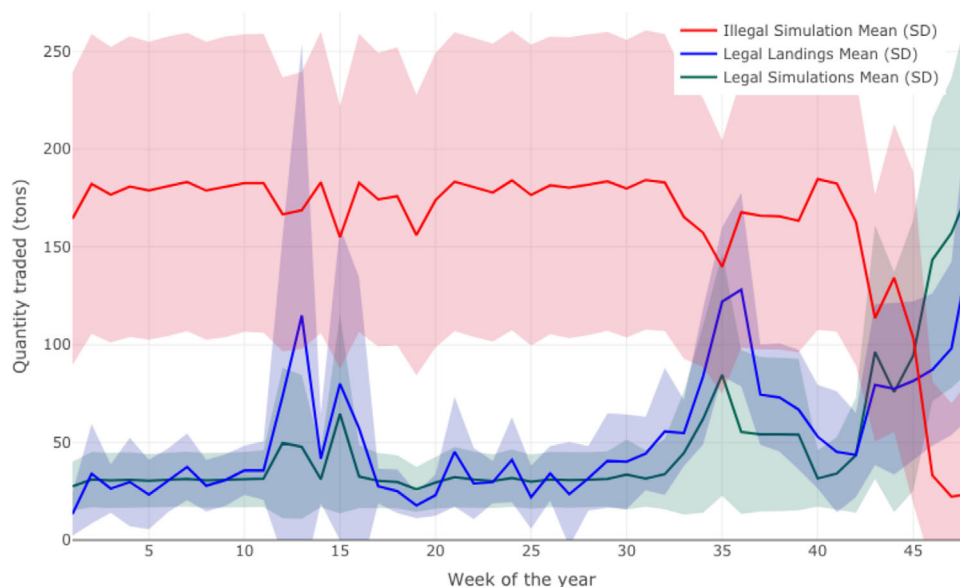


FIGURE 4 Mean (SD) from simulations of legal (green) and illegal (red) units traded compared with legal landings data from official records (blue, mean [SD] from 2014 to 2019)

