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Subnational institutions and power of landholders drive illegal deforestation in a major commodity production frontier

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A R T I C L E I N F O

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A B S T R A C T

Deforestation is a main threat to the biosphere due to its contribution to biodiversity loss, carbon emissions, and land degradation. Most deforestation is illegal and continues unabated, representing around half of the total deforestation in the tropics and subtropics. Quantifying illegal deforestation is challenging, let alone assessing the social and institutional processes underlying its occurrence. We tackle this challenge by quantifying the relative influence of individual (i.e., landholders' power, landholding size) and contextual (i.e., subnational institutions, agricultural suitability) factors on the type and size of illegal deforestation in the Argentine Dry Chaco, a major commodity production frontier and global deforestation hotspot. We build a Bayesian network fed with data of 244 illegal deforestation events, obtained from journalistic articles, grey literature, key informant interviews, and geospatial analyses. The results reveal that more powerful landholders were associated with larger illegal deforestation events. Policy simulations suggest that higher concentration of land in the hands of powerful landholders and more flexible subnational forest regulations would escalate illegal deforestation. This points to the need for a smart policy mix that integrates across economic, agricultural, and environmental sectors to halt illegal deforestation at commodity production frontiers. A land tenure reform can facilitate forest protection, while incentives to land-use diversification and the criminal prosecution of illegal deforestation are critical to shift landholder behavior towards more balanced production and conservation outcomes.

1. Introduction

Deforestation is a major threat to the biosphere and continues unabated, despite substantial efforts to curb the high deforestation rates (Curtis et al., 2018). The need to halt deforestation is urgent in light of its contribution to climate change (Fargione et al., 2008; IPCC, 2014; Rajão et al., 2020), biodiversity loss (Fahrig, 2003; Mastrangelo and Gavin, 2012; Tilman et al., 2017) and land degradation (Haddad et al., 2015). Deforestation also has manifold health and social consequences, like rising incidence of infectious diseases (Burkett-Cadena and Vittor, 2018;

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Patz et al., 2004; K. F. Smith et al., 2014), rural exodus, often accompanied by violence (Aldrich et al., 2012; Cáceres, 2015; London and Kelly, 2007), and land ownership concentration (Aguiar et al., 2016; Cotula et al., 2009; Galaz et al., 2018). Policies and governance actions aimed at reducing deforestation have only been partially effective, as around half the deforestation in commodity production frontiers of the Global South is illegal (Dummet and Blundell, 2021; Margono et al., 2014; Rajão et al., 2020).

Previous studies have mostly focused on explaining the magnitude, location, and timing of deforestation (i.e., the "how much", "where" and "when" questions), while descriptions of the agents and the social and institutional processes that enable illegal clearings (i.e., the "who" and "how" questions) have lagged behind. There is a vast literature on the spatial determinants that associate the location of deforestation with biophysical characteristics and road accessibility (Gasparri et al., 2015; Müller et al., 2012; Volante et al., 2016). Also, the impact of demographic change and land use policies on the spatial and temporal variability of deforestation are increasingly well understood (Carr et al., 2009; Schlesinger et al., 2017; Tesfaw et al., 2018). These studies rely on time-series of remotely sensed deforestation that are coupled with exogenous explanatory variables, such as population and economic data, to identify broad patterns of association. As such, these studies implicitly assume that deforestation agents (e.g., private landholders) respond passively to the contextual factors that shape their profit maximization goals (e.g., agricultural yields, returns to production). While this conceptual model has considerable explanatory power in some contexts, there is a need to better understand the influence of human agency and strategic action of agents on the occurrence of deforestation (Berbés-Blázquez et al., 2016; Verburg et al., 2019). The pathways that connect the individual and contextual factors underlying deforestation events have rarely been contrasted with quantitative hypothesis testing. This is particularly needed at the landholding level in highly dynamic commodity production frontiers, where the relationship between agents, institutions, and deforestation is more driven by *de facto* governance (i.e, what happens on the ground) than by *de jure* governance (i.e., what is stated in the legal framework) (Nansikombi et al., 2020).

Quantifying the share of illegal deforestation in total deforestation is challenging, let alone assessing the social and institutional processes underlying its occurrence (Gore et al., 2019; Tellman et al., 2020). Estimates of illegal deforestation in major commodity production frontiers suggest that between 40% (Lawson, 2014) and 69% (Dummet and Blundell, 2021) of deforestation is linked to illicit activity. In Indonesia, 40% of deforestation between 2000 and 2012 was reported to be illegal (Margono et al., 2014). In Central Africa, illegal logging represented nearly 90% of total deforestation (Lawson, 2014; Siebert and Elwert, 2004). Nearly half of the properties in the Amazon and Cerrado of Brazil are non-compliant with the Forest Code, and hence deemed illegal (Rajão et al., 2020), while others estimate illegality to reach 60 to 80% in the Amazon (Boekhout van Solinge, 2014.). In the Argentine Dry Chaco, estimates of the proportion of illegal deforestation range between 28% (Vallejos et al., 2021) and 44% (our own estimations based on UMSEF-MAyDS, 2019), depending on the period considered.

Over the last four decades, the Argentine Dry Chaco has displayed a dynamic that is illustrative of other South American regions that are oriented to export commodity production, such as the Brazilian Cerrado, the Bolivian Chiquitania, and the Paraguayan Chaco (Baumann et al., 2016; Hansen et al., 2013; Nolte et al., 2017a). In the last two decades, a combination of macroeconomic, technological, and climatic changes stimulated the arrival of soybean farmers, cattle ranchers, and land investors from richer neighboring regions, especially the humid Pampas (Gasparri et al., 2013; Paolasso et al., 2012). As a result, the Argentine Dry Chaco became a global deforestation hotspot with provincial annual deforestation rates above 3% until 2008 (Camba Sans et al., 2018), 15 times higher than global averages (0.2%).

