Letter

Forest governance and development effects on tropical charcoal production and deforestation

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Abstract

Severe loss and degradation of tropical forests affects ecosystem services and livelihoods. Charcoal, an important energy and income source for millions of people, causes 7% of tropical deforestation and forest degradation. Forest governance aims to manage forest-related issues. On the one hand, development allows for financial investments in forest governance, e.g., in monitoring and enforcement, with the aim to control deforestation. On the other hand, deforestation often continues with increased human wellbeing. Here, we aim to (a) globally examine the effects of forest governance on charcoal production and deforestation, and (b) understand its association with development. We developed a typology of tropical forest governance systems based on a literature review of 54 USAID Country Profiles and combine it with global data on charcoal production, deforestation, governance quality and development. Our results suggest that countries’ development statuses affect charcoal production rather than governance quality; we observe a negative relationship between development status and charcoal production per capita (HDI: $F_{(1,50)} = 4.85, p = 0.032$; GNI: $F_{(1,50)} = 4.64, p = 0.036$). The limited influence of governance quality and rights on charcoal production per capita and deforestation suggests mismatches between formal and informal governance and exposes challenges in top-down percolation of governance goals. Our results highlight the potential importance of tenure rights and potential opportunities for regional governing bodies to bridge local formal and informal actors to improve forest governance. Positive effects of regional tenure are driven by mixed effects of high development and governance quality related to decentralization in Asia and South America, highlighting transitions from charcoal as a livelihood energy source to a global commodity. Variability in results for FAO and UN charcoal production data advocates for better monitoring programs. However, for the first time, we explore global interactive patterns in charcoal production, development and governance—a starting point to differentiate good governance.

1. Introduction

Severe loss of forests (Curtis et al 2018) affects the supply of ecosystem services, such as woody biomass production, and biodiversity (Miles and Kapos 2008), and livelihoods depending on them (Carrasco et al 2017). Compared to temperate forests, tropical forests face larger risks of deforestation and forest degradation (Sloan and Sayer 2015). Forest governance aims to limit deforestation and forest degradation through formal and informal institutions (laws, rules and norms) of public and private governing bodies (e.g. governments, private companies and indigenous organizations), which negotiate, make and enforce binding decisions about management, use and conservation of forest resources (FAO Program on Forests 2011). Impacts of forest governance on forest use and conservation are variable (Persha and Andersson 2014), despite continuous efforts to enhance its quality and effectiveness (Biermann and Pattberg 2008, Arts et al 2010). Financial investment is necessary to uphold quality forest governance, such
as investments in institutional development or monitoring and enforcement by governing bodies (FAO Program on Forests 2011, Köthke 2014). Therefore, forest governance quality is expected to positively relate to development status (i.e. a country’s quality of life and economic wellbeing), because it allows for investment in forest governance (Asongu and Jingwa 2012, Houballah et al 2020), and other societal assets, such as education (Lin 2004) and infrastructure (Fan et al 2016), which can affect governance quality. However, research indicates that deforestation often continues with increased human wellbeing (Jha and Bawa 2006, Delabre et al 2020). Therefore, we need a better empirical understanding of the relation between forest governance characteristics and forest use and protection (Biermann and Pattberg 2008, Arts and Vissen-Hamakers 2012, and its association with development (Beauchamp et al 2020).

In the majority of tropical countries a formal forest governance system has been implemented (Fischer et al 2020). Across the tropics varying forest governance systems exist, ranging from centralized to regionalized and decentralized systems, which vary across continents (Arts and Vissen-Hamakers 2012). Multiple governance systems may co-occur and change over time due to new and changing policies (Schreckenberg and Luttrell 2009, Arts et al 2010), strongly influenced by colonial history and governance in other nations (Tucker 1982, Becker 2001, Von Hellermann 2013). For example, many centralized governance systems have been replaced by decentralized ones over the past decades, as it has been shown that local or regional institutions and a distribution of responsibilities result in better governance outcomes (Arts et al 2010, Arts and Vissen-Hamakers 2012). Decentralization is thought to produce better outcomes because it relies on the participation of multiple governing bodies, believed to foster political accountability and more responsive governments, theoretically resulting in both accountable and effective governance (Rondinelli et al 1983). However, variable outcomes for forest use and conservation are observed across decentralized governance systems (Larson and Petkova 2011), likely because they contain a large diversity of governing bodies, which differ in the tasks they have and the way they collaborate with each other (Andersson et al 2014).