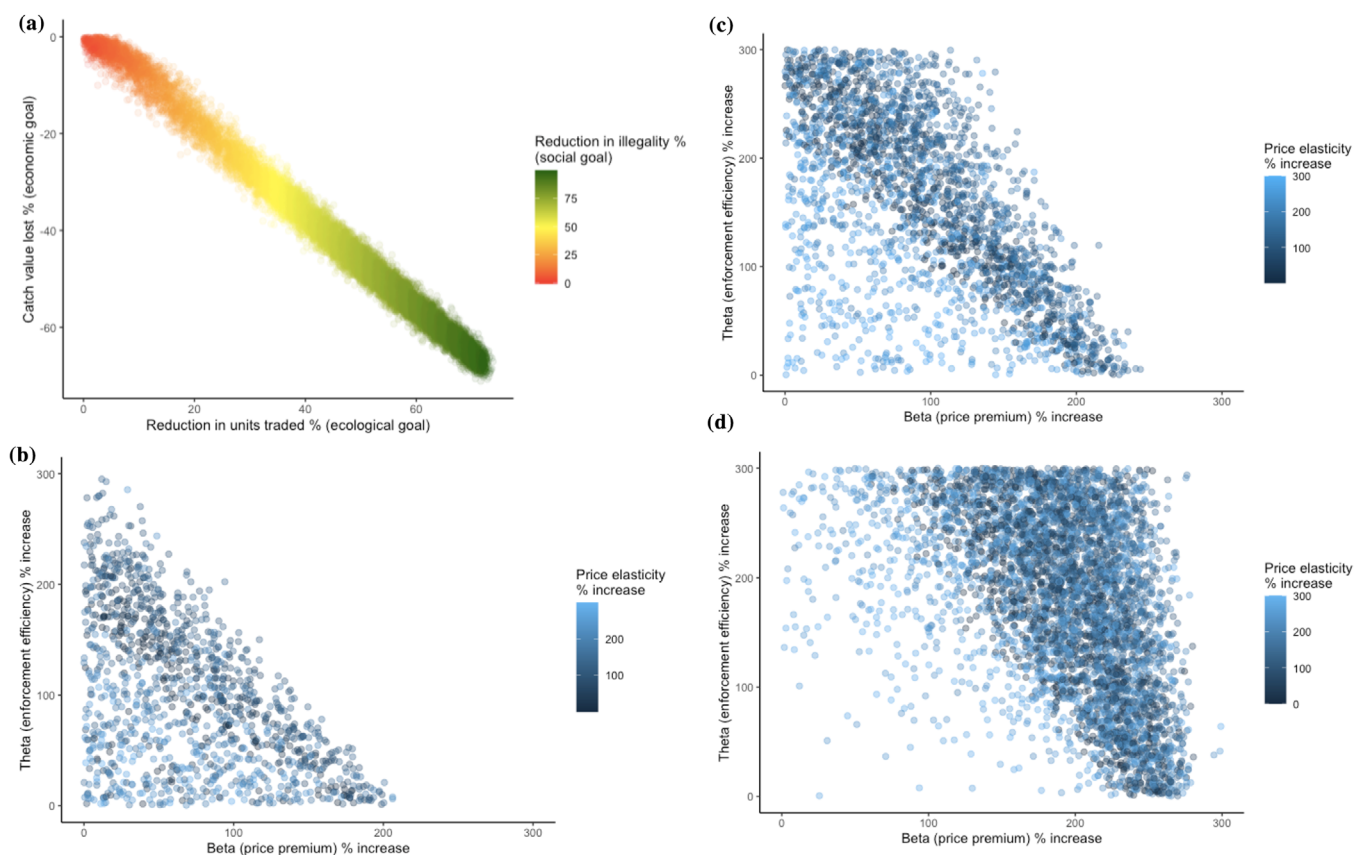


FIGURE 5 For 15,000 simulation runs of the common-hake case-study model, (a) scenario results in terms of social, ecological, and economic sustainability goals and (b, c, and d) values of parameters (policy levers) needed to accomplish ecological sustainability (measured as a decrease in overall units traded) of at least 10%, 30%, and 50%, respectively, and an economic sustainability (measured as catch value lost) of no more than -20% , -40% , and -60% , respectively (the brighter the circle, the more extreme levels of change in price elasticity; top right quadrant, extreme levels of change in beta [price premium] and theta [enforcement efficiency])

available; this is a relatively common situation for wildlife markets. Understanding these dynamics is especially important in small-scale resource use settings, where even data on legal trade might be limited. By combining data from different sources and using an Approximate Bayesian Computation approach (ABC), our model allowed us to uncover hidden illegal trade dynamics. Moreover, it helped disclose previously unknown information about the market through the estimation of posterior distributions. As such, our approach can help elucidate the operation of hard-to-assess markets and how legal and illegal trade dynamics interact within them.

Our approach is innovative because it focuses on the trader's economic incentives to trade legal or illegal products, which allowed us to explore an untapped facet of wildlife markets (González-Mon et al., 2019; Jones et al., 2019). By modeling the determinants of trader decision-making, we were able to reconstruct legal and illegal wildlife harvest rates over time (Figure 4), suggesting that these traders might play an essential role in defining the overall dynamics of legal and illegal wildlife markets, at least when they are supply driven (Oyanedel et al., 2021). As such, focusing on better understanding traders' incentives could catalyze a richer understanding of how to de-incentivize illegal wildlife trade in legal markets. Research is slowly starting to include traders in assessments of wildlife use (Crona et al., 2010; Purcell et al., 2017; O'Neill et al., 2018; González-Mon et al., 2019). However, more research is needed to understand whether traders influence legal and illegal wildlife trade dynamics in other contexts, such as in demand-driven markets.

The capacity of uptake of our model and approach by researchers and practitioners will vary depending on the type of market and supply chain being assessed. This, in turn, needs to be accounted for in decision-making so that lessons learned from the application of the model consider the uncertainties and limitations of both the model and the data used. We have provided the code of our model to encourage uptake, but on-the-ground adoption might require adaptations, especially in cases when different products are derived from the same species, when trading involves multiple species, or when there is transformation along the supply chain (Rosales et al., 2017; Arias et al., 2020). Similarly, researchers and practitioners might struggle to acquire or obtain the necessary data to run the model as presented here. To account for this, we offer several options depending on data availability in the model code included in Appendix S6. For instance, we provide an alternative code option for contexts lacking enforcement-effort data, where researchers will need to use the model with a fixed probability of detection parameter over time.