In response to the huge rates of deforestation, the Argentine government passed a Forest Law in 2007 which dictates minimum standards of forest protection and delegates to the provinces the design and enforcement of land-use zoning plans of their native forest lands. Between 2008 and 2011, land-use zoning plans in the Argentine Dry Chaco provinces came into force allocating 21% of the native forest lands to protection (red zone), 57% to sustainable use (yellow zone), and 22% to potential agricultural expansion (green zone) (MAyDS, 2017). Despite minimum standards dictated by the national law, successful lobbying from the agricultural sector resulted in heterogeneous designs and enforcement of the land-use zoning across provinces (García Collazo et al., 2013; Milmanda and Garay, 2019). The effectiveness of decentralized forest governance in the Argentine Dry Chaco is a subject of an intense debate (Camba Sans et al., 2018; Nolte et al., 2017b; Volante and Seghezzo, 2018). Existing evidence suggests that subnational governments play a fundamental role in shaping deforestation outcomes; however, how these institutional contexts influence the occurrence of illegal deforestation at the landholding level remains an open question.

Since the enactment of land-use zoning plans, the agricultural sector lobbied provincial governments for violating the National Forest Law, and found different mechanisms to achieve this goal (Aguiar et al., 2018; Cabrol and Cáceres, 2017; Seghezzo et al., 2011). For example, the governments of the provinces of Salta and Chaco allowed landowners to request downgrading of the conservation category of their landholdings, from protection (red) or sustainable use (yellow) zones to deforestation permitted (green) zone, under the argument of the presence of native forests with high agricultural suitability within their landholdings (Nolte et al., 2017b). Also, provincial governments allowed roller-chopping (i.e., mechanical clearing of forest understory to develop pastures with scattered trees) in lands with high agricultural suitability, even in areas that had been allocated to the sustainable use zone. The agricultural sector promoted this land-use system under the label of "sustainable silvopastoral use" but in effect it resulted in open pastures due to the high mortality of the remnant, isolated trees after roller-chopping and fire (Fernández et al., 2020; Nolte et al., 2017b). We hypothesize that both the subnational institutional context and the agricultural suitability of the landholding are crucial determinants of the type of illegal deforestation.

As most environmental legislation in the Global South, Argentinés Forest Law and provincial land-use zoning plans are implemented in a highly heterogeneous socio-economic and cultural context. Large variability in landholding size and gross profit per hectare characterize the Dry Chaco region (Mastrangelo et al., 2019), indicating strong power asymmetries among landholders (Richards et al., 2003; Sundström, 2016). Powerful landholders can have large influence on provincial governments and modify existing norms (e.g., downgrading of conservation category) and/or avoid sanctions from noncompliance. For example, a large landholder from Salta province deforested 11,000 ha in the sustainable use zone in 2013. This landholding contained forestlands traditionally used by indigenous people (a common situation in Salta, Vallejos et al., 2020), who were excluded from these lands after they were converted into soybean monocultures. The government of Salta sanctioned the landholder with fines, conditional imprisonment, and the obligation to restore deforested lands, but this sanction has been only partially fulfilled and has not deterred further illegalities (Aguiar et al., 2018). Thus, the size of illegal deforestation might be influenced by the power of the deforestation agent, in close interaction with subnational institutions.

The question that motivates this research is how individual (i.e., social and economic) and contextual (i.e., institutional and biophysical) factors influence the size and type of illegal deforestation events in the Argentine Dry Chaco. To answer this question, we collected data of 244 illegal deforestation events that capture any kind of loss of native forest that was in violation of Argentinás Forest Law. All events are linked to landholdings located in the Chaco region of the provinces of Chaco, Salta, or Santiago del Estero between 2008 and 2020. We rely on four complementary sources of information: investigative journalism and media reports, grey literature, interviews with key informants, and geospatial data. We used non-parametric Bayesian networks to test the relative influence of nine individual and contextual factors on the size of deforestation and the type of illegality as the two outcome variables. We also assess how both outcomes would change under hypothetical yet plausible policy simulations.

2. Methods

2.1. Study area

The South American Gran Chaco contains the largest continuous Neotropical dry forests (Portillo-Quintero and Sánchez-Azofeifa, 2010), most of which (60%) is in the north of Argentina. The Argentine Dry Chaco is a large sedimentary plain covered by xerophytic vegetation, originally with forests, grasslands and shrublands interspersed across the landscapes (Cabido and Zak, 1999). The climate is subtropical with a dry season, the rains are concentrated in the summer, and the driest months are July and August (Peel et al., 2007). Annual rainfall varies between 400 and 600 mm in the core of the region and 800–1000 mm towards the ecotones with Yungas rainforest in the west and the Humid Chaco in the east, and the annual average temperatures range between 19 and 22 °C (Murphy, 2008). The Argentine Dry Chaco harbors a high biodiversity (Bucher and Huszar, 1999; Giménez et al., 2011), as well as large carbon reservoirs (Baumann et al., 2016).

In the Argentine Dry Chaco, the primary sector represents a high share of the GDP (MEFP, 2012), more than double the national average, triple that of Brazil, and similar to Bolivia and Paraguay (Nolte et al., 2017a). The Argentine Dry Chaco has been traditionally inhabited by peasant mestizo and indigenous people that carry out small-scale

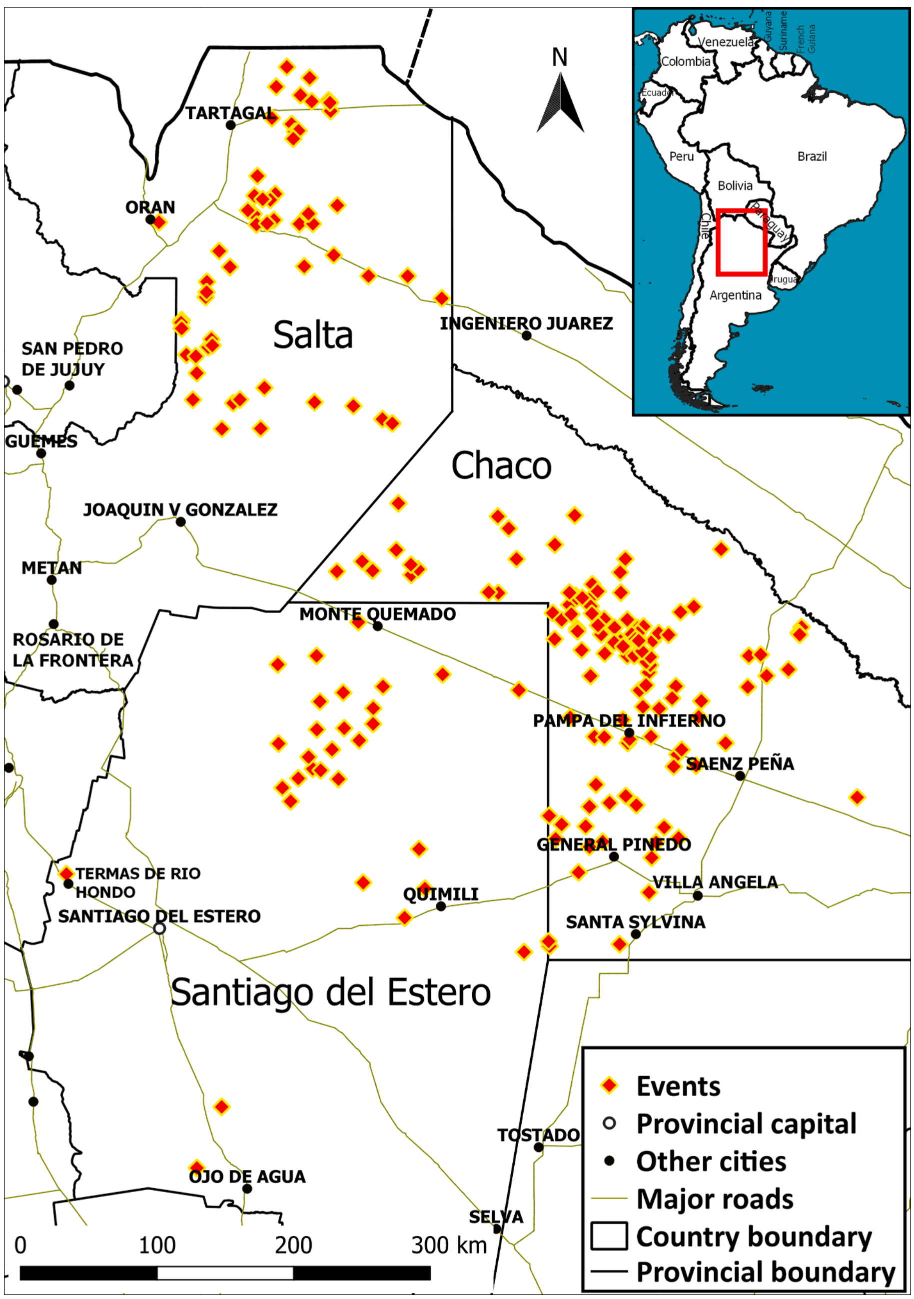

Fig. 1. Spatial distribution of surveyed illegal deforestation events (red dots) in the Argentine Dry Chaco. Inset: location of the study area in South America. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

agriculture and livestock raising, wood extraction, charcoal production, hunting and gathering (Aguiar et al., 2016). Mestizo and indigenous people typically have insecure land tenure in the form of pre-titles or possession titles (Reboratti, 2008; Slutzky, 2005). The region also has the highest indices of unsatisfied basic needs in Argentina (Bolsi et al., 2009; Torrella and Adámoli, 2005). In the last three decades, the Argentine Dry Chaco has been the scenario for the rapid expansion of agricultural commodity production (mainly soybean and beef) coupled with land privatization and large-scale deforestation (Faingerch et al., 2021; Gasparri and Grau, 2009). The three study provinces of the Argentine Dry Chaco (i.e., Chaco, Salta, and Santiago del Estero, Fig. 1) contained almost 70% of Argentina's deforestation during 2016 and 2017 (AGN, 2017; Gómez Lende, 2018; Vallejos et al., 2015).

2.2. Definition of illegal deforestation

Deforestation events were considered illegal when clearings were non-compliant with the higher-order political regulation, which in this case is the National Forest Law of Argentina. This classification of "illegality" is identical to other salient assessments of deforestation in the Argentine Chaco region (Camba Sans et al., 2018; Ceddia and Zepharovich, 2017; Nolte et al., 2017b; Vallejos et al., 2021; Volante and Seghezzo, 2018). More specifically, a clearing was considered illegal when it occurred in areas that provincial authorities categorized as of being of medium or high conservation value (the so-called yellow and red zones, respectively). In these protected zones, clearings are not allowed according to the National Forest Law. Also, a clearing was considered illegal when it occurred in an area of low conservation value (green zone), but without permission from the legal authority, or over an area larger than that permitted by the authority.

Under this definition, deforestation in landholdings for which provincial authorities downgraded their conservation category (from high or medium to low conservation value, i.e., from red or yellow to green) was considered illegal. Higher-order authorities (i.e., the Ministry of Environment and the Federal Environment Council) established that downgrading by provincial authorities violate the principle of non-regression, and thus clearings on land that was downgraded to a lower conservation status are non-compliant with the National Forest Law (Di Pangracio et al., 2014). Indeed, governor decrees allowing downgradings had to be revoked in Salta and Chaco provinces after public campaigns led to interventions by the national government (Di Pangracio and Cáceres, 2020). Both political and social regulations on deforestation in downgraded areas were high; thus, deforestation events occurring under this mechanism should be considered illegal (Magliocca et al., 2021; Van Schendel and Abraham, 2005).

Similarly, roller-chopping in protected zones (yellow and red) is illegal because after this transformation the forest progressively loses its character, giving place to pastures with scattered trees (locally known as silvopastoral systems). As said, the higher-order political regulation established that forests must not be lost in protected zones, but in this case the provincial authority allowed the development of so-called silvopastoral systems in areas of medium conservation value (yellow zone), making use of its political power to complement the National Forest Law. Thus, provincial governments tolerated this type of illegal deforestation, which shifted the power balance towards agricultural stakeholders and production objectives. This illustrates that what is considered illegal is fluid rather than fixed (Magliocca et al., 2021; Van Schendel and Abraham, 2005), depending heavily on the changing contexts and power relations among stakeholders.

2.3. Data collection

We used multiple complementary sources of information to identify and characterize illegal deforestation events in the Argentine Dry Chaco in the twelve years from September 2008 (i.e., the sanctioning of the National Forest Law) to August 2020. Firstly, we collected journalistic articles published in this period through Google Search and Google Alerts using the keywords "*desmonte*" and "*deforestación*", which mean *clearing* and *deforestation*, respectively, in Spanish. This search yielded >2200 news, some of them from local newspapers and radio stations. We read all these journalistic articles and selected those that met two conditions: (i) described an event of illegal deforestation, and ii) the illegal deforestation event described occurred in the Argentine Dry Chaco between 2008 and 2020. Secondly, we reviewed grey literature (e.g., official documents, NGO reports) to validate and complement information from illegal deforestation events gathered in journalistic articles. Thirdly, we conducted semi-structured interviews with eight key informants, with the aim of (i) filling in missing information from illegal deforestation events, (ii) increasing the coverage of events in Santiago del Estero, where information was less available, and (iii) understanding the processes underlying the occurrence of illegal deforestation to select the variables and relationships to be included in the Bayesian network. We interviewed two former government officials from Chaco, two NGO researchers (one from Salta and one from Santiago del Estero), two rural extension agents (one from Chaco and one from Santiago del Estero), one NGO director from Chaco, and one scientific researcher from Santiago del Estero. In Salta, our key informant manages an exhaustive historical and georeferenced database, which allowed us to reduce the number of interviewees, while in Santiago del Estero we interviewed three key informants to fill in the data gaps. Interviews occurred between February and April 2019. Finally, we integrated the information from journalistic articles, grey literature, interviews with the key informants and geospatial analysis, and obtained a sample of 244 illegal deforestation events.

2.4. Bayesian networks

Bayesian networks (BN) are probabilistic models that explicitly capture conditional dependence among random variables with directed acyclic graphs (Jensen, 2001). The BN is a non-parametric statistical tool that can be used to conduct inference analysis and analyze the relative importance of a set of explanatory variables in terms of their ability to explain the variance of one or more target variables. A BN consists of two parts. First, a directed acyclic graph (DAG), also known as the structure of a Bayesian network, which describes the potential dependent relationships (which can be causal or an association) between the variables using arrows connecting nodes (which correspond to the variables). The second component are conditional probability tables (CPTs), also known as the parameters of a BN, which define the conditional probability distributions of the nodes given by the values of their parent nodes (nodes with direct arrows pointing to them). The CPT of a child node (where an arrow ends) contains the conditional probability of being in a certain state given the states of its parent node. Nodes are characterized for being discrete, mutually exclusive, and collectively exhaustive, and denote an attribute or hypothesis about an event with a set of state values in a context of uncertainty. Continuous variables must be discretized in a similar number of categories based on finding thresholds, the opinion of experts and statistical methods (Cobb et al., 2007).

The ability of BN to combine causal knowledge of experts with empirical data based on observations explains their increasing importance in environmental studies (Pollino et al., 2007; Ticehurst et al., 2011). BNs have several advantages (Sun and Müller, 2012; Uusitalo, 2007). First, BN allows us to deal satisfactorily with information gaps, which are frequent in socio-environmental problems. Second, by having a schematic component, the DAG facilitates the understanding of ideas by non-specialist public and improves the communication of the results. Third, BN allows the incorporation of qualitative information supplied by experts during the construction of the model, as well as quantitative and spatially explicit data. Fourth, based on Bayesian principle, BN can readily incorporate new evidence to continue revising the beliefs and improving the model. This can potentially make the network an evolving model with capability to incorporate new events in the future. Finally, BN allows simulating different scenarios by purposely modifying one or more variables while keeping the rest unmodified (Mastrangelo et al., 2019).

2.5. Construction of Bayesian networks

To build the DAG, i.e., to define the relationships between the variables, we rely on existing information and literature, and on our own knowledge and that of interviewed informants regarding the social-ecological processes underlying the occurrence of illegal deforestation in the Argentine Dry Chaco (Darwiche, 2008; Mastrangelo et al., 2019). We asked our interviewees to propose, through a scheme of boxes and arrows, which factors are involved in illegal deforestation and how they interact. The structure of the model contains the links raised in the hypotheses, and its parameterization based on the data collected allows these hypotheses to be tested.

Finally, to build the DAG we followed the principle of parsimony, by which we tend to have a functional model with the fewest possible entities (nodes or variables), in order to simplify the modeling (Chen and Pollino, 2012; Marcot et al., 2006). One of the methods in avoiding too many direct parent nodes in BN is the so-called divorcing technique, i.e., to create latent variables by combining parent nodes. For example, in our BN the variable *Landholderś power* is multidimensional and difficult to represent with a single variable, therefore it is measured through the aggregation of three variables, each one capturing a different dimension of the concept: *Links with political power*, *Economic capital* and *Origin of the agent*. Once the structure was defined, the model parameters (i.e., the CPTs) were calculated using the collected data. We built the model with Netica (https://www.norsys.com), a Bayesian network platform with user-friendly interface, intuitive visualization, and powerful functions.

2.6. Description of target variables

We focused on understanding what factors influence the size and type of illegal deforestation events (Table 1, Fig. 2). The size of the events is indicated with the variable *Landholding area deforested illegally*, which is a continuous variable and represents the number of hectares of native forests illegally cleared in a landholding. The *Type of illegality* is a categorical variable, and represents the mechanism used by landholders to clear forest illegally, violating the National Forest Law. It has four categories defined following our knowledge, that of interviewed informants, and Vallejos et al. (2021). *Clearing in protected zone* occurs when landholders deforest in areas of medium or high conservation value (yellow or red zones), or in green zones without permission from the provincial authority. *Clearing in downgraded areas* occurs when landholders deforest in landholdings for which the provincial authority downgraded its level of protection, in violation of the National Forest Law. *Undercover deforestation* occurs when landholders use provincial permissions to develop so-called sustainable silvopastoral systems for implementing clearings that leave less tree density than that required by law, which end up in total clearings after a few years. *Exceeded cleared area* occurs when landholders deforest an area of forest larger than that permitted by the provincial authority.

2.7. Description of influencing variables

In the BN, the size and type of illegal deforestation events are influenced by nine variables (Table 1, Fig. 2). *Institutional context* is a categorical variable that captures the institutions (i.e., legislations and their enforcement bodies) at the subnational level, and is indicated by the province where the illegal deforestation event occurs. *Landholderś power* captures the capacity of landholders to implement illegal clearings. Given the multidimensional character of power, it is a latent variable made up of *landholderś economic capital*, *landholderś origin* and *landholderś links with political power*. *Landholderś economic capital* describes the material assets owned and produced by the landholder that implements the illegal clearing. The categories for this variable were ´very high´, ´high´, ´medium´, and ´low´. We investigated whether each agent met the following conditions: (i) being in the highest income category, according to the Argentine Federal Tax system, (ii) owning landholdings in addition to the one where the illegal deforestation event occurred, (iii) having a high position in a medium-sized or large enterprise, and (iv) having investments in an agroindustrial sector other than primary production, such as processing or transport. *Landholder's economic capital* was categorized as very high when three of these conditions were met, as high when two conditions were met, as medium when one condition was met, and as low when none of these conditions was met. *Landholderś origin* indicates the place where the landholder that implements the illegal clearing comes from. *Landholderś links with political power* describes the strength of the ties between landholders and public officials and/or agencies in charge of implementing land-use or land-tenure regulations. The categories for this variable were ´strong´, ´weak´, or ´no´ links with political power. *Landholder's links with political power* were categorized as strong if the agent has or has had long-lasting government positions or family/personal ties with public officials. This was the case when, for example, a journalistic article stated that

Table 1
Description of variables included in the Bayesian network.

Variables and units	Description	Categories and distribution or Range	Median
Landholding area deforested illegally (hectares)	Landholding area of native forest that has been deforested violating the Forest Law	1–11,000	409
Type of illegality	Mechanism used by landholders to clear forest illegally, violating the Forest Law	Clearing in protected zone = 54% Clearing in downgraded area = 35% Undercover clearing = 8% Exceeded cleared area = 3%	
Institutional context	Province where the illegal deforestation event occurred	Chaco = 56% Salta = 28% Santiago del Estero = 16%	
Soil quality (%)	Index of soil productive capacity that integrates drainage, texture, organic matter content, depth, alkalinity, salinity and slope.	11–95	37
Annual rainfall (mm)	Mean rainfall between 1970 and 2000.	609–1210	821
Landholding size (hectares)	Area of the landholding where the illegal deforestation event occurred.	10–240,000	1940
Landholder's origin	Place where the landholder originates from.	Same province = 49% Non-neighboring province = 35% Neighboring province = 13% Other country = 3%	
Landholder's economic capital	Landholder's material assets and level of income	Very high = 29% High = 47% Medium = 14% Low = 10%	
Landholder's links with political power	Landholder's ties with public officials and agencies in charge of land-use regulations	Strong = 49% Weak = 13% No = 38%	

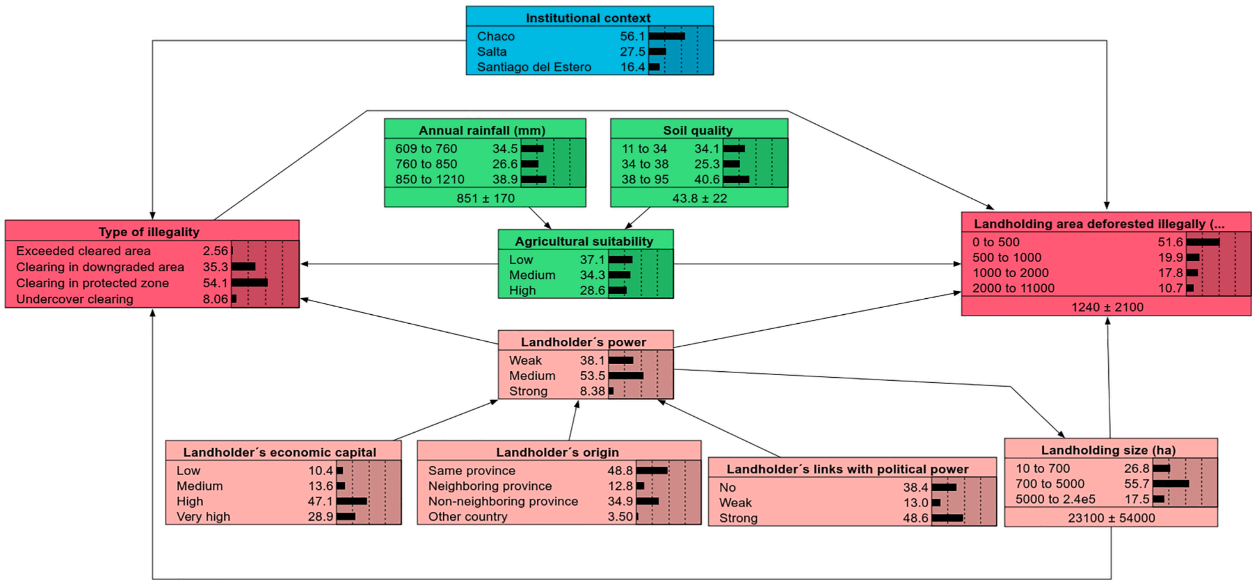

Fig. 2. Final Bayesian network with hypothesized relationships among influencing variables, and between these and the target variables *Landholding area deforested illegally* and *Type of illegality*. Target variables (red boxes) are influenced by biophysical variables (green boxes), institutional context variables (cyan box), and individual, agent-level variables (pink boxes). Horizontal bars in each node show the initial probability distribution of the variable. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

"*the farmer is a close relative of the head of the municipal government*". This variable was categorized as weak if the agent has had a one-off or sporadic relationship with government agencies. This was the case when, for example, an NGO document reported that "*the landowner did contract work in the provincial Forest Office in the previous administration*". When none of these conditions were met, the agent was categorized as having no links with political power. *Landholding size* is a continuous variable indicated by the number of hectares of the landholding where the illegal deforestation event occurred. *Agricultural suitability* is a latent variable made up of the *annual rainfall* and *soil quality* of the landholding where the illegal deforestation event occurred. *Annual rainfall* is the mean annual rainfall for the period 1970–2000 (Fick and Hijmans, 2017), while *soil quality* is the value of the soil quality index (INTA, 1990) which integrates drainage, texture, organic matter content, depth, alkalinity, salinity, and slope.

2.8. Validation, accuracy assessment and robustness check

The validation of a BN involves validating the model structure and its predictive power. The construction of the directed acyclic graph (DAG) and the discretization of continuous variables entails a substantial degree of subjectivity. We analyzed different configurations of the DAG, with different variables, which in some cases failed to explain in a robust way the occurrence of illegal deforestation. We conducted group discussions to better understand the opinions of the experts about the various processes underlying illegal deforestation The final model is parsimonious and contains the key variables and relationships, given that our goal is to identify the most influential factors behind different types and magnitudes of illegal deforestation, and not to maximize predictive accuracy.

The proposed BN contains the landholding *area deforested illegally* and the *type of illegality* as the target variables, which are influenced by nine variables through three main paths (Fig. 2). From the top-down, the *subnational institutional context* (i.e., provinces) influences the *size* and *type of illegal deforestation* events through its considerable leeway to interpret and implement the National Forest Law, and its ability and willingness to enforce land-use zoning plans. From the bottom-up, the *power* of individual landholders influences the target variables both directly (e.g., through lobby) and indirectly via the size of the landholding (i.e., a proxy for the volume of agricultural commodities exported). *Landholderś power* is a multidimensional variable made up of *landholderś economic capital, links with political power,* and *origin.* Finally, the *size* and *type of illegal deforestation* events are also influenced by the *agricultural suitability* of landholdings, which is made up of variables describing *soil quality* and *annual rainfall.*

We then performed quantitative analysis using the "k-fold cross validation" method to assess the accuracy of the model (i.e., how the model performs on the unknown events). Specifically, 80% of the data was used for training the model, and the other 20% was used for the model testing. The 244 events were randomly partitioned into five groups, i.e., k = 5. Four groups of the data were used to train the model, i.e., learning CPTs with the training data. The trained model was then used to predict the target variables (*type of illegality* and *area deforested illegally*). The predicted values were then compared to the observation values with a confusion matrix (Tables S1 and S2). The process was repeated to ensure every group has a chance to be acted as test data. To ensure the robustness of the validation, we conducted 5 rounds of cross validations with different random splits.

We used the trained and calibrated model to carry out four policy simulations, seeking to analyze what would happen in the target variables in hypothetical yet plausible scenarios. We conducted simulations by artificially changing the value distribution of influencing variables according to the policy narratives. We then compared the original values of the target variables with their simulated values. We tested the response of the landholding *area deforested illegally* to the following policy simulations: (i) *Large downgradings*, in which all illegal deforestation events occurred through clearing in downgraded areas, (ii) *Low enforcement*, in which all illegal deforestation events occurred through clearing in protected zones, (iii) *Land concentration*, with a shift in the distribution of landholding sizes towards a higher proportion of larger landholdings (i.e., 10–700 ha = 10%, 700–5000 ha = 30%, 5000–240000 ha = 60%), and (iv) *Large downgradings and land concentration*, with a combination of policy scenarios (i) and (iii).

3. Results

3.1. Illegal deforestation events

We obtained high data coverage for 244 events of illegal deforestation, which altogether involved the clearing of 275,592 ha of Chaco forests. This sample covers approximately 34% of the area deforested illegally in the provinces and the period under study. The average *area deforested illegally* per event was 1139 ha, with substantial differences among provinces, i.e., in Salta (2197 ha) was 1.2 times larger than in Santiago del Estero (1853 ha) and 5.5 larger than in Chaco (402 ha). The main *type of illegal deforestation* in the three provinces was clearing in protected zones, while more than a third of illegal deforestation in Salta (36%) and Chaco (37%) occurred through clearing in downgraded areas.

The average landholding *area deforested illegally* was 18 times larger in landholdings managed by landholders with high and very high economic capital and strong links with political power (2516 ha) compared to those managed by landholders with low capital and weak links with political power (141 ha), equivalent to 15% and 1% of the average landholding size, respectively. At the same time, the landholding area deforested illegally was 2.5 times larger in landholdings managed by extra-local landholders (1689 ha) compared to those managed by local landholders (685 ha). Deforestation events executed by powerful landholders occurred mainly through clearing in protected zones (50%) and clearing in downgraded areas (46%). All deforestation events in downgraded areas were executed by powerful landholders.

3.2. The Bayesian network

As for the model performance, the average error rate based on the confusion matrix in the cross validation was consistently around 30% (standard deviation 13%, 95% CI) for the target variable *type of illegality* and 38% (standard deviation 11%, 95% CI) for the target variable *landholding area deforested illegally*. These error rates are acceptable considering the parsimoniousness of the model, which has only nine influencing variables to represent the complex network of relationships underlying the occurrence of illegal deforestation, which is a highly heterogeneous and uncertain social phenomenon. Besides, very low error rates are not always preferable, as these may point to overfitting of the model. Lastly, both target variables have four categories each, and it is challenging to accurately predict the exact categories with our parsimonious Bayesian network. In the case of the landholding area deforested illegally, many of the incorrectly predicted areas were

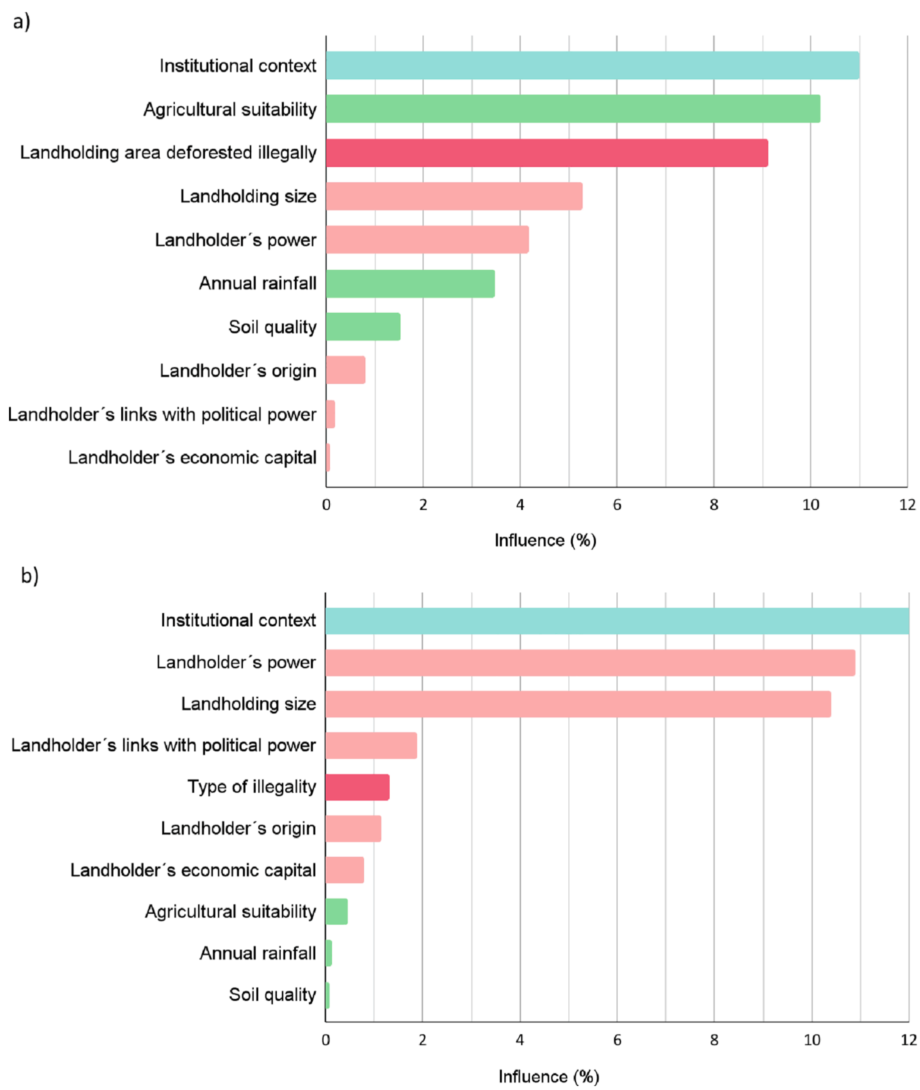

Fig. 3. Influencing variables in the type of illegality (a) and the landholding area deforested illegally (b). Red bars show target variables, green bars show biophysical variables, cyan bars show institutional context variables, and pink bars show individual, agent-level variables. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

assigned to adjacent categories.

3.3. Sensitivity analysis

The influencing variables analyzed in the model explained 46% of the variation in the *type of illegality* and 39% of the variation in the landholding *area deforested illegally* (Fig. 3). The *type of illegality* was mainly influenced by the subnational institutional context (11%), followed by the agricultural suitability of the landholding (10%) in which the deforestation event occurred (Fig. 3a). The landholding *area deforested illegally* was also mainly influenced by the subnational institutional context (12%), but the next influencing variables were related to individual characteristics of the landholder, that is, its power (11%) and the size of its landholding (10%) (Fig. 3b).

3.4. Policy simulations

The simulations suggest that a policy promoting large downgradings would increase the proportion of medium-size deforestation events (500–1000 ha) by 12% and of large deforestation events (1000–2000 ha) by 6%, while it would reduce the proportion of small deforestation events (0–500 ha) by 17%, compared to the situation without simulation (BAU scenario, Table S3). In turn, weakening the enforcement of land-use zoning plans (i.e., subnational governments being permissive with clearings in protected zones) would increase the proportion of small deforestation events (0–500 ha) by 11%, while having a small impact (5–6%) on medium to large deforestation events (Table S4). A land policy allowing further increases in landholding size (i.e., land concentration) would have a small impact on the type of illegal deforestation events but a considerable impact on its size, as the proportion of large deforestation events (1000–2000 ha) would increase by 7% and of very large deforestation events (2000–11,000 ha) by 14% (Table S5). Finally, a policy combining large downgradings and the concentration of land in fewer hands would increase the proportion of large and very large deforestation events by 14% and 18%, respectively (Table S6).

4. Discussion

Tropical and subtropical deforestation for the expansion of commodity production frontiers is a major driver of biodiversity loss, climate change, and land degradation (Curtis et al., 2018). Anti-deforestation policies have demonstrated limited effectiveness and illegal clearings continue unabated (Börner et al., 2020; Dummet and Blundell, 2021; Rajão et al., 2020). Institutional context and power dynamics underlying illegal deforestation have remained understudied, despite their key role in shaping conservation policy outcomes (Berbés-Blázquez et al., 2016; Milmanda and Garay, 2019). Here we contribute to filling this knowledge gap by quantitatively assessing the influence of individual (power) and contextual (institutions and environment) factors on the type and size of illegal deforestation events in the Argentine Dry Chaco, a major commodity production frontier and global deforestation hotspot (Hansen et al., 2013). We modelled these relationships with a Bayesian network fed with empirical data from 244 illegal deforestation events occurred during the implementation of the National Forest Law and provincial land-use zoning plans (2008–2020) in three core Chaco provinces: Chaco, Santiago del Estero, and Salta.

Four key findings emerge from this analysis. First, both contextual and individual factors shape illegal deforestation outcomes and explain almost half of the variation in the type and size of illegal deforestation events. Second, the subnational (provincial) institutional context largely determines the way in which illegal deforestation events are produced, and the size of those events. Third, subnational institutions drive illegal deforestation events differently, depending on the agricultural suitability and size of the landholding as, for instance, clearings in downgraded areas in Salta and Chaco provinces occurred in larger landholdings with more suitable land. Fourth, the power of landholders is highly influential for the size of illegal deforestation events, as more powerful landholders deforest larger areas. These findings have implications for reforming the design, implementation, and monitoring of anti-deforestation policies in the Argentine Chaco, but are also relevant for other commodity production frontiers.

Modelling complex social and institutional phenomena, such as illegal deforestation, commands some level of simplification in model design, which tends to increase the model error. In our model, we chose to categorize the type of illegal deforestation following the National Forest Law, as done in other studies (Camba Sans et al., 2018; Ceddia and Zepharovich, 2017; Nolte et al., 2017b; Vallejos et al., 2021; Volante and Seghezzo, 2018). Given the leeway of subnational governments for implementing the law, some nuances in the provincial definition of illegality may not be captured in the model design. Thus, the attribution of influential factors to the different types of illegal deforestation adds to the model error. More certainty can be gained by comparing the impact of influential factors on illegal vs. legal deforestation. Unfortunately, the effects of individual, agent-level factors on deforestation have not been examined in the Argentine Chaco before this study. Nevertheless, this kind of factors are expected to have a weaker influence on overall and legal deforestation, as the issue of legal permits is subject to more accountable and less arbitrary processes, compared to illegal deforestation.

Our study adds critical evidence to the regional and global debate over the effectiveness of decentralized policies to combat deforestation. Whether subnational governments are willing and able to reduce deforestation has remained controversial but understudied (Torrella et al., 2018). In the Argentine Chaco, Nolte et al. (2017b) assessed the impact of decentralized policies on deforestation and concluded that the delegation of design and enforcement to subnational (provincial) governments has been effective at protecting forests, while Camba Sans et al. (2018) showed that it could not reduce illegal deforestation. Using the same dataset as Nolte et al. (2017b), Volante and Seghezzo (2018) reported that illegal deforestation in the protected (yellow and red) zones was even higher than legal deforestation in the non-protected (green) zone during the early implementation of the Forest Law (2008–2014). Focusing on the same three Chaco provinces assessed by Nolte et al. (2017b), we showed here that the type and size of illegal deforestation events from 2008 to 2020 differed between provinces and that such variation was mainly explained by the subnational institutional context. Thus, the two latter studies identify the low enforcement capacity of subnational governments and high levels of non-compliance of landholders with forest conservation policy as key causes for the high deforestation rates.

The lack of interest and/or capacity of subnational governments to protect forests has been associated with several factors, among them the economic dependence of provincial States on taxes from export sales, which confers considerable power to landholders that produce agricultural commodities for export (Alcañiz and Gutierrez, 2020; Seghezzo et al., 2011). Milmanda and Garay (2019) argue that executive (governors) choices for the design of the land-use zoning plans and their enforcement depend on the relative power of large landholders and conservation coalitions. They propose that (i) where provincial conservationist groups are strong, governors design and enforce strict regulations (i.e., in Chaco province), (ii) where both groups are powerful, governors design strict regulations but their enforcement is low to satisfy the demands of large landholders (i.e., in Santiago del Estero province), and (iii) where conservationists are not organized and landholders are influential, regulations are permissive and weakly enforced (i.e., in Salta province). In contrast, we found that enforcement of forest zoning plans has been homogeneously low as clearing in protected zones represented more than half of the area affected by illegal deforestation in all three provinces. In addition, we found that in two out of three provinces (Chaco and Salta) governors changed regulations to make them more permissive. They allowed clearings of downgraded areas in medium to large landholdings with more agriculturally suitable lands. Therefore, *de* *facto* forest governance has been mobilized "following the market" (Nansikombi et al., 2020; Nolte et al., 2017a; Seghezzo et al., 2011) and has amplified power asymmetries, as subnational governments made regulations more flexible where expected profits were higher and landholders were already powerful.

Power dynamics are increasingly considered as key determinants of conservation outcomes (Berbés-Blázquez et al., 2016); however, empirical and quantitative evidence of such influence is scarce. Here we show that individual characteristics of landholders (i.e., their power and landholding size), in combination with the subnational context, explain a third of the variation in the size of illegal deforestation events. The mechanisms behind non-compliance of powerful landholders are related to their economic capital and links with the political power. Existing economic sanctions for violations of the law are insufficient to prevent illegal clearings, but instead are incorporated as an additional production cost by landholders with high economic capital (Di Pangracio and Cáceres, 2020). In parallel, lobbying and campaign funding by landholder groups as well as partisan and family ties between landholders and government officials foster corruption, which results in illegal clearings in exchange of political support (Milmanda and Garay, 2019; Smith et al., 2012). Tight interactions and alliances between powerful landholders and subnational governments have also been associated with low enforcement of land-use regulations and deforestation in protected areas in Africa (Albertazzi et al., 2018; Samndong et al., 2018; Sulaiman et al., 2017), in agricultural frontiers in Southeast Asia (Bettinger, 2015; Currey et al., 2001), and in the Brazilian Amazon (Boekhout van Solinge, 2014.; Lawson, 2010; London and Kelly, 2007).

Our modelling results lend support to a positive feedback loop between landholderś power and the area deforested illegally, mediated by landholding size and the type of illegal deforestation. In this loop, already powerful landholders (usually extra-local agents from other regions who invest surplus capital) expand their landholdings by dispossessing and displacing smallholders (Cáceres, 2015; Goldfarb and van der Haar, 2015; Román et al., 2007; Schoneveld et al., 2011). Larger landholdings are associated with higher economic power through high profits and have a larger influence on provincial governments through taxes from export sales (Seghezzo et al., 2011). Large powerful landholders are able to simultaneously privatize and concentrate land tenure (Faingerch et al., 2021) and lobby the government to relax land-use regulations in their landholdings (Seghezzo et al., 2011). Two additional findings provide evidence on this feedback loop. First, the average landholding area deforested illegally was 18 times larger in landholdings managed by powerful landholders, who were the only ones that cleared in downgraded areas. Second, the policy simulation that combined land concentration and large downgradings was associated to increases in the size of illegal deforestation events larger than those caused by either policy alone. This is a plausible scenario considering the increasing trend in international commodity prices and extraordinary rents from commodity production (Alcañiz and Gutierrez, 2020; Godar et al., 2012).

Disassembling the pervasive institutional and power dynamics that are underlying illegal deforestation requires a smart policy mix. Given the strong influence of international commodity trade on land-use change, the effectiveness of forest conservation policies depends on the integration of instruments across economic, agriculture, and environment sectors, as well as the alignment of their conflicting goals (Börner et al., 2020; Gutierrez, 2017; Harahap et al., 2017; Huaranca et al., 2019). A key policy with the potential for enabling forest conservation entails reforming land tenure to prevent further land concentration and power accumulation by already large landholders (Börner et al., 2020), for example, by increasing the security of tenure of land managed by mestizo and indigenous people (Faingerch et al., 2021). This should be accompanied with policy incentives for the promotion of land-use systems that add value to forests locally (e.g., non-timber forest products) and supply chains that increase the opportunity cost of deforestation (Alcañiz and Gutierrez, 2020; Lambin et al., 2018; Nepstad et al., 2014). Disincentives to further illegal deforestation will also be critical. Considering the ineffectiveness of economic sanctions, illegal deforestation must be typified as an environmental crime in Argentinian legislation. In sum, a smart policy mix is needed to disrupt the vicious cycle of landholderś power accumulation and subnational institutional weakness that underlies illegal deforestation.

5. Conclusions

Our case study in the Argentine Chaco illustrates how interactions between powerful landholders and weak institutions, in a context of extraordinary land rents, enable illegal deforestation. We add critical quantitative evidence and valuable qualitative insights on the role of subnational institutions and landholderś power in shaping illegal deforestation outcomes in this important commodity production frontier, which harbors globally relevant biodiversity and carbon stocks. To do so, we used Bayesian networks, which allowed us to combine data on illegal deforestation events extracted from news and reports with quantitative locational data as well as agent-level socioeconomic information. Policy simulations revealed the interacting effect of land-tenure settings and land-use regulations on illegal deforestation. Understanding the simultaneous and interrelated influence of multiple factors (i.e., social, institutional, and biophysical) corroborates the need for instigating smart policy mixes to effectively tackle conservation problems that cut across scales and sectors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2022.102511.

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