Generally, all governance systems explicitly define formal institutions in binding policy and legal documents, e.g. forest acts (FAO Program on Forests 2011). For example, governments outline governing bodies with the right of forest tenure, which, if secure, play an important role in the adoption and implementation of sustainable forestry (Arnot et al 2011). Simultaneously, informal institutions, i.e. societal norms, may complement or defy formal ones (Pacheco et al 2008). In the majority of tropical countries, the forestry sector is still informally governed, as formal governing bodies may have limited resources and capacity to implement formal governance, resulting in the persistence of illegal forest use (Pacheco et al 2008, Osei-Tutu et al 2015, Ashu 2016). Effective incorporation of informal institutions may foster higher forest governance quality (Osei-Tutu et al 2015, Yeboah-Assiamah et al 2017). However, the extent of informal forest governance and its effects on forest use and conservation remains unclear (FAO and UNEP 2020), although evidence from local studies suggests that informal governance through self-organization can foster more effective governance than formalized governance systems in certain scenarios (Andersson et al 2014).

Institutions implemented by governing bodies are not singular but vary depending on forest tenure, involved governing bodies (Kohler and Schmithusen 2004), forest products extracted (Brobbey et al 2015), and whether products are used for self-sustaining or commercial purposes (Ribot 2001). Charcoal is arguably among the least examined forest products, despite being an important energy and income source for hundreds of millions of people in the tropics (FAO 2017). Charcoal production is an important cause of forest degradation (Sedano et al 2016) and is responsible for up to 7% of annual deforestation globally, especially under ineffective governance scenarios without investment in post-harvesting management (Chidumayo and Gumbo 2013). Overall, charcoal production is projected to increase by 5% by 2100, likely causing further deforestation and forest degradation (Santos et al 2017). Effective forest governance that incorporates energy substitution options to reduce demand (van’T Veen et al 2021) is required to mitigate these negative effects (Schure et al 2013), besides routine monitoring and enforcement to control access and forest use.

In many tropical countries, forest governance already aims to control charcoal production (Schure et al 2013), indicating that charcoal production should in theory be influenced by countries’ formal governance systems (Laan et al 2010). Formal forest governance intends to foster sustainable use and conservation of forests, a practice that requires substantial financial investment and the efforts of many governing bodies involved (Fischer et al 2020). The manner in which formal forest governance aims to achieve this is documented (USAID 2014) and its quality is quantified (Kaufmann et al 2010), allowing for an assessment of its eventual impact on forest use and conservation. Therefore, it is important to study formal governance (Larson et al 2008, Schure et al 2013), especially when formal and informal governance are antagonizing (Goetter 2019). Besides investments in routine forest governance interventions, other investments have been made in efficient cooking stoves and alternative energy and income sources for communities (Zulu and Richardson 2013, Cotton et al 2021) to foster energy transitions with the aim to reduce charcoal demand (Santos et al...
2017, van’T Veen et al 2021). The size of such investments relates to tropical countries’ access to financial resources to fund them (Laan et al 2010). Besides this, higher financial means may provide incentives for urban consumers to shift to alternative energies (e.g. gas), as observed in South American and Asian countries (FAO 2017). This indicates a likely effect of development status on charcoal production and (related) deforestation in tropical countries (Schure et al 2013).

In this study, we aim to (a) examine the effects of formal forest governance on charcoal production and subsequent deforestation, and (b) understand its association with development. We hypothesize that formal forest governance has a limited effect on charcoal production and deforestation because of a lack of resources to finance effective governance and because of the potentially important role of informal governance. Furthermore, we expect that decentralized governance and tenure rights foster higher governance quality and provide better outcomes for charcoal production than centralized governance systems. Finally, we expect lower charcoal production and deforestation in countries with higher development status because financial resources should enable higher-quality governance, access to alternative energies on the demand side, and alternative incomes on the supply side in rural areas, as often other activities than charcoal production are adopted with enhanced wellbeing (FAO 2017). Hence, we expect continental patterns, with high development and low charcoal production in Asia and South America and low development and high charcoal production in Africa (FAO 2017).