With regard to our fishery case study, key informants indicated that illegality dominated the market. Interviews allowed us to build priors for unknown parameters by informing the ranges within which these parameters might vary. Posterior distributions and model results confirmed that the vast majority of the market was illegal, except toward the end of the year (Figure 4). Moreover, our model allowed us to better understand and explain the within-year temporal variability of trade in the small-scale common hake fishery. For instance, we elucidated a somewhat counterintuitive dynamic of the fishery by includ-

ing the permit fee elasticity parameter. That is, in this fishery legal landings increased dramatically at the end of the year but decreased as soon as the new year started. This dynamic is not a result of market or environmental factors but rather of how the fishery is managed. As fishers who still have quota permits at the end of the year rush to sell them, they lower the permit price and shift the traders' incentives toward more legal trading. This phenomenon dissipates when the new year starts, and fishers get new quota permits. In sum, by combining a qualitative initial interview stage to familiarize ourselves with the market and a quantitative approach with the ABC model, we were able to shed light on the legal and illegal trading dynamics of the small-scale common hake fishery in Chile.

Our results suggest that improving the sustainability of the fishery by de-incentivizing traders to trade illegal units requires significant increases in the policy levers we assessed (Appendix S5 and Figure 5). To reduce the total units traded by at least 30%, the policy levers generally needed to increase by >200%. Although the government could potentially directly increase the efficiency of enforcement, the other policy levers (increasing the price premium in the end market for legally sourced fish and increasing the price elasticity of demand via consumers shifting more readily between hake and alternatives as the price changes) are more complex to increase and uncertain in their outcomes because they involve the market responding to policy changes. These results show how unbalanced the market's current incentives are toward trading illegal over legal products and the scale of the interventions that would be required to improve the fishery's sustainability. Indeed, our results suggest that solving the illegality problem in this fishery is challenging and would require a combination of different interventions to start shifting traders' incentives toward trading more legal products.

Although ecological and economic goals are usually discussed in conservation, social goals are also key to sustainability (Newing, 2010). Increasing compliance is a crucial social goal because it can help improve legitimacy of regulations and cohesion within the community and reduce tension and mistrust caused by non-compliance (Faasen & Watts, 2007; Oyanedel et al., 2020b). Moreover, considering impacts with respect to the 3 pillars of sustainability (social, ecological, and economic) when intervening in wildlife markets can help avoid unintended consequences (Larrosa et al., 2016). This can shed light on where to direct efforts and which interventions to avoid. For instance, although increasing the quota has been proposed as a solution for this specific fishery (Oyanedel et al., 2021), our results indicate that increasing the quota alone would have no effect on the ecological sustainability of the fishery, but would only legalize the illegal catch (Appendix S5). Moreover, taking a broader perspective when planning interventions can help managers and policy makers evaluate the trade-offs between goals and enact policies with a clear understanding of their potential effects on the ground. Indeed, our results (Figure 5a) lay out the trade-offs between the social, economic, and ecological goals for the case study. Visualizing these trade-offs serves to predict where interventions might help and where they might bring negative or unintended consequences.

Trading wildlife brings unavoidable risks (Booth et al., 2020; Bennett et al., 2021). Managing these risks can help sustain wildlife use and trade over time, delivering the broad suite of benefits this activity can bring (Milner-Gulland et al., 2003; Challender & MacMillan, 2014; t Sas-Rolfes et al., 2019; Andersson et al., 2021). The risk of illegal products entering legal markets is present in many contexts (Bennett et al., 2021). Thus, tools that help assess the effects of interventions that reduce this risk are of great importance for sustainability. Our approach shows that understanding the risk of illegality requires a more profound recognition of traders' role in determining wildlife use dynamics. Indeed, traders are an understudied stakeholder in wildlife use contexts but can be of significant importance in determining how wildlife is used (Crona et al., 2010; Oyanedel et al., 2021). As such, advancing the understanding of the role of traders in diverse wildlife use contexts is critical. Our approach contributes to this task by delivering a versatile tool to quantify illegal wildlife trade in legal markets and assess the trade-offs between potential interventions that specifically target trader's incentives. Sustainable wildlife trade requires better assessment of how to incentivize legal over illegal wildlife trade, considering the potential social, ecological, and economic impacts of interventions.

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LITERATURE CITED

- Andersson, A. A., Tilley, H. B., Lau, W., Dudgeon, D., Bonebrake, T. C., & Dingle, C. (2021). CITES and beyond: Illuminating 20 years of global, legal wildlife trade. *Global Ecology and Conservation*, 26, e01455.
- Arancibia, H., & Neira, S. (2008). Overview of the Chilean hake (*Merluccius gayi*) stock. *CalCOFI Reports*, 49, 104–115.
- Arias, M., Hinsley, A., & Milner-Gulland, E. J. (2020). Characteristics of, and uncertainties about, illegal jaguar trade in Belize and Guatemala. *Biological Conservation*, 250, 108765.
- Beaumont, M. A. (2010). Approximate Bayesian computation in evolution and ecology. *Annual Review of Ecology, Evolution, and Systematics*, 41, 379–406.
- Bennett, E. L., Underwood, F. M., & Milner-Gulland, E. J. (2021). To trade or not to trade? Using Bayesian belief networks to assess how to manage commercial wildlife trade in a complex world. *Frontiers in Ecology and Evolution*, 9, 1–16.
- Booth, H., Arias, M., Brittain, S., Challender, D. W. S., Khanyari, M., Kuiper, T., Li, Y., Olmedo, A., Oyanedel, R., Pienkowski, T., & Milner-Gulland, E. J. (2020). Saving lives, protecting livelihoods, and safeguarding nature: Risk-based wildlife trade policy for sustainable development outcomes post-COVID-19. *Frontiers in Ecology and Evolution*, 9, 99.
- Bowen-Jones, E., & Pendry, S. (1999). The threat to primates and other mammals from the bushmeat trade in Africa, and how this threat could be diminished. *Oryx*, 33, 233–246.
- Brashares, J. S., Arcese, P., Sam, M. K., Coppolillo, P. B., Sinclair, A. R. E., & Balmford, A. (2004). Bushmeat hunting, wildlife declines, and fish supply in West Africa. *Science*, 306, 1180–1183.
- Bulte, E. H., & Van Kooten, G. C. (1999). Economic efficiency, resource conservation and the ivory trade ban. *Ecological Economics*, 28, 171–181.
- Burton, M. (1999). An assessment of alternative methods of estimating the effect of the ivory trade ban on poaching effort. *Ecological Economics*, 30, 93–106.
- Challender, D. W. S., & MacMillan, D. C. (2014). Poaching is more than an enforcement problem. *Conservation Letters*, 7, 484–494.
- Costello, C., Cao, L., Gelcich, S., Cisneros-Mata, M. Á., Free, C. M., Froehlich, H. E., Golden, C. D., Ishimura, G., Maier, J., Macadam-Somer, I., Mangin, T., Melnychuk, M. C., Miyahara, M., de Moor, C. L., Naylor, R., Nøstbakken, L., Ojea E., O'Reilly E., Parma A. M., ... Lubchenco J. (2020). The future of food from the sea. *Nature*, 588, 95–100.
- Crona, B. I., Nyström, M., Folke, C., & Jiddawi, N. (2010). Middlemen, a critical social-ecological link in coastal communities of Kenya and Zanzibar. *Marine Policy*, 34, 761–771.
- Faasen, H., & Watts, S. (2007). Local community reaction to the “no-take” policy on fishing in the Tsitsikamma National Park, South Africa. *Ecological Economics*, 64, 36–46.
- Fukushima, C. S., Mammola, S., & Cardoso, P. (2020). Global wildlife trade permeates the Tree of Life. *Biological Conservation*, 247, 108503.
- Gavin, M. C., Solomon, J. N., & Blank, S. G. (2009). Measuring and monitoring illegal use of natural resources. *Conservation Biology*, 24, 89–100.
- González-Mon, B., Bodin, Ö., Crona, B. I., Nenadovic, M., & Basurto, X. (2019). Small-scale fish buyers' trade networks reveal diverse actor types and differential adaptive capacities. *Ecological Economics*, 164, 106338.
- Hall, R. J., Milner-Gulland, E. J., & Courchamp, F. (2008). Endangering the endangered: The effects of perceived rarity on species exploitation. *Conservation Letters*, 1, 75–81.
- Hinsley, A., Nuno, A., Keane, A. M., St. J. F., & Ibbett, H. (2019). Asking sensitive questions using the unmatched count technique: Applications and guidelines for conservation. *Methods in Ecology and Evolution*, 10, 308–319.
- Holden, M. H., & Lockyer, J. (2021). Poacher-population dynamics when legal trade of naturally deceased organisms funds anti-poaching enforcement. *Journal of Theoretical Biology*, 517, 110618.
- Jones, S., Papworth, S., Keane, A., St John, F., Smith, E., Flomo, A., Nyamunue, Z., & Vickery, J. (2019). Incentives and social relationships of hunters and traders in a Liberian bushmeat system. *Biological Conservation*, 237, 338–347.
- Larrosa, C., Carrasco, L. R., & Milner-Gulland, E. J. (2016). Unintended feed-backs: Challenges and opportunities for improving conservation effectiveness. *Conservation Letters*, 9, 316–326.
- Loannides, C., & Whitmarsh, D. (1987). Price formation in fisheries. *Marine Policy*, 11, 143–145.
- McNamara, J. F., J. E., & Ntiemo-Baidu, Y. (2019). Understanding drivers of urban bushmeat demand in a Ghanaian market. *Biological Conservation*, 239, 108291.
- McNamara, R. M., Cowlishaw, G., Alexander, J. S., Ntiemo-Baidu, Y., Brenya, A., & Milner-Gulland, E. J. (2016). Characterising wildlife trade market supply-demand dynamics. *PLoS ONE*, 11, 1–18.
- Milner-Gulland, E. J. (1993). An econometric analysis of consumer demand for ivory and rhino horn. *Environmental & Resource Economics*, 3, 73–95.
- Milner-Gulland, E. J., Bennett, E. L., Abernethy, K. A., Bakarr, M., Bennett, E., Bodmer, R., Brashares, J. S., Cowlishaw, G., Elkan, P., Eves, H., Fa, J. E., Peres

- C. A., Roberts C. M., Robinson J., Rowcliffe M., & Wilkie D. (2003). Wild meat: The bigger picture. *Trends in Ecology & Evolution*, 18, 351–357.
- Milner-Gulland, E. J., & Clayton, L. (2002). The trade in babirusas and wild pigs in North Sulawesi, Indonesia. *Ecological Economics*, 42, 165–183.
- Milner-Gulland, E. J., & Leader-Williams, N. (1992). A model of incentives for the illegal exploitation of black rhinos and elephants: Poaching pays in Luangwa Valley, Zambia Author. *Journal of Applied Ecology*, 29, 388–401.
- Moyle, B. (2017). Wildlife markets in the presence of laundering: A comment. *Biodiversity and Conservation*, 26, 2979–2985.
- Newing, H. (2010). *Conducting research in conservation: Social Science methods and practice*. Routledge.
- O'Neill, E. D., Crona, B. I., Ferrer, A. J. G., Pomeroy, R., & Jiddawi, N. S. (2018). Who benefits from seafood trade? A comparison of social and market structures in small-scale fisheries. *Ecology and Society* 23, 12.
- Oyanedel, R., Gelcich, S., & Milner-Gulland, E. J. (2020a). Motivations for (non-)compliance with conservation rules by small-scale resource users. *Conservation Letters*, 13, 1–9.
- Oyanedel, R., Gelcich, S., & Milner-Gulland, E. J. (2020b). A synthesis of (non-)compliance theories with applications to small-scale fisheries research and practice. *Fish and Fisheries*, 21, 1120–1134.
- Oyanedel, R., Gelcich, S., & Milner-Gulland, E. J. (2021). A framework for assessing and intervening in markets driving unsustainable wildlife use. *Science of The Total Environment*, 792, 148328.
- Oyanedel, R., Keim, A., Castilla, J. C., & Gelcich, S. (2018). Illegal fishing and territorial user rights in Chile. *Conservation Biology*, 32, 619–627.
- Phelps, J., Biggs, D., & Webb, E. L. (2016). Tools and terms for understanding illegal wildlife trade. *Frontiers in Ecology and the Environment*, 14, 479–489.
- Purcell, S. W., Crona, B. I., Lalavanua, W., & Eriksson, H. (2017). Distribution of economic returns in small-scale fisheries for international markets: A value-chain analysis. *Marine Policy*, 86, 9–16.
- Rosales, R. M., Pomeroy R., Calabio I. J., Batong M., Cedo K., Escara N., Facunla V., Gulayan A., Narvadez M., Sarahadil M., & Sobrevega M. A. (2017). Value chain analysis and small-scale fisheries management. *Marine Policy*, 83, 11–21.
- SUBPESCA. (2016). *Plan de Manejo de la Pesquería de la Merluza Comun*. Author.
- t Sas-Rolfes, M., Challender, D. W. S., Hinsley, A., Verissimo, D., & Milner-Gulland, E. J. (2019). Illegal wildlife trade: Scale, processes, and governance. *Annual Review of Environment and Resources*, 44, 201–228.

SUPPORTING INFORMATION

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