

Understanding the role of illicit transactions in land-change dynamics

Beth Tellman ^{1*}, Nicholas R. Magliocca ², B. L. Turner II^{3,4} and Peter H. Verburg ^{5,6}

Anthropogenic land use has irrevocably transformed the natural systems on which humankind relies. Advances in remote sensing have led to an improved understanding of where, why and how social and economic processes drive globally important land-use changes, from deforestation to urbanization. The role of illicit activities, however, is often absent in land change analysis. The paucity of data on unrecorded, intentionally hidden transactions makes them difficult to incorporate into spatially specific analyses of land change. We present a conceptual framework of illicit land transactions and a two-pronged approach using remotely sensed data to spatially link illicit activities to land uses.

Land — the terrestrial component of the biosphere — is essential to the biophysical processes that sustain life. The purpose to which land is employed (land use) has been pivotal for the transformation of the structure and function of ecosystems of the Earth system, with increasing consequences on the biogeochemical cycles that sustain life¹. Changes in land use precipitate changes in land cover; that is, the biophysical material on the Earth's surface. These land changes influence species distributions, water availability, temperature, net primary production, ocean chemistry, fish stocks and a host of other components of the biosphere that are essential to human well-being^{2–4}. Understanding where, why and how land-use changes occur is essential to address global sustainability issues.

The pursuit of this understanding has generated emerging research fields, such as landscape sustainability⁵ and land systems science⁶, among others. Much of the research in these fields seeks to examine the causal factors of land change as a social–environmental system^{7,8}, commonly employing earth observations via remote sensing⁹. Despite considerable progress in understanding and modelling land change with or without remote sensing data^{10,11}, an important blind spot remains in the assessments of the causes and consequences of land change: those following from illicit land transactions.

Illicit transactions (variously labelled as illegal, corrupt, criminal, illegitimate or fraudulent) are exchanges that are not allowed or permitted by formal or informal rules and norms that govern social interactions, which are enforced through various societal mechanisms or institutions¹². For these reasons, illicit transactions or exchanges are commonly clandestine, invariably hidden from public view because the actors involved seek to avoid detection and potential sanctions.

Illicit is a fluid and subjective concept, making it difficult to distinguish illicit from licit activities and to delineate a concrete typology of the two. What constitutes illicit varies by social context for both de jure and de facto institutions; for example, small bribes from citizens to a government's officials to expedite required certificates¹³ may be an expected informal interaction, although formally not permitted. Alternatively, government officials may tolerate

certain de jure illegal activity, making it de facto licit; for example, gedogen, or toleration of offenses in the Netherlands, such as the state's non-enforcement of small amounts of cannabis¹⁴. These distinctions notwithstanding, the existence of illicit transactions (those that are sufficiently different to governmental and societal rules and norms to require secrecy) are recognized by research communities as relevant to global environmental change and sustainability.

Numerous observations indicate that illicit land transactions may match or exceed licit transactions in some cases, and include land uses, transfer of entitlements, permission to access, zoning and investments; for example, 40% of deforestation globally is estimated to be illegal, a figure that reaches 80% in Indonesia and Brazil¹⁵. Local politicians who control land-use permits may abuse this power by providing land access to their political supporters. In election years, for example, deforestation increases dramatically (by over 40%) in Indonesia¹⁶ and by 8–10% in the Brazilian Amazon when an incumbent runs for mayor¹⁷. Other examples include urbanization development via kickbacks¹⁸, revenue generation through agriculture by terrorist groups¹⁹, narco-deforestation in Central America²⁰, as well as a litany of other activities that involve use and access to land (examples in Table 1). Many land changes globally involve clandestine transactions that are not expressly illicit. Examples include large-scale land acquisitions that involve private companies that lease large tracts of land from governments with little transparency²¹ and tax havens that conceal financial transactions relating to investment in land resources, for example, in the Amazon²².

In these and other examples, illicit land transactions are notable in two ways. First, they are typically unrecorded (that is, missing in official records), even if the land use is openly observable. Second, they may result in land changes that would probably not take place otherwise (for example, narco-deforestation, see below). Due to the paucity of data regarding illicit activity, illicit transactions have, for the most part, been absent in theories and models of land uses and their environmental impacts, despite the recognition of the prominent role that they maintain in many landscapes²³.

Examining these transactions is difficult because officially documented knowledge about their operation is rarely available to be connected with the land change that is observed in remotely sensed

¹Earth Institute, Columbia University, New York, NY, USA. ²Department of Geography, University of Alabama, Tuscaloosa, AL, USA. ³School of Geographical Science and Urban Planning, Arizona State University, Tempe, AZ, USA. ⁴School of Sustainability, Arizona State University, Tempe, AZ, USA. ⁵Institute for Environmental Studies, VU University Amsterdam, Amsterdam, the Netherlands. ⁶Swiss Federal Research Institute for Forest, Snow and Landscape, Birmensdorf, Switzerland. *e-mail: et2663@columbia.edu

Table 1 | Examples of illicit transactions linked to land use or cover changes

Illicit Transaction	Process	Land change	Reference
Sand mining, India	Mafias extract sand from non-permitted areas, payoff regulators and sell to constructors	Riverbank erosion	Ref. ⁷⁸
Gold mining permits used by foreigners to illegally mine gold, Ghana	Foreign investors use national brokers for national permits to render legal otherwise illegal foreign mining	Deforestation from mining	Ref. ⁴²
Sale or usurpation of indigenous lands, Central America	Narco-funds purchase (often via involuntary sale) from indigenous land holders and bribe state officials to make holdings legal to launder drug money	Forest loss to cattle ranching and other agribusiness	Refs. ^{41,43,56,57}
Large scale land acquisition, Cambodia	Elites (national and foreign) launder money by resale of rural land purchased (or stolen) from indigenous people or government officials for commodities (for example, rubber) which displaces subsistence agriculture	Forest loss to plantations and displaced subsistence agriculture	Ref. ⁷⁹
Slum clearance for construction, Mumbai, India	Mafias bribe officials to clear slums to build commercial malls	From residential urban to commercial urban	Ref. ¹⁸
Tolerance, titling, and eviction of informal settlements, Mexico City, Mexico and Bogota, Colombia	Politicians prevent eviction and facilitate titles in exchange for political support that brokers garner from settlers	Urbanization of conservation land	Refs. ^{44,80}
Housing zoned for development in floodplains, Houston, USA	Kickbacks from developers to politicians to allow floodplain development	Urbanization in flood prone areas	Ref. ²⁵
Rezoning land use for urban development, Milan, Italy	Infiltration of mafia in urban planning departments influence land development through kickbacks and threats	Urbanization of farmland with historic value	Ref. ²⁶

pixels, hindering the corroboration of illicitness to the observed change. Given this impediment, do approaches exist that support inferences about the location, extent, pattern and consequences of illicit transactions linked to the pixel-based data? We suggest that they do. We insert illicit land transactions within a conceptual framework that provides a characterization of their illicitness, and provide two ‘pixel-based’ approaches that can be used synergistically to identify land uses associated with these illicit activities. We also identify new or unused data and analytical methods that facilitate the effort.

Illicit transactions in land change research

Undertaken across formal and informal institutional contexts, illicit transactions can be illegal as defined by rules of governance of the state or a lower-order administrative unit, or subvert informal norms and ethics (for example, societal or community sanctions, taboos, customs, traditions and codes of conduct)²⁴ as noted in the examples above. A large range of illicit land transactions exist that involve clandestine characteristics (Table 1). Furthermore, licit transactions (for example, land legally bought and sold) may follow from illicit processes; for example, funding for land purchases that is derived from illegal activities. Considerable attention has been given to such transactions in low- and middle-income countries owing to concerns about tropical deforestation, arid land degradation, biodiversity losses and environmental justice (for example, Table 1). However, illicit clandestine transactions take place in the developed world as well and are commonly associated with bribes and kickbacks to gain access to land for various types of urban development^{25,26}.

Although underdeveloped in land change and land system research, illicit activities that are linked with land uses and their consequences have garnered considerable attention in other research fields. Political economy, for example, has examined how illicit transactions strengthen versus weaken State power and an increase in conflicts. Due to inadequate data, however, many analyses tend to overstate the role of international illicit activity²⁷. Economics has explicitly analysed the conditions for corruption (an unauthorized transaction between an elected or appointed official and a

third party) or rent seeking (a specific form of corruption where a government actor facilitates access in exchange for an economic kick back). Economists have studied the conditions for corruption at the individual level²⁸ and examined its consequences at the State level (for example, decreasing likelihood of enacting climate change mitigation policies as corruption increases²⁹). New institutional economics has examined how contracts between parties differ from illicit versus licit transactions³⁰. Criminology, by contrast, has addressed where illicit activity occurs, how to regulate it³¹ and how the dominance of markets over non-market institutions (such as police or community governance) increase opportunistic ‘illicit’ economic transactions³².

Several interdisciplinary frameworks that link illicit transactions to environmental change have been proposed. Conservation criminology considers some illicit land transactions as a subset of environmental crime, which has received growing attention as a threat to sustainable development²³. Frameworks to understand environmental crimes — such as spatial socio-ecological dynamics and feedbacks of poaching³³ — integrate risk and decision science with political, social, economic and other contextual variables that lead to the actor committing a crime³⁴.

Other research fields — from urban sociology to conservation and livelihoods studies — emphasize the difficulty of categorizing illicit activity^{34–36}, because powerful actors who make the rules³⁷ can render illegal activities legal. By contrast, less powerful actors may be forced into ‘illegal’ livelihoods under conditions of social or environmental stress³⁸. These insights suggest categorizing the illicitness of specific goods and actors proves difficult. Focusing on illegal goods or actors in environmental crimes fails to incorporate legal land-use changes enabled by illicit activity and, importantly, the powerful actors behind the less powerful actors committing crimes. Examining illicit land transactions (as opposed to only illegal land change) and the actors, rules and institutions enabling them, necessarily broadens the scope of analysis to include actors undergirding much of the land-use change.

Taken as a whole, the attention to illicit activities provide various insights into the land transaction problems we confront in

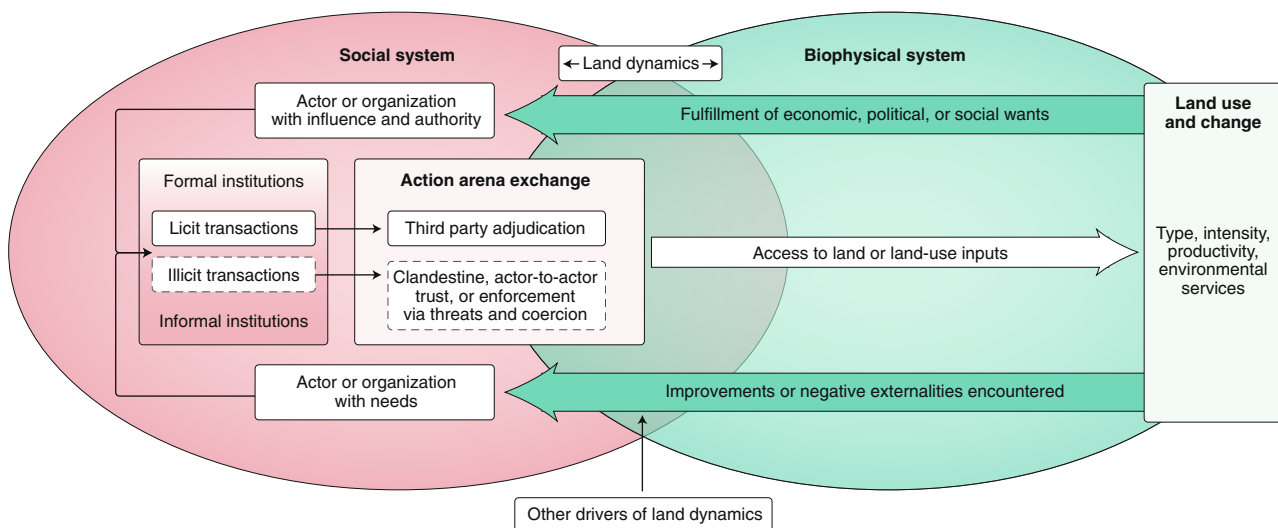


Fig. 1 | Adding illicit transactions into an action arena for land use (following refs. 6,12). The small arrows link actors to institutional mechanisms of illicit transactions that occur across a spectrum of formal to informal institutions. Licit transactions can be adjudicated by a third party, whereas illicit transactions are largely contracts between two types of actors. Dashed grey boxes denote ambiguous boundaries, as the definition of what is illicit is in some cases subjective. Large arrows denote feedbacks between transactions and land-use change.

this Perspective. For the most part, however, this attention has not focused on illicit and clandestine land change or land systems per se, has not grounded the transactions within conceptual frameworks that explicate illicit human–environment interactions nor has it examined how the spatially explicit outcomes of these interactions can be identified through the use of remote-sensing analysis; that is, the workhorse approach that is employed in land-change research. These three elements underscore potential advances in land-change observation monitoring, theory and modelling.

A framework for illicit land transactions

Our illicit transaction framework draws on that developed by Ostrom¹² for institutional analysis in general (Fig. 1). Actors with land-based or monetary wants and needs and those with the authority and influence (or power) to fulfil them make exchanges in the ‘action arena’, where actors weigh the costs and benefits of potential transactions and outcomes. These outcomes may include land entitlements and improvements, resource output, monetary funds or externalities (for example, environmental disservices, such as loss of biotic diversity) for actors with needs and political, economic or social gains and losses for actors with authority and influence. The degree of authority or control of each actor, the perceived benefits each expects from the outcome, and formal and informal institutions (for example, rules of governance) shape conditions of exchange and the adjudicating authority in the action arena. The social and environmental land system co-evolves, producing the landscape or land uses and patterns observed.

All institutions — formal and informal — maintain legitimacy through trust, norms and powers to sanction. Illicit transactions, however, have special characteristics (illustrated in Fig. 1). In either formal or informal institutional settings, these exchanges typically involve considerable differential power (that is, social, political, economic or informational capital mobilized to achieve a goal) between the actor with wants and needs and the actor with authority or influence³⁹. Two types of this power differential are common in land transactions.

In the first type, fiscally powerful actors want formal legitimacy for otherwise illegal access to land or its resources, engaging political actors who can enable access through bribes or kickbacks. Actors often pay bribes when legal transaction costs outweigh either

the likely sanction or the cost of a bribe to a government official⁴⁰. For example, powerful actors have bribed officials to not prosecute illegal land sales in Guatemala⁴¹, to clear slums for shopping mall development in Mumbai¹⁸ or to expedite the process to obtain gold mining concession permits in Ghana⁴².

In the second type, the wants of powerful actors and/or the needs of marginalized actors engender illicit transactions between the two. For instance, powerful narco-traffickers threaten peasants to force land sales in Central America⁴³, or authorities selectively enforce urban land regulations to gain political support of informal settlers in Bogota and Lima who cannot afford to purchase land in formal markets⁴⁴.

Illicit land transactions may blend in with licit activities because powerful actors co-opt or even change existing economic, legal and social structures to avoid detection or sanction⁴⁰. Furthermore, access to land (either licit or illicit in kind) may be a screen for a more central illicit activity, such as access for cattle ranching to launder drug monies in Central America (below), or vanilla exports to launder rosewood trafficking in Madagascar⁴⁵.

Importantly, although licit transactions and contracts are typically public and enforced by a third party, for example, either a formal institution (such as a court of law) or an informal institution (such as a community board), illicit transactions are invariably clandestine and adjudicated without a third party. They require trust between the two actors involved, as opposed to the societal trust establishing legitimacy in institutions. Enforcement in illicit transactions tends to involve threats or intimidation, including extortion and violent action³⁰. Our framework does not focus on activity that is illegal but not intentionally hidden, because there tends to be no enforcement or two party contract required, such as cannabis in the Netherlands (above) or some examples of livestock foraging in protected areas⁴⁶.

Accounting for illicit transactions is challenging because they are intentionally hidden, leading to gaps in official data and field-based efforts to understand the transaction processes. Official data that attempt to track ‘the hidden’ are commonly not available for public use or are incomplete. Observations may also be unreliable when a highly sensationalized activity causes biases in reporting, such that lower or moderate levels of the same activity are missed elsewhere. Even more problematic is political manipulation of data regarding

illicit activities from authorities, who may be incentivized to hide activities they are formally charged to control or to tout the success of their controlling efforts. As a result, observations of illicit transactions are incomplete, fragmented and/or unreliable.

Primary data collection of illicit land transaction may be dangerous, even when the researcher builds long-term trusted relationships in the field⁴⁷. Anecdotes or side comments made in surveys only partially elucidate mechanisms of illicit transactions and tend to be specific to one location or community. Furthermore, mismatches occur on the spatio-temporal scales between the level at which illicit-land transactions are perpetrated and the scale of analysis engendered by the remote sensing data employed. Existing methods used to analyse illicit transactions produce diverse types of data (for example, ethnographies, material or capital flows, and social/organized criminal organization network structures) that are difficult to reconcile in space and time. These impediments notwithstanding, remote-sensing data could render illicit activity spatially and temporally explicit in some cases, providing a needed link for human environment systems analysis.

Identifying illicitness through remote sensing

A bevy of data and knowledge gaps surround examinations of illicit land transactions, as do various challenges of using remote sensing data to identify, monitor, explain and model land uses and their change spatially. An array of new and relatively unused data and analytical methods, however, is applicable to two principal approaches that are common to analyses that employ remote sensing data to address these transactions. We label the two ‘pixelizing the social’ and ‘socializing the pixel’ (Fig. 2) as a useful heuristic to understand distinct approaches to the problem at hand, borrowing from their use in previous remote sensing assessments of land-use change⁴⁸.

The pixelizing approach entails knowing that the observed land cover (that is, biophysical character of the land surface) in the remotely sensed data is associated with a land use or social process (Fig. 2). Given initial knowledge of the key drivers at play, alternative inferences are formed about the land outcome of interest under varying contextual conditions. Data are collected on contextual and causal factors that could explain variation in observed land outcomes. Causal inference and correlation methods (most commonly, regression) provide a partial inference into how outcomes vary as the consequence of the variables operating in heterogeneous conditions. The influences of conventional (and licit) causes of land-use change must be accounted for first in order to isolate and quantify the potential contribution of illicit activities to the amount or pattern of land change. If there is sufficient spatio-temporal data of illicit transactions (or a proxy) to allow empirical hypothesis testing, then this ‘pixelizing’ approach can move forward. If the link between illicitness and their land outcomes is unknown, however, then the ‘socializing’ approach may be a more appropriate starting point (below).

A few pixel-based approaches addressing illicit land change have been undertaken. These include studies of the eradication of illicit coca plantations via government reports on forest regrowth⁴⁹ and classifying aerial photographs of coca production and correlating growth areas to deforestation in multi-level regression models⁵⁰. Fixed effects models — which control for omitted variable bias for time-invariant factors⁵¹ — are especially useful to test hypotheses that illicit activities influence variation in land change outcomes over time above and beyond ‘licit’ or conventional drivers of change⁵².

Gaps in official data for illicit transactions have hindered the use of pixel-based approaches. New data and extant methods, however, could fill this gap, including high resolution spatio-temporal satellite data; initiatives such as The Panama Papers that open, leak or digitize data from governments and companies; or records of

human activity online from Twitter and news media⁵³. These data can in turn be used in causal inference methods that are already used to study land uses and cover including fixed effects regression, difference-in-differences and matching^{54,55}, to attribute spatial and/or temporal patterns to illicit transactions. Investigator risks notwithstanding, methods to link survey data to parcel level land uses to investigate licit land-use change can be used to address illicit transactions. Although pixel-based approaches estimate the influence of illicit transactions on land change, socializing approaches better elucidate decision making and behavioural mechanisms to explain how illicit transactions cause land change.

The socializing approach leverages process-based insights that are informed by logical inferences to link human activities to observed land cover. Process-based insights may come from empirically based hypotheses and theory, or ethnographic and other expert knowledge. In cases in which illicit transactions are known to exist and logical inference indicates a link to land outcomes, systematically associating process with specific land-use patterns (especially anomalous patterns) helps identify illicit land-use change. Methods using this approach to identify illicit activity in observed land change include commodity chain analysis⁵⁶, event processing tracing⁴⁴, agent-based models (ABMs) or pattern analysis⁵⁷.

Advances in relating land-use patterns directly to social processes tend to be driven by remote-sensing data. Unusual timing, type, shape, location or a combination of land-use change outside of the expected mean spatial temporal pattern can be identified via spatial-temporal outlier analysis⁵⁸, which is already used in remote sensing (for example, BFAST⁵⁹) epidemiology and crime studies (for example, Knox and ESDA⁶⁰). Given initial assumptions about the structure of variable or factor interactions, alternative explanations are developed about illicit activities and their outcomes over space or time. Data (for example, illicit commodity flows, permits, field observation, and the media) are assembled to establish whether landscape pattern outliers are attributable to illicit transactions.

A variety of methods exist to render this information spatially explicit via land change simulation models, such as ABM. Recognizing their limitations⁶¹, ABMs can codify decision-making processes and interactions among actors in the ‘action area’ (Fig. 1) to produce testable causal explanations of observed patterns of land change⁶². This approach has recently been used in the context of illicit transactions⁶³.

Innovative means of establishing the logical inferences of illicit land transactions are underway. In rare cases, various documents and cadasters may exist that allow a direct link between an actor that engages in illicit or clandestine transactions and third parties who register land titles. For example, ethnographic and media data have been integrated to estimate value captured by actors from transporting cocaine and associated land changes in eastern Honduras⁵⁶. Cadastral data are useful when land or permits are held legally by a third party, commonly a relative or an off-shore shell company. Linking the legal landowner or shadow business to an illicit actor may require leveraging data from crime records, media, business databases or ethnography. Such information, however, tends to be spatially limited, reducing the generalizability to study landscapes systematically.

Methods such as event process tracing from political science, commodity chain analysis from economic geography, anomalous transaction identification from finance, and investigative journalism may be useful as well. Event process tracing follows chains of records of official transactions searching for anomalies⁴⁴. Commodity chain analysis is used to understand how, why and where illicit capital is captured in spaces where goods are produced, transported and consumed⁶⁴, and how variations in illicit capital capture may lead to land-based investments⁵⁶. Financial studies use statistical analysis of outliers and artificial intelligence pattern recognition⁶⁵ to identify fraudulent transactions. Investigative journalism has used network

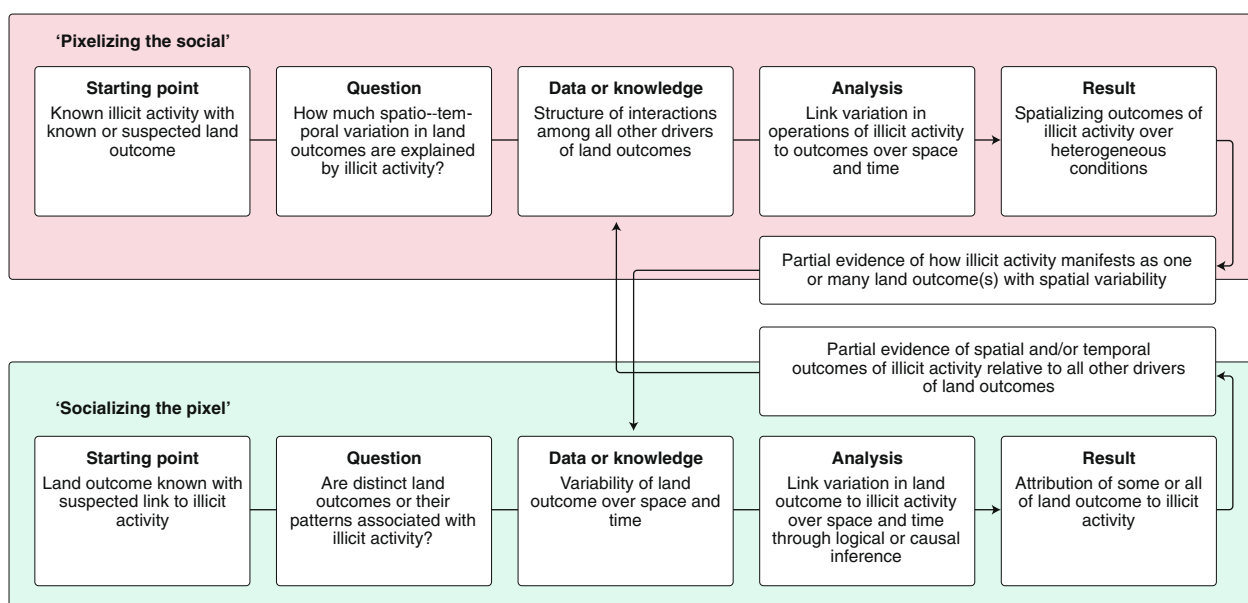


Fig. 2 | Two approaches to address illicit land transactions involving remote sensing data. 'Pixelizing the social' and 'Socializing the pixel' are shown in pink and green, respectively.

analysis to link documented perpetrators of illicit activity to land ownership of parcels by using cadasters or permit data. Examples include linking lesser-known members of a cartel to specific land parcels in the Petén⁶⁶, as well as connecting linked illegal palm oil permits and shell companies with electoral dynamics in Indonesia⁶⁷. Researchers could make better use of investigative journalism efforts and systematize these reports at landscape scales (for example, ref. ⁵³).

Pixelizing and socializing approaches should inform one another to build understanding (Fig. 2). Leveraging both approaches to triangulate and overcome weaknesses in each is essential to overcome the two major challenges when studying illicit activity; fragmented and/or unreliable data, and incomplete understanding of decision processes leading to environmental change.

Narco-deforestation

Moist tropical forest loss has increased, with the rates of loss high in Guatemala, Nicaragua and Honduras⁶⁸. Researchers noticed a new pattern of large, rapid forest clearing over the past decade in remote protected and indigenous areas²⁰. Ground studies and expert opinion led to the logical inference and subsequent observations that linked this deforestation to narco-trafficking activities. Traffickers acquired (and in some cases transformed) land as sites to move cocaine through Central America, and laundered a portion profits in cattle, oil palm and other land-based activities. Traffickers in some cases gained rights to frontier spaces illicitly, clearing the land to lay claim to territory and gaining political and economic capital for their activities⁶⁹.

These data and observations generated the inference that deforestation by narco-trafficking in Central America generates a distinctive land-cover pattern — rate, shape or absolute/relative location — from that exhibited by the aggregate actions of smallholders in the same area (Fig. 2b, socializing approach). This inference was tested by establishing variables to measure the observed spatial patterns using a ready to analyse Hansen Forest Loss data set⁷⁰. Sesnie and colleagues⁵⁷ developed spatial and temporal pattern metrics for patches of forest loss for each country in Central America and used a clustering algorithm to identify statistically 'unique' groups of deforestation. This method found 'anomalous' deforestation in several departments of Nicaragua,

Honduras and Guatemala, accounting for 15–30% of forest loss in the region from 2000–2014.

Causally connecting this pattern to the process of narco-trafficking required associating cocaine flow estimates to spatial units (pixels) and testing for significant correlation between kilos of cocaine and anomalous deforestation patterns over time (Fig. 2, pixelizing approach). Yet more stringent tests (Before After Control Impact) revealed that only in Honduras was the increase in these anomalous patterns important post 2005, the date cocaine transit dramatically shifted away from the Caribbean littoral and into central America, owing to the increased interdiction in Mexico and the Caribbean around 2006. This provided partial evidence that anomalous patterns were linked to drug trafficking, but did not discount the possibility that other licit processes could lead to the same pattern.

Estimating the relative role of licit and illicit drivers of forest loss required gathering additional proxies of narco-trafficking activity by spatializing media content analysis, digitizing government records of environmental crimes and systematizing spatio-temporal ethnographic knowledge. Each narco-proxy variable was linked to pixelized data of annual forest cover change by summarizing both social and land change variables at the same administrative unit. Fixed effects panel models then quantified the influence of the narco-trafficking activity in comparison with, or as an acceleration of, conventional drivers of forest loss in the region⁷¹.

The outcome of this regression model (coefficients on socioeconomic variables) informed an ABM⁶³, providing evidence for the rule sets for where and under which conditions narco-traffickers are more likely to clear land. The ABM was also informed by illicit commodity chain analysis from sparse data and comparisons of ethnographic case studies across Central America. Results from this 'NarcoLogic' model tested alternative hypotheses of narco-trafficking network operation, illuminating spatial dynamics of social process that causal inference models could not provide. Indeed, the NarcoLogic model revealed the nature of trafficking networks as complex adaptive systems that co-evolved with counterdrug forces and their interdiction efforts.

Developing this empirical evidence to demonstrate where and how cocaine trafficking influences land change in Central America required both pixelizing and socializing approaches (Fig. 2), generating new data and methods that will probably mark research efforts

that are applied to other illicit land transactions. The high degree of uncertainty in spatial and temporal measurement and extreme non-stationarity of illicit transactions such as drug trafficking challenge this work. The approaches outlined here, however, have the potential to push the methodological frontiers of linking landscape patterns to illicit processes forwards.

A more expansive understanding of land change

Narco-deforestation is far from the only type of illicit transaction that influences land uses/covers and their change. Some contemporary, illegal land grabs, informal urbanization, land zoning change and other types of illicit transactions affect landscapes worldwide. These transactions remain largely unaccounted and unmeasured but are important for global environmental change and sustainability models. Deriving insights from the data produced by satellite and citizen sensors⁷², the computing power that is capable of separating the signal from the noise in ready-to-analyse time series, and improving the culture of data access and transparency all provide fertile ground to bring previously unexamined or heretofore-undetectable land system signatures of illicit transactions to light.

Research on illicit activities in general has unique safety, ethical and social-justice implications for the collection and dissemination of data. Journalists that document illicit activities such as cocaine trafficking and environmental crimes have been targeted and killed⁷³. Researchers have an obligation to provide insights about the problem at hand without causing harm to themselves or others, primarily by keeping specific actors and places names anonymous. Studies of illicit transactions can shed light on the root causes of environmental change by highlighting the powerful actors who often go unrecognized, potentially absolving marginalized populations that are often blamed or even criminalized for activities over which they have little agency⁷⁴. Releasing spatially explicit data regarding illicit transactions, however, can harm marginalized communities, such as informal settlements⁷⁵, if a government uses the information for evictions or to cut services. Identifying specific locations of deforestation that are likely to be related to narco-trafficking can assist law enforcement to aid interdiction activities. Drug interdiction can have adverse consequences on local communities and push trafficking activities into other areas, as in the case of Central America⁶³.

Beyond such ethical concerns, further steps are needed to better address illicit transactions affecting land use. Explicitly examining how they shape landscapes requires bridging large and small divides existing between research communities (such as political ecology and land system science⁷⁶) as well as closer collaborations with research fields that address illicit behaviour, but are not necessarily focused on spatially explicit land–environment interactions. For example, political science has emphasized the mechanisms by which government officials differentially enforce land-use policies to key groups to maintain their electoral allegiance⁴⁴. This work, however, tends to lack a spatial component on which much land–environment research is anchored. Similarly, studies from criminology have examined the spatial displacement of drug trafficking activities in response to law enforcement actions⁷⁷, but have not linked spatial shift in drug trafficking activity to subsequent changes in land use. Efforts to better spatialize the mechanisms and consequences of illicit transactions in livelihoods research and conservation criminology³⁴ could also yield new insights into what shapes land change and how it could be regulated under different conditions. Methods to identify illicit financial transaction patterns could be borrowed to identify anomalous land use patterns and potential illicit transactions with remote sensing data.

The framework presented here distinguishes the institutional characteristics that constitute illicit land transactions. Pursuit of the identification of these transactions can be enhanced through the use of new, spatially explicit data that are applied to extant methods. The broader dynamics associated with illicit land transactions con-

stitute a lacuna that, given sufficient attention and addressed appropriately, should improve models of land-use change, with important implications for global environmental and sustainability concerns.

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Competing interests

The authors declare no competing interests.

Additional information

Correspondence should be addressed to B.T.

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