2. Methodology

2.1. Study system and typology of forest governance

Our study system consists of 54 tropical countries and their forest governance systems. We define a typology of formal forest governance systems by identifying the scales at which governing bodies operate and the rights they have over forest resources. In this typology we recognize that forest governance is a nested process in which multiple governing bodies have a range of overlapping rights (Agrawal et al 2008, Biermann and Pattberg 2008, Arts 2014).

We reviewed USAID country profiles on tenure rights (USAID 2013) to inform our typology (supplementary materials A available online at stacks.iop.org/ERL/17/024040/mmedia). We used these profiles because they provide detailed and consistent overviews of forest governance in tropical countries (USAID 2020). Forest governance information from other sources is scattered and multi-lingual, hence challenging to utilize.

We define four types of governing bodies: (a) national, (b) regional, (c) local, and (d) individual, which operate at different scales. National governing bodies operate at a national scale, e.g. ministries. Regional governing bodies are sub-national entities operating at a regional level, e.g. province or state. Local governing bodies are sub-regional entities operating at the lowest communal governing level, e.g. municipalities or village governments. Finally, individual governing bodies are individual people and companies operating locally on forest land or trees over which they have rights. In the case of regional governing bodies, there may be multiple nested bodies in one country, such as provincial and district governments. Individual governing bodies do not include actors further up the charcoal value chain, like wholesalers, because they lack direct rights over forests.

We define two main rights governing bodies may have in forest governance systems: (a) enforcement, and (b) tenure. Enforcement is the formal right to enforce (by-) laws on forest use and protection. Tenure is the formal right to tend forest land or trees, like ownership and lease rights. Governing bodies may have multiple rights at once or may not have specific rights. We specifically focused on formal rights of enforcement and tenure because they are specified by countries’ forests acts (USAID 2013), and can influence forest governance outcomes (Robinson et al 2014). We only include governing bodies operating in the statutory domain, not those operating informally (e.g. traditional local leadership that is not formally acknowledged in existing forest acts). However, we acknowledge that in many cases, especially in most African countries, informal institutions tend to be powerful and may prevail over the formal ones (Larson et al 2008). This explains the mismatch between formal distribution of tenure rights and the actual rights of governing bodies later described in section 4.2 of the discussion.

We recognize that other factors beyond enforcement and tenure may influence forest governance effects on charcoal production and deforestation, e.g. market-oriented certification schemes and NGO projects (Agrawal et al 2008), potentially affecting deforestation (Bare et al 2015). Additionally, charcoal is exported to other countries and trade is increasing (Proskurina et al 2019). We also acknowledge that tenure right distribution does not equal the security of those rights (Robinson et al 2014). Tenure security affects conservation more than the distribution of tenure rights alone (Robinson et al 2011). Hence, assessments of the effects of tenure rights on forest governance, charcoal production, and deforestation may indicate issues of tenure security, rather than the effect of tenure right distribution as dictated by formal forest acts.

We calculated governance richness—an indicator of polycentricity—for the entire governance system, and for tenure and enforcement rights per country by summing the number of governing bodies
involved. We used the typology of governance systems and governance richness indicators derived from it to assess the effects of inclusion of specific types of governing bodies (e.g. regional bodies) and governance composition on charcoal production, deforestation, forest governance quality and development.

2.2. Data collection

We used data on charcoal production and consumption from the United Nations (UN) of 2018 (http://data.un.org/Data.aspx?d=EDATA%26f=cmI on from the United Nations (D%3ACH), and charcoal production data from the Food and Agriculture Organization (FAO of 2017) (http://faostat.fao.org). The first was collected through the UN Energy Statistics Questionnaire (UN 2017). The second was gathered through an annual survey by the FAO Forestry Division and estimated using trade journal reports, statistical yearbooks and other sources. Charcoal production data from both the UN and FAO correlated well ($R^2 = 0.53, F_{1,52} = 61.4, P = 2.3 \times 10^{-10}$) (supplementary materials figure B1), but charcoal production varied per country between the two data sources ranging from 0 to 2197 000 Mg.

We obtained data on total population per country (2018) from the World Bank (https://data.worldbank.org/indicator/SP.POP.TOTL). We used it to calculate charcoal production per capita for both the UN and FAO data; these are relative measures of charcoal production. We assessed charcoal production per capita because formal governance affects rural charcoal producers, urban consumers, transporters and wholesalers (e.g. through permits for production, transportation or sale) (Schure et al 2013), while subsidies for alternative energies and efficient cooking stoves mainly influence urban consumers (Mwampamba et al 2013). We used data on total forest land per country ($x$1000) of 2017 and 2018 from FAO (http://faostat.fao.org). To calculate deforestation we subtracted forest land of 2017 from that of 2018, multiplied it by -1 and divided it by the total forest land of 2018 to derive relative values of deforestation and afforestation. In our deforestation index, deforestation is positive and afforestation negative. See the Global Forest Resource Assessment (www.fao.org/forest-resources-assessment/background/en/) for more information.

We used governance quality data from the Worldwide Governance Indicators (WGI) of 2017 (https://info.worldbank.org/governance/wgi/), which reflect the conditions under which forest governance operates (Umemiya et al 2010, Afaawubo and Noglo 2019). We expect that governance quality influences the effectiveness of forest governance to control charcoal production and (related) deforestation. The data includes information on (a) Voice and Accountability, (b) Political Stability and Absence of Violence, (c) Government Effectiveness, (d) Regulatory Quality, (e) Rule of Law and (f) Control of Corruption indicators (see Kaufmann et al 2010 for indicator definitions). Unfortunately no global data on informal governance nor on its quality were available at the time of study. As indicators for development, we included Gross National Income (GNI) of 2017 and the Human Development Index (HDI) of 2017. We obtained GNI from the World Bank (https:// data.worldbank.org/indicator/NY.GNP.PPP.CD), and we obtained HDI from the United Nations Development Program (http://hdr.undp.org/en/content/human-development-index-hdi). Table 1 explains rationales for the inclusion of governance quality and development indicators.

For all datasets, we downloaded the most recently available data at the time of study.

2.3. Data analyses

First, we calculated pairwise Spearman rank ($\rho$) correlations (Zar 1972) between (a) charcoal production per capita (FAO, UN), (b) deforestation rate, (c) governance quality, (d) governance richness, and (e) development. We used linear regression to assess the relationships between the indicators for which normality could be achieved. We used transformations to achieve normality; namely, we square-root transformed charcoal production per capita (UN), deforestation rate, and all governance quality indicators, and we log-transformed GNI. Finally, we conducted a principal component analysis (PCA), which is a method that identifies the number of orthogonal (i.e. independent) dimensions in any given data set. This method is commonly used to reduce dimensionality in large datasets, by identifying axes where the original variables are combined, hereby minimizing loss of information (Wold et al 1987). The PCA conducted in this study included the variables charcoal production per capita, deforestation, governance quality, governance richness, HDI and GNI. First, we scaled the variables included in the PCA, to ensure each variable contributes equally to the analysis, using the ‘scale’ function of the R-package ‘base’. Second, we computed a covariance matrix to differentiate relationships between all variables. Third, we computed the eigenvalues and eigenvectors of the covariance matrix, which correspond to the principal components that explain the maximal amount of variance in the data, with the first principal component containing the maximal information, followed by the second and so on (Wold et al 1987, Abdi and Williams 2010). We calculated factor loadings, where a factor (or principal component) is a combination of variables and the loadings reflect the extent to which variables are related to that factor (Yong and Pearce 2013).
Table 1. Rationale for including World Governance Indicators (WGI) from the World Bank, the Human Development Index (HDI), and Gross National Income (GNI) to assess the effect of governance quality and development on charcoal production and deforestation.

| Indicator         | Rationale for inclusion in this analysis                                                                 |
|-------------------|----------------------------------------------------------------------------------------------------------|
| Corruption control (GQ_Cor) | Corruption occurs when laws, rules and regulations are not respected, including those on forest use, which may affect deforestation in multiple countries (Koyuncu and Yilmaz 2009, Galinato and Galinato 2011). |
| Rule of Law (GQ_RoL)   | Rule of law influences the enforcement of property rights and ownership of land by governing bodies, which affects the way forests are used and laws, rules and regulations of forest governance systems are obliged to (Deacon 1994). Rule of law may both influence deforestation levels (Umemiya et al 2010) and increase likelihood of a forest transition (Barbier and Tesfaw 2015). |
| Regulatory quality (GQ_RQ) | Markets are thought to rely on reliable forest policies that permit and promote private sector development (i.e. regulatory quality) to assure a return on investment (Pedroni et al 2009), hereby providing incentives to protect the forest (Barbier and Tesfaw 2015), which may reduce deforestation at a global scale (Umemiya et al 2010). However, better access to markets can also increase deforestation because certain policies enhance access to forests (e.g. providing infrastructure to access forests) or promote land clearing (Barbier and Tesfaw 2015). Overall, it depends on which forest policies are implemented to promote private sector development and whether they aim to limit deforestation (Barbier and Tesfaw 2015). |
| Political stability (GQ_PS) | Political instability may incite enhanced forest exploitation because of a lack of control over forest resources and insecure property rights (Deacon 1994, McCarthy and Tacconi 2011), or because specific units, such as rebel groups, actively profit from the sale of forest products, such as charcoal (Mapesa et al 2013). It may, however, also halt forest exploitation, e.g. because of reduced conversion of forest land to agriculture (Galinato and Galinato 2013). |
| Government effectiveness (GQ_Eff) | Effective implementation of policies and public services for the use and protection of forests may reduce deforestation (Umemiya et al 2010, Afawubo and Noglo 2019). However, effective implementation of policies that disregard forest protection may give rise to deforestation (Jha and Bawa 2006). |
| Voice and accountability (GQ_VaA) | When voice and accountability is high, people are allowed to speak up to influence decision making, which is an indicator of decentralized democratic governance (Wright et al 2016). Decentralized governance systems in which local users actively engage with local governing bodies have a more stable forest cover (Wright et al 2016). However, enhanced decentralization and means to speak up may also increase conflicts (e.g. conflicts over land rights), which could enhance deforestation, despite opportunities to engage in forest management (Yasmi et al 2009). |
| Human Development Index (HDI) | Human development may negatively influence deforestation rates, even at high population growth (Jha and Bawa 2006). However, policy choices that disregard forest protection may inhibit the positive influences of human development on forest cover (Jha and Bawa 2006). |
| Gross National Income (GNI) | Forest-income curves may be U-shaped, with an initial increase in deforestation upon a rise in income because people initially have more means to exploit forests and convert forest land, until a tipping point is reached and forest exploitation reduces due to a transition to other sources of income, resources and intensified agriculture (Galinato and Galinato 2011). Besides this, national debt may lead to increased pressure on forests to relieve debt in the short term (Kahn and McDonald 1995). |

3. Results

3.1. Tropical forest governance typologies

Globally, we distinguished 13 typologies for forest governance systems (see supplementary materials A for the full typology and a visualization of it) but found no clear geographical patterns (figure 1).

3.2. Impact of development and governance on charcoal production and deforestation

Figure 2 shows the strength and direction of Spearman correlations between charcoal production per capita, deforestation rate, GNI and HDI, average...
Figure 1. Geographical distribution of the governance systems of tropical countries around the world. The numbering is based on the governance typology visualized in appendix A. No clear geographical pattern was found.

Figure 2. Spearman correlations between charcoal production per capita (Charcoal) for FAO and UN data, deforestation rate, development indicators (GNI and HDI), governance quality indicators, and governance richness. WGI governance quality indicators include voice and accountability (GQ_VaA), political stability (GQ_PS), government efficiency (GQ_Eff), regulatory quality (GQ_RQ), rule of law (GQ_RoL), and corruption control (GQ_Cor) (see table 1 for an explanation of each development and governance quality indicator and why it is included in the analysis). We calculated the governance richness (GovRichness) of the entire governance system per country by summing the number of governing bodies with rights of tenure and enforcement.

governance quality and governance richness. We observe a weak negative correlation between governance richness and charcoal production per capita for the UN data ($\rho = -0.16$). We also observe weak negative correlations between charcoal production per capita and government effectiveness (UN: $\rho = -0.13$, FAO: $\rho = -0.31$), political stability (FAO: $\rho = -0.26$), and regulatory quality (FAO: $\rho = -0.25$). HDI and GNI negatively correlate with charcoal production per capita for both FAO ($\rho = -0.68$ and $\rho = -0.61$ respectively) and UN data ($\rho = -0.28$ and $\rho = -0.26$ respectively). Further, negative linear relationships between UN charcoal production per capita, HDI and GNI are statistically significant but weak (HDI: $R^2 = 0.07$, $F_{(1,50)} = 4.85$, $p = 0.032$; GNI: $R^2 = 0.07$, $F_{(1,50)} = 4.64$, $p = 0.036$).

We find a positive correlations between deforestation and charcoal production per capita (FAO: $\rho = 0.33$, UN: $\rho = 0.25$) (figure 2). We observe weak negative correlations between deforestation, government effectiveness ($\rho = -0.30$), rule of law ($\rho = -0.23$), and corruption control ($\rho = -0.18$). We also find weak negative correlations with HDI ($\rho = -0.31$) and GNI ($\rho = -0.22$). However, there were no significant linear relationships.

We find significant positive relationships between average governance quality, HDI ($R^2 = 0.37$, $F_{(1,49)} = 36.58$, $p = 1.97e^{-07}$) and GNI ($R^2 = 0.38$, $F_{(1,49)} = 39.14$, $p = 1.97e^{-07}$).
Table 2. Factor loadings of the principal component analysis (PCA). The outlier (Ivory Coast) is removed. Small loadings are replaced by spaces, to focus the eye on the patterns of the larger loadings. We test the hypothesis that four factors are sufficient to explain the variation in the data (i.e. the p-value should be higher than 0.05 for the model to fit) and find that four principal components explain the variation in the data sufficiently ($F_{(4,96)} = 33.53, p = 0.09$), with a fit of 0.98 based on off-diagonal values.

| Variable                          | PC1  | PC2  | PC3  | PC4  |
|-----------------------------------|------|------|------|------|
| Proportion explained by principal components | 0.37 | 0.17 | 0.09 | 0.08 |
| Governance richness               |      |      |      |      |
| GNI                               | 0.44 | 0.63 |      | 0.47 |
| HDI                               | 0.42 | 0.78 |      | 0.45 |
| Corruption control (GQ_Cor)       | 0.92 |      |      |      |
| Rule of law (GQ_RoL)              | 0.81 |      |      |      |
| Regulatory quality (GQ_RQ)        | 0.81 | 0.32 |      |      |
| Political stability (GQ_PS)       | 0.58 |      |      | 0.42 |
| Government effectiveness (GQ_Eff) | 0.89 | 0.44 |      |      |
| Voice and accountability (GQ_VaA) | 0.67 |      |      | 0.43 |
| Charcoal production per capita (UN) | —   | −0.33|      |      |
| Charcoal production per capita (FAO) | —   | −0.71|      |      |
| Deforestation                     | −0.30| −0.23|      |      |

$F_{(1,49)} = 31.95, p = 7.99e^{-07}$), and a weak negative correlation between governance richness and political stability ($\rho = −0.18$).

The first four principal components of the PCA explain the variation in our data sufficiently, with a fit of 0.98 based on off-diagonal values, where the explained proportion of variation by the first component is 37%, the second 17%, the third 9%, and the fourth 8% (table 2; figure 3). Hereby, we removed the outlier Ivory Coast, which has 50 times higher charcoal production per capita than the subsequent highest charcoal production per capita (Haiti). We find strong negative loadings for charcoal production per capita for the second component. In contrast, we find strong positive loadings for HDI and GNI for the second component. We find strong positive loadings for governance quality indicators for the first component. Governance richness exhibits high negative loadings for the third component. We find negative loadings for deforestation for the first and second components.

3.3. Impact of governance characteristics on charcoal production and deforestation

Color coding countries with tenure rights in the PCA reveal that regional tenure separates systems within PC2, associated with GNI and HDI and showing relatively lower charcoal production per capita (figure 4). Separability in PC1 is associated with local tenure, deforestation and charcoal production. Opposite relations between tenure richness and charcoal show lower charcoal production per capita for countries with more than four governing bodies involved. We do not observe separate effects of governing bodies on enforcement rights or enforcement richness. Finally, we observe that governance systems of Asian and South American countries appear separate within PC2, associated with GNI, HDI and government effectiveness, while governance systems of African countries appear separate within PC1 and are associated with charcoal production per capita and deforestation (figure 5; supplementary materials figure B2).

4. Discussion

For the first time, we explore global patterns in charcoal production, development and governance, providing a starting point to differentiate good governance of charcoal energy systems. Our analysis shows that charcoal production is mainly affected by a country’s development status rather than its governance quality, likely brought about by a shift from charcoal as an urban energy source in African countries to charcoal as a global commodity in Asian and South American countries (FAO 2017). We find indications that several characteristics of forest governance systems, such as numbers and types of governing bodies involved, influence charcoal production and deforestation.

4.1. Impact of governance quality and development status on charcoal production and deforestation

The low correlation between charcoal production per capita and governance quality indicators may be due to limited access to the financial resources necessary to sustain high-quality forest governance through funding of the (development of) governance programs and governing bodies, such as those involved in monitoring and enforcement (FAO Program on Forests 2011, Köthke 2014, Persha and Andersson 2014), as well as to support alternative income-generating activities for communities (Zulu and Richardson 2013, Cotton et al 2021). Further high-quality governance systems may still implement policies that disregard forest protection (Jha and Bawa 2006). Weak negative correlations between
Figure 3. Principal component analysis (PCA) including charcoal production per capita (Charcoal) for FAO and UN data, deforestation rate, development indicators (GNI and HDI), governance quality indicators, and governance richness. WGI governance quality indicators include voice and accountability (GQ_VaA), political stability (GQ_PS), government efficiency (GQ_Eff), regulatory quality (GQ_RQ), rule of law (GQ_RoL), and corruption control (GQ_Cor) (see table 1 for an explanation of each development and governance quality indicator and why it is included in the analysis). We calculated the governance richness (GovRichness) of the entire governance system per country by summing the number of governing bodies with rights of tenure and enforcement. The outlier that can be observed in the upper left is Ivory Coast.

Figure 3. Principal component analysis (PCA) including charcoal production per capita (Charcoal) for FAO and UN data, deforestation rate, development indicators (GNI and HDI), governance quality indicators, and governance richness. WGI governance quality indicators include voice and accountability (GQ_VaA), political stability (GQ_PS), government efficiency (GQ_Eff), regulatory quality (GQ_RQ), rule of law (GQ_RoL), and corruption control (GQ_Cor) (see table 1 for an explanation of each development and governance quality indicator and why it is included in the analysis). We calculated the governance richness (GovRichness) of the entire governance system per country by summing the number of governing bodies with rights of tenure and enforcement. The outlier that can be observed in the upper left is Ivory Coast.

The observed negative relationships between charcoal production per capita, governance effectiveness, political stability and regulatory quality corroborate previous findings that stable nations, which formulate and uphold high-quality policies and services, are better equipped to govern forest use (Deacon 1994, Umemiya et al 2010).

Weak negative correlations between deforestation, government effectiveness, corruption control and rule of law, furthermore, corroborate findings that effectively upholding implemented policies reduces deforestation (Deacon 1994, Koyuncu and Yilmaz 2009, Umemiya et al 2010). This is likely caused by upholding high-quality policies and services, which helps to simultaneously enhance adoption of conservation strategