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Review

Measuring and Monitoring Illegal Use of Natural Resources

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Abstract: *Illegal use of natural resources is a threat to biodiversity globally, but research on illegal activities has methodological challenges. We examined 100 studies that empirically identify targeted resources, techniques used to procure resources illegally, locations of illegal activities, characteristics of typical violators, incentives driving illegal use of resources, magnitude of the problem of illegal use (e.g., quantities used), or frequency of illegal activity. We based our evaluation of the methods used in these studies on their ability to provide these empirical data, relative labor demands, training and technology requirements, and levels of uncontrollable bias. We evaluated eight different methods: law-enforcement records, indirect observation, self-reporting, direct observation, direct questioning, randomized response technique (a survey method designed to improve accuracy of responses to sensitive questions), forensics, and modeling. Different situations favored different methods, each with distinct advantages and limitations. Six context-specific factors—location of resource use (in situ vs. ex situ), budget, technology and training capacity, ease of detection of illegal activity, scope of illegal activity (limited vs. widespread), and researchers' willingness to accept bias in results—help narrow the choice of methods. Several methodological concerns applied to any study of illegal resource use: regular monitoring can detect trends; modeling can incorporate sampling error and data uncertainties; researchers must manage levels of bias that vary between methods; triangulation of results from multiple methods can improve accuracy. No method is a panacea, but a combination of techniques can help address the lack of data on illegal activity. Researchers empirically compared results from different methods in only four studies, and no one has compared more than two methods simultaneously. Conservation would benefit from more research focused on: methods comparisons that include cost effectiveness, time efficiency, and statistical rigor; unique applications of the eight techniques currently in use; and testing of new methods.*

Keywords: conservation management, endangered species, illegal natural resource use, law enforcement, poaching, protected areas, violation rates

Medición y Monitoreo del Uso Ilegal de Recursos Naturales

Resumen: *El uso ilegal de recursos naturales es una amenaza global para la biodiversidad, pero la investigación sobre actividades ilegales tiene retos metodológicos. Examinamos 100 estudios que identifican empíricamente los recursos utilizados, las técnicas usadas para la procuración ilegal de recursos, las localidades con actividades ilegales, las características de los violadores típicos, los incentivos que guían el uso ilegal de recursos, la magnitud del problema del uso ilegal (e.g., cantidades utilizadas) o la frecuencia de la actividad ilegal. Basamos nuestra evaluación de los métodos usados en estos estudios en su capacidad para proporcionar datos empíricos, las demandas relativas de trabajo, los requerimientos de capacitación y tecnología y los niveles de sesgo incontrolable. Evaluamos ocho métodos diferentes: registros de cumplimiento de la ley, observación indirecta, observación directa, cuestionamiento directo, técnica de respuesta aleatoria (un método de muestreo diseñado para mejorar la precisión de respuestas a preguntas sensibles), argumentación y modelado. Diferentes situaciones favorecieron a diferentes métodos, cada uno con ventajas y limitaciones distintas. Seis factores específicos del contexto—localización del uso del recurso (in situ vs. ex*

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situ), presupuesto, capacidad tecnológica y de adiestramiento, facilidad de detección de actividades ilegales, alcance de la actividad ilegal (limitado vs. extendido) y la disponibilidad de los investigadores para aceptar sesgos en los resultados—ayudan a reducir la elección de métodos. Varias preocupaciones metodológicas aplicadas a cualquier estudio del uso ilegal de recursos: el monitoreo regular puede detectar tendencias, el modelado puede incorporar error de muestreo e incertidumbre en los datos; los investigadores deben manejar niveles de sesgo que varían entre métodos; la triangulación de resultados de múltiples métodos puede mejorar la precisión. Ningún método es una panacea, pero una combinación de técnicas puede abordar la carencia de datos sobre actividades ilegales. Los investigadores compararon empíricamente los resultados de diferentes métodos en solo cuatro estudios, y ninguno ha comparado más de dos métodos simultáneamente. La conservación se beneficiaría de más investigación sobre: comparaciones de métodos que incluyan relación costo-beneficio, eficiencia de tiempo y rigor estadístico; aplicación de las ocho técnicas en uso actualmente; y experimentación de métodos nuevos.

Palabras Clave: áreas protegidas, cacería furtiva, cumplimiento de la ley, especies amenazadas, gestión de la conservación, tasas de violación, uso ilegal de recursos naturales

Introduction

Illegal use of natural resources is a major threat to biodiversity globally. Here, we defined illegal resource use as commercial and subsistence use that violates regulations. These illegal activities entail violations of ownership rights, such as taking of resources from protected areas or private land without permission; illegal land occupation; and violation of resource-use regulations, including use that is in excess of established limits, out of season, and conducted with prohibited extraction methods, without required permits, or in prohibited areas. Illegal resource use also includes extraction of prohibited resources, such as protected species.

The threat posed by illegal resource use is nearly universal; illegal activities affect protected area management (e.g., Bleher et al. 2006; Hilborn et al. 2006; Yonariza & Webb 2007) and conservation of endangered species (e.g., Burton 1999; Koch et al. 2006; Dinerstein et al. 2007) in nearly every biome. The impacts of illegal resource use vary in scale and scope depending on the extent and intensity of illegal activity and the degree of resistance and resilience of the ecological and socioeconomic systems affected. Biological impacts range from declines in genetic diversity (e.g., large-tusked elephants; Okello et al. 2008) and species richness to changes in community composition and ecosystem services (e.g., Pauly et al. 2002; Pitcher et al. 2002; Edirisinghe 2003). Economically, illegal resource use can provide alternative livelihood strategies to marginalized people and windfall profits to poachers of prized species (Pratt et al. 2004; Yonariza & Webb 2007; Tacconi 2008), but legitimate resource users can suffer significant revenue losses as a result of illegal use of resources (Gigliotti & Taylor 1990; Gutierrez-Velez & MacDicken 2008). Socially, illegal resource use can reflect and further exacerbate differences in access to resources. Illegal use of natural resources has even funded national and regional conflicts (McNeely 2003).

More accurate data on illegal resource use are needed. With accurate measures of illegal activities, managers could monitor success of conservation efforts, which would allow them to design more efficient interventions (Davies 1996; Hockings et al. 2000). Furthermore, with appropriate methods, illegal resource use may be detected before it has biological impacts and, thereby, provide early warning of threats to biodiversity (Pitcher et al. 2002). Nevertheless, the illegal nature of the activities poses unique methodological challenges. Here, we focused on four central questions that research on illegal resource use should answer: (1) What is the illegal resource use (i.e., what species and what extraction techniques)? (2) Where does illegal resource use occur? (3) Who extracts resources illegally? (4) Why does illegal resource use occur (i.e., behavioral incentives)?

To answer these questions, researchers must gather data on identities of resources targeted (e.g., which species), techniques used to procure resources illegally, locations of illegal activities, identities of violators (or characteristics of typical violators), and incentives driving illegal resource use (e.g., income generation). In addition, answers to the target questions must account for the magnitude of illegal resource-use problems (e.g., quantities of resources used, prevalence at different spatial scales, number of people involved, size of incentives driving illegal activity) and the frequency of illegal activity (i.e., are there seasonal or long-term changes in targeted resources, quantities extracted, or locations of and participants in illegal extractions). This list of questions and associated data requirements may not be exhaustive, but we believe that it represents the majority of information needed to assess conservation challenges posed by illegal resource use.

None of these questions are easy to answer. Illegal resource use is mostly covert, and significant incentives exist for informants to withhold information. Budget and human resource constraints also restrict efforts to measure and monitor illegal resource use (James et al. 1999;

Gray & Kalpers 2005). We considered the advantages and disadvantages of methods available for gathering data on illegal resource use. In addition, we reviewed the few studies in which methods were compared empirically. We determined data-gathering techniques that are best suited to answering the focal questions under different resource use and management scenarios. Finally, we identified gaps researchers should seek to fill to improve analyses of illegal resource use.

Methods

To create an initial list of relevant articles we searched both ISI (Web of Knowledge) and Google Scholar with the following keywords: illegal resource use, illegal resource*, resource*, illegal*, poaching effort, poach*, conserv*, method*, estimat*, quanti*, compliance, enforce*. Google Scholar searches for peer-reviewed articles, as well as books, book chapters, theses, and grey literature. Because some of these sources can be underrepresented on the Internet, we also included relevant studies cited by articles found via keyword searches. We then narrowed the list by identifying studies that presented empirical evidence to answer at least one of the critical questions outlined in the Introduction.

We based our evaluation of methods on the following criteria: ability to answer the four critical questions (see Introduction), relative labor demands (number of hours needed to gather sufficient data), relative training and technology requirements, and relative uncontrollable bias (which directly influences data reliability). We described each method and analyzed each method's advantages and disadvantages relative to our evaluation criteria (Table 1).

Results

We identified eight different methods used to study illegal resource use: law-enforcement records, indirect observation, self-reporting, direct observation, direct questioning, randomized response technique, forensics, and modeling (Table 1).

Law-Enforcement Records

This method relies on records that enforcement agencies keep on arrests, warnings, sanctions for violations of resource-use regulations, and seizures of illegal products. The use of law-enforcement records does not usually place large labor demands on conservation agencies and does not require special skills or technology. In most cases, enforcement personnel already maintain some records, and agencies can add value to databases by expanding the types of information recorded and through more consistent data collection. If each violation record notes a specific location, investigators can analyze the spatial distribution of illegal activity (e.g., Holmern et al. 2007). Although we found no studies in which arrest records were used to examine characteristics of typical violators, such an analysis is possible if agencies collect sociodemographic information with each violation. Data recorded with seizures of illegal goods can identify targeted resources and estimate quantities of illegal take (e.g., Davis et al. 2004). Investigators can examine trends in illegal activities, if consistent records exist (e.g., Hilborn et al. 2006).

Nevertheless, methodological constraints may limit the usefulness of law-enforcement records. Greater patrol effort can lead to more encounters with violators. The relationship between patrol effort and encounters, however, is not necessarily linear because more patrols increase risks for violators, which can reduce poaching (Leader-Williams & Milner-Gulland 1993). To correct for patrol effort, enforcement agencies must record additional information, including the number of patrols, number of personnel per patrol, area covered by patrols, and time spent on patrol (Holmern et al. 2007). Patrol efficiency also varies on the basis of personnel training and patrol resources (e.g., vehicles), which in turn determine the patrol effort required (Hilborn et al. 2006). Another bias is corruption by enforcement agencies, which can result in deliberate underreporting and ineffective enforcement. Finally, enforcement records can be biased toward readily apparent violations, including illegal activities closer to enforcement headquarters and activities violators cannot conceal.

Indirect Observation—Signs of Illegal Activity

Signs of illegal activity can serve as indirect indicators of violation. For example, cut stems and tree stumps are evidence of illegal logging or firewood collection (Vermeulen 1996; Gray & Kalpers 2005; Bleher et al. 2006; Baranga 2007). Researchers have also examined illegal logging via satellite imagery (Kuemmerle et al. 2007). Counts of carcasses (Koch et al. 2006), snares (Yom-Tov 2003), hunting camps (Blake et al. 2007), and blasts from dynamite fishing (Guard & Masaiganah 1997) all help examine illegal activity. Market surveys can also gather information on illegal resource use (Edderai & Dame 2006; Flores-Palacios & Valencia-Diaz 2007). Fisheries researchers have calculated the difference between quantities of commercial trade and landings to determine illegal, unreported, and underreported catch (Lack & Sant 2001; Pitcher et al. 2002). Finally, researchers have monitored populations of target species to estimate illegal take (Maliao et al. 2004; Francini-Filho & de Moura 2008).

Different indirect observations vary in their ability to provide information about illegal resource use. In most cases, evidence collected can indicate where illegal

Table 1. Comparison of methods used to measure and monitor illegal resource use.

Method	*Possible data outputs*[a] *what*	*where*	*who*	*why*	*Relative labor demand*	*Relative technology and training requirements*	*Relative bias*	*Possible biases*	*Possible controls of bias*
Law enforcement records	√	√	□	-	low	low	med./high	opportunistic—data only available where and when rangers patrol requires accurate records corruption bias toward overt violations	correct for patrol effort and efficiency, but relationship between patrol effort and illegal activity not linear consistent protocol
Indirect observation: signs of illegal activity	√	√	-	-	low (except for market survey)	low (except for remote sensing)	med.	differences in observer reliability opportunistic—data only available where and when patrols occur can be difficult to distinguish natural disturbance/ mortality from illegal extraction	consistent training and protocol correct for patrol effort and efficiency, but relationship between patrol effort and illegal activity not linear
Self-reporting	√	√	□	□	low	low (except some computer data loggers)	very high	recall bias motivation to underestimate (especially when resource economically valuable)	increase data recording frequency
Direct questioning	√	√	√	√	med.	med.	med./high	fear of retribution or desire to please interviewer leads to response bias recall bias	use independent interviewers; development of rapport; questionnaire design use of memory anchor points
Direct observation	√	√	√	√	high	low	med.	presence of researcher/ranger may discourage illegal activities opportunistic—data only available where and when researchers patrol	inconspicuous observation points correct for patrol effort and efficiency, but relationship between patrol effort and illegal activity not linear
Randomized response technique[b] (RRT)	√	√	√	-	med.	med.	low	belief of trickery; interviewer bias statistical noise recall bias	introduction with role reversal; development of rapport; use independent interviewers; questionnaire design large sample size use of memory anchor points
Forensic studies	-	√	-	-	high	high	low	small samples produce large error requires seized goods	
Modeling	√	√	-	√	low	high	low	numerous confounding variables quality of predictor variables directly impacts reliability of estimates produced	triangulation with other methods

[a]*Key:* √*, studies published in which the method for this data output was used;* □*, theoretically possible to use the method, but it has not been used in any published study (i.e., key research gap);* -*, not possible to use the method.*
[b]*Has been used to examine what species and what extraction techniques violators use, but no one has used RRT to quantify illegal resource use (see text for details).*

activities occur. Notable exceptions are market studies, fishery comparisons of landings versus commercial trade, and carcass counts, where researchers only encounter evidence away from original extraction sites (e.g., turtle carcasses in towns; Koch et al. 2006). The ex situ nature of this evidence poses additional challenges when resource use is legal in some locations, but prohibited in others. Most indirect observation methods provide some indication of which resources are used and estimate quantities of take, but these estimates have large or unknown standard errors. For example, with carcass counts, researchers have no estimate of animals killed for which no carcasses remain. Likewise, to examine illegal take with counts of snares or hunting camps, researchers rely on only rough estimates of average take per snare or camp. Market surveys do not account for products intended for personal use and thus underestimate total take (Flores-Palacios & Valencia-Diaz 2007). Estimates derived from monitored changes to target populations must account for other factors that contribute to population declines, including natural population fluctuations. Such corrections in population estimates often suffer from a lack of sufficient baseline data. Periodic monitoring with indirect observation can document short- and long-term trends in illegal activity (Jachmann & Billiouw 1997). Nevertheless, none of the indirect observation methods indicate who violators are or why illegal behavior occurs.

Most advantages and disadvantages of indirect observation relate to data collection efforts. Indirect observations do not usually require large amounts of labor or specialized equipment and training. Typically, routine enforcement patrols can record indirect observations of illegal activity (Bleher et al. 2006). Exceptions include market studies, which involve extra labor for stand-alone surveys, and remote sensing, which requires special equipment and trained personnel. In addition, if conservation personnel record signs of illegal activity simultaneously with biological data, investigators can obtain a more complete picture of the impact of illegal activities (e.g., Jachmann 2008*b*). Increased data collection requirements, however, can lead to personnel fatigue and reduce effectiveness of enforcement (Leader-Williams et al. 1990). Indirect observations also vary with patrol effort and efficiency. Staff efforts, and thus data reliability, also change depending on performance incentives (e.g., Jachmann 2008*a*). Finally, with some indirect observation methods (e.g., satellite imagery), researchers may struggle to distinguish natural disturbances or mortality from evidence of illegal activities (Kuemmerle et al. 2007).

Self-Reporting

Resource users can record data on their own activities. Fishing and hunting licenses may require records of resource use. Diaries can also track resource use patterns (Gavin & Anderson 2005). With properly designed data-recording systems, self-reporting can document quantities of resources used, locations of illegal activities, characteristics of violators, and trends in illegal resource use. In cases where perceived risk of prosecution is low, or where potential violators have limited knowledge of regulations, informants may have less fear of retribution and, therefore, more accurately self-report illegal activities (Gavin 2007).

Although these methods provide information without a lot of labor or special training and technology, the data can be heavily biased. Many resource users, particularly with highly valuable resources, have large incentives to underreport violations, and this bias is very difficult to measure or control. For example, Blank and Gavin (2009) used the randomized response technique (see below) to estimate that 15–29% of recreational fishers violate abalone fishing regulations in California. By comparison, of the thousands of mandatory self-report cards returned each season by licensed fishers (e.g., 15,004 from 2002), virtually none (1–3) self-reported illegal take (Kalvass & Geibel 2006; P. E. Kalvass, personal communication).

Direct Questioning

Researchers administer direct questions through different mechanisms, including face-to-face interviews, phone-based interviews, and self-administered questionnaires. Direct questioning can provide information on the proportion of the population violating regulations, the sociodemographic profile of potential violators, and the incentives to violate (e.g., Yonariza & Webb 2007). Direct questioning can also gather data on locations of illegal activities, identify resources used illegally, and estimate quantities of illegal take (e.g., Mann 1995). Finally, direct questioning can track short- and long-term trends in illegal activities (e.g., Smethurst & Nietschmann 1999).

Direct questioning suffers from several sources of bias. Unless informants trust the interviewer, significant incentives exist to provide false or misleading answers. Respondents may fear retribution, including sanctions or public scrutiny (Renzetti & Lee 1993). Careful choice of interviewers (i.e., with no link to regulating agencies) and survey design (e.g., sensitive questions at the end of questionnaires) can increase the reliability of responses to sensitive questions to a certain degree (Catania et al. 1996). On the basis of social norms, respondents may provide answers they believe interviewers want to hear, regardless of truthfulness (Catania et al. 1996). Nevertheless, researchers can correct for some of this response bias if they also survey known violators (e.g., Gray & Kaminski 1994). Recall bias is another challenge because people tend to remember rare events more than common ones (Sudman & Schwarz 1989). Similarly, although direct questioning can record names of species used over time, the method is less suited for gathering data on exact quantities collected in the past (Gavin & Anderson 2005). Because questionnaire design and administration (i.e., consistent interview techniques) can greatly influence results, direct questioning requires focused training. Direct questioning also often involves finding and interviewing numerous informants; therefore, the technique can be more labor intensive than some other methods.

Direct Observation

Direct observation of illegal activities can avoid many biases present in direct questioning. Direct observers may accompany resource users on collecting trips (e.g., Rowcliffe et al. 2004) or record information from strategic locations near sites of resource use (e.g., Korschgen et al. 1996). Because researchers observe illegal activities firsthand, spatial distribution of illegal take can be ascertained (e.g., Agnew 2000). If observers record sociodemographic information, direct observations can determine characteristics of typical violators (e.g., McCrary et al. 2004). Direct observation can also identify target species and extraction techniques and estimate levels of illegal take (e.g., Allard & Chouinard 1997). If investigators consistently record observations, short- and long-term trends can be tracked (e.g., Matsuishi et al. 2006). Finally, direct observations can test theories regarding drivers of illegal behavior (e.g., impact of laws on hunter prey choice; Rowcliffe et al. 2004).

Direct observation also has several limitations. For one, estimates obtained with direct observation must account for sampling effort. Observers cover only a portion of the total area and time in which illegal activities occur. Therefore, researchers must extrapolate overall estimates, a process that reduces reliability (Agnew 2004). Due to temporal and spatial variability of extraction activities, accurate estimation of illegal resource use may require large sample sizes (Shankar et al. 1998). Although direct observation does not usually require a large investment in special training, the need for large samples can lead to high monitoring costs, particularly for time-intensive observation programs such as onboard fisheries observers (Allard & Chouinard 1997). The presence of observers can also bias estimates by discouraging illegal activities (Ainsworth & Pitcher 2005).

Randomized Response Technique

Warner (1965) developed the randomized response technique (RRT) to increase response rates to sensitive questions and improve the accuracy of responses when compared with direct questioning (Unmesh & Peterson 1991). The RRT method begins with the use of a randomizing device or activity (e.g., a coin toss) in which participants take part and remember, but do not disclose, the result. Respondents then randomly select one of two undisclosed questions: one sensitive (e.g., Did you kill a deer out of season last year?) and one innocuous and linked to the result of the randomizing activity (e.g., Did you get "heads" in the coin toss?). Respondents answer only yes or no to the question. The interviewer does not know which question respondents choose, so the method encourages respondents to provide truthful answers. The interviewer does know, however, the probability of receiving the sensitive question (e.g., half the respondents get the question on poaching) and the probability of a yes response to the innocuous question (e.g., half get heads in the coin toss). Therefore, although the interviewer cannot link individual respondents to sensitive answers, aggregate estimates of illegal behavior are obtained.

Randomized response technique has been used to study the use of natural resources in only five studies (Wright 1980; Chaloupka 1985; Schill & Kline 1995; Solomon et al. 2007; Blank & Gavin 2009). The use of RRT can help set conservation priorities by comparing the proportion of the population that violates different regulations (e.g., Solomon et al. 2007). If researchers have a large sample and collect RRT and sociodemographic data simultaneously, subsampling can examine which sectors of the population are more likely to violate regulations (e.g., Blank & Gavin 2009). The RRT can also indicate spatial variation in illegal activities (e.g., Schill & Kline 1995). Researchers can examine temporal trends with periodic RRT surveys (e.g., Wright 1980). Although no one has used RRT to quantify illegal take, researchers in other fields have adapted RRT for this purpose (Fox & Tracey 1986).

The RRT reduces response bias and evasive answers to sensitive questions. Several validation studies show that RRT is more accurate than direct questioning when sampling known violators (Lensvelt-Mulders et al. 2005). Nevertheless, RRT requires careful attention to survey design. Many respondents, particularly those unfamiliar with probability theory, may think RRT involves trickery (I-Cheng et al. 1972). Interviewers can increase respondent confidence with role reversals, where respondents become interviewers, or by lowering the probability that respondents receive sensitive questions (Fox & Tracey 1986; Solomon et al. 2007). Lower probabilities for sensitive questions, however, further exacerbate problems of statistical noise inherent with RRT. The RRT usually requires large sample sizes to ensure accuracy (Fox & Tracey 1986); therefore, labor costs can be high. Recall bias can also affect RRT questions that target past events (Junger-Tas & Marshall 1999), but interviewers can reduce this bias with prominent historical events serving as anchor points to guide respondents (Solomon et al. 2007). The use of RRT also requires some special training to ensure proper design and administration of questionnaires.

Forensics

Researchers may use forensics in initial stages of investigation to determine the identity and geographic origins of confiscated goods. Serology (Lorenzini 2005), entomology (Anderson 1999), genetic analysis (Moore et al. 2003; Palsboll et al. 2006; Magnussen et al. 2007), and chemical indicators (e.g., for cyanide, Mak et al. 2005) help identify whether confiscated material is from a prohibited source. Genetic analyses (Baker et al. 2000; Wasser et al. 2008) and isotope signatures (Vogel et al. 1990; Amin et al. 2003) can link confiscated goods to particular geographic locations. Nevertheless, forensic techniques can be expensive and time intensive, and small sample sizes increase error in estimates. In many cases, investigators need large reference databases to pinpoint geographic origins of confiscated material. This quantity of background data only exists for a limited number of species (e.g., elephants), and database establishment requires an enormous amount of labor. The specific tests (e.g., DNA analysis) require high levels of training and special equipment, which increases costs of forensic methods. Unlike other methods we reviewed, forensics relies completely on confiscated material; therefore, the method cannot account for illegal activities when violators are not caught. Usually confiscations account for only a small percentage of illegal take, and forensic methods do not provide a means to extrapolate estimates. Finally, because authorities usually confiscate material far down the supply chain, forensics cannot usually identify violators responsible for illegal activities in situ or ascertain incentives for illegal behavior.

Modeling

Because accurate direct measures of illegal activity are difficult to obtain, models have become a popular means of estimating key parameters associated with illegal resource use. Regression models determine the relationship between known levels of illegal activity in the past and key predictors, such as measures of enforcement effort (e.g., Dublin et al. 1995; Jachmann & Billiouw 1997). These models then use estimates of key predictors to extrapolate levels of illegal activity over time. Other models, including tuned VPA (virtual population analysis), stock-assessment models, age-structured models, and spatially explicit population models, focus on population dynamics of illegally harvested species (Patterson 1998; Plaganyi et al. 2001; Kritzer 2004). These models use data on past take or biological surveys of target species to estimate illegal take and biological impacts of take. Caughley et al. (1990) combined population models with effort and yield functions to estimate elephant population levels, total ivory harvest, and hunting effort. Researchers have also combined population models with models of illegal behavior to examine impacts of different enforcement interventions on illegal take and impacts on target species (e.g., Milner-Gulland & Leader-Williams 1992; Byers & Noonberg 2007). Simulation models provide a range of estimates on quantities of illegal resource use on the basis of levels of uncertainty attached to available data (e.g., Pitcher & Watson 2000; Ainsworth & Pitcher 2005; Tesfamichael & Pitcher 2007).

Modeling can be used to examine several aspects of illegal resource use. Spatially explicit population models can predict geographic patterns of illegal activity (Kritzer 2004). Most modeling studies we reviewed predicted quantities of illegal take or the impact of take on harvested populations (e.g., Kritzer 2004; Byers & Noonberg 2007). Researchers have also used models to examine incentives for illegal behavior (Dublin & Jachmann 1992; Milner-Gulland & Leader-Williams 1992; Dublin et al. 1995). We did not review any models that identified actual violators or characteristics of typical violators because these models are inherently hypothetical. Finally, models can predict and retrodict short- and long-term trends in illegal resource use (e.g., Dublin & Jachmann 1992).

A major advantage models provide is the ability to examine illegal activities with limited data. Simulation models incorporate all forms of data, from empirical studies to subjective expert opinions, account for uncertainty in available figures and provide margins of error for resource-use estimates (Pitcher et al. 2002). Therefore, models fill an important gap by allowing conservation action to advance despite a lack of accurate data on illegal resource use. Nevertheless, an important caveat exists: model accuracy depends on the quality of data input into the system (Burton 1999; Pitcher et al. 2002; Ainsworth and Pitcher 2005). If large error exists in key parameters (as is often the case when few data are available) or if the degree of error is unknown, models produce very rough estimates. Therefore, models are most effective when paired with other estimation tools, particularly those with error estimates (e.g., RRT). Other major dilemmas for modeling are the number of confounding variables and the related risk of equating association and correlation with causation (Burton 1999). Although modeling may not require as much labor as other methods, modeling generally involves high levels of analytical sophistication and, in turn, may be of limited use for some conservation managers (McGarvey & Gaertner 1999).

Direct Comparisons of Multiple Methods

Few researchers have empirically compared estimates of illegal resource use collected through different methods (Table 2). Abbot and Mace (1999) found that direct observation shows a higher proportion of the population violating resource-use regulations than law-enforcement patrols. Similarly, Mann (1995) concludes that direct questioning provides higher estimates of illegal take than enforcement records. Both these studies demonstrate the

Table 2. Studies in which empirical comparisons of methods were used to measure illegal resource use.

Estimation	*Methods comparison*			*Study location (reference)*
Women illegally collecting fuelwood (%)	direct observation	vs.	enforcement data	Lake Malawi National Park (Abbot & Mace 1999)
	83.5		64.3	
Catch rate from illegal gill and seine netting (fish/100 m of net/night)	direct questioning	vs.	enforcement data	St. Lucia Game Reserve, South Africa (Mann 1995)
	31.0		14.3	
Community members using resources inside protected area (%)	RRT*	vs.	direct questioning	Kibale National Park, Uganda (Solomon et al. 2007)
	charcoal: 51.6		2.5	
	hunting: 39.4		1.7	
	pole collection: 62.2		40.3	
	timber: 25.8		4.2	
	firewood: 88.2		37.0	
	grazing: 28.8		13.5	
Fishers violating angling regulations (%)	RRT	vs.	direct observation	three Idaho (U.S.A.) waters (Schill & Kline 1995)
	used bait: 0.0		0.9	
	kept trout: −0.4		0.0	
	barbed hooks: 28.0		21.7	

*Randomized response technique (see text for details on the method).

limitations of enforcement data, which is biased by the limited number of encounters enforcement personnel have with violators. Nevertheless, although direct questioning may provide better estimates than enforcement data in certain scenarios, Solomon et al. (2007) concluded that RRT produces higher estimates of the proportion of the population violating regulations than direct questioning (Table 2). Schill and Kline (1995) noted that estimates of the proportion of the population violating regulations from RRT are similar to those produced via direct observation. One might conclude from these comparisons that RRT and direct observation are the best estimation methods, followed by direct questioning. No one, however, has compared more than two methods simultaneously, and methods have been compared only across a relatively narrow range of illegal activities.

Researchers tend to use certain methods more frequently than others. In 67 of the 100 articles we reviewed, only one method was used to study illegal resource use. The most frequently used method was indirect observation (36 studies, Fig. 1), which may reflect the method's ability to provide information without defining and surveying potential violators. Because self-reporting and direct questioning have numerous inherent biases that are difficult to reduce, we were encouraged to see that so few studies (10) rely solely on these methods. Although RRT can provide more accurate estimates than many other methods when large enough sample sizes are used, the technique is one of the least used.

Discussion

None of the methods we reviewed can be universally applied. Nevertheless, between one and six context-specific factors narrow the options of which method, or suite of methods, can be used to gather information on the four central questions surrounding illegal resource use (see Fig. 2 for decision trees). The relative location of illegal resource use is a critical first factor in deciding on a method to use to determine where illegal use of resources occurs, the species, techniques, and quantities involved, and who violators may be. If resource use is ex situ (i.e., away from the site of initial extraction), then the choice of methods can be further narrowed on the basis of levels of training and technology available to conservation researchers and managers. If technology and training are limited, the only appropriate methods to study ex situ illegal use of resources may be direct questioning and enforcement records. Nevertheless, higher levels of technological capacity open up the possibility of also using forensics (to determine origins of extracted resources) or modeling.

For in situ illegal use of resources (i.e., at or near the extraction site), the scope of the illegal activity can allow researchers to narrow their choice of methods further. For example, some illegal activities are highly

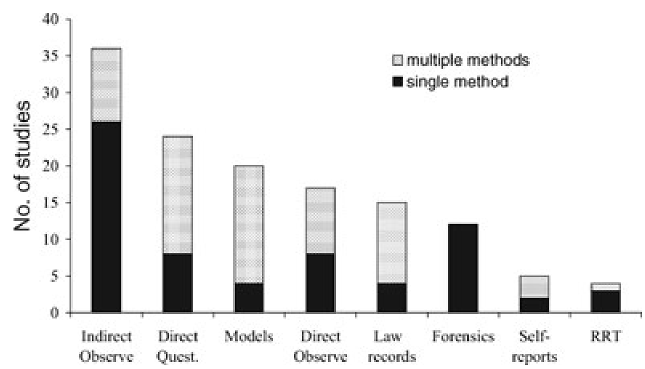
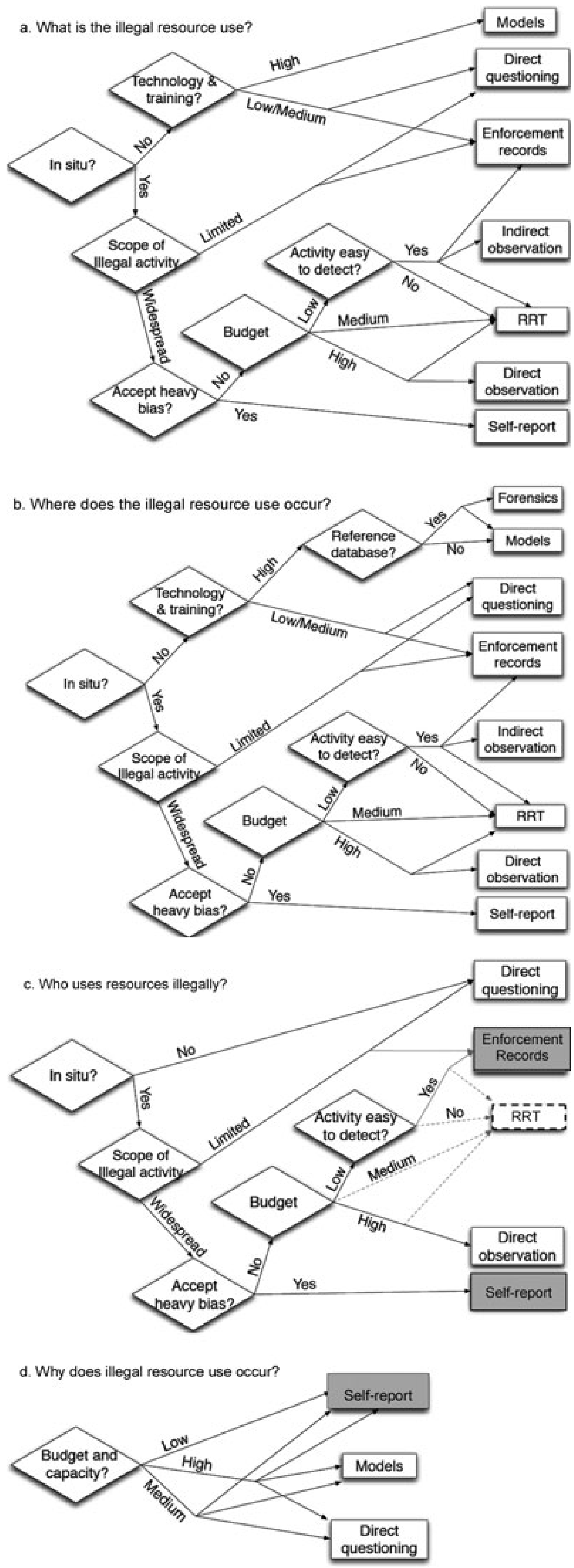


Figure 1. Number of studies in which the different methods of examining illegal resource use were used (RRT, randomized response technique).



specialized, require specific equipment, or focus on rare or highly protected species. These activities (e.g., poaching of rhinoceros horn) are often undertaken by a limited number of people, who are the first link in a chain of international conspirators. In these cases the only options may be arrest records (especially those including sociodemographic details), direct questioning, and indirect observation.

The scope of the in situ illegal activity may be much wider and include a large percentage of the local population (e.g., subsistence firewood collection). In these cases, conservation budgets will be a key factor in narrowing methodological options. Programs with lower budgets need to consider how easy it will be to detect illegal activity. For illegal activities that are relatively easy to detect (e.g., forest clearance for agriculture), a combination of enforcement records, indirect observation, and RRT can be used. In cases where detection is more difficult (e.g., subsistence fishing), RRT may be the most effective method if a sufficient sample size can be achieved.

Different scenarios require different techniques, but several methodological concerns apply to any study of illegal resource use. First, monitoring is critical. Regular monitoring will detect trends in illegal activities, which an adaptive management approach can adjust to in real time. Nevertheless, given the widespread lack of comprehensive baseline data for conservation, modeling can play a vital role. Modeling can incorporate sampling error and data uncertainties to provide a range of estimates regarding quantities, locations, and trends in illegal resource use. In addition, with any method reviewed here, managers must control for bias. Internal biases plague some methods, such as self-reporting and direct questioning. With other methods, such as indirect observations and enforcement records, corrections can be made to limit the impact of bias. Finally, triangulation, by comparing outcomes of multiple methods used simultaneously, can obtain the most accurate results (Gribble & Robertson 1998; Raymakers & Lynham 1999; Pitcher et al. 2002).

Figure 2. Decision trees for determining the appropriate methodology to address four critical questions (a–d) regarding illegal resource use. In (a) for certain scenarios models may be the best primary method. Nevertheless, models are also useful in testing sensitivity of the results of all other methods (see text for details). In (c) the dotted square and lines indicate that RRT (randomized response technique) can be used to study what sectors of the population have undertaken illegal activities, but cannot identify specific people. In (c) and (d) the gray squares indicate that the method can be used to answer this question, but no published research has done so yet.

Given that illegal resource use is, and will continue to be, a major threat to conservation, we were surprised to find only four studies in which results from different methods were compared empirically. Illegal resource use varies in scope (number of people involved) and scale (subsistence vs. market based, local vs. international markets); therefore, different types of illegal activity may require different methods. In addition, investigations of illegal resource use face different challenges depending on the financial and human resources available. A proper comparison of methods would ideally examine how well different methods estimate resource use across a wide array of illegal activities and would incorporate concerns about cost and time efficiency. Future methods comparisons should also examine the statistical power of different techniques to detect changes in illegal resource use over time (cf. Jones et al. 2009). In Table 1 (see data outputs), we identified research gaps in which different methods could theoretically provide data on critical questions regarding illegal resource use, but for which no examples exist. In addition, other methods used to study sensitive behavior by different disciplines remain untested by researchers examining illegal resource use. For example, the item-count method (Droitcour et al. 1991) asks half the respondents to report how many behaviors they have done from a list that includes the illegal activity. The other half of the sample receives a list without the illegal activity. The difference in mean number of behaviors reported provides an estimate of violation rates.

The conservation literature leaves little doubt that illegal resource use is a major problem. An equally common claim, however, is that sufficient data on illegal resource use do not exist and that collection of this information is too difficult. We have outlined different methods available for collection of vital data on illegal resource use. Although no method is a panacea, a combination of different techniques can go a long way toward addressing the current lack of data on illegal activity present in many conservation projects. Researchers need to provide more tests of the methods available, but managers and researchers can still use the appropriate combination of methods outlined here to gather baseline data and develop monitoring and adaptive management programs to address illegal resource use.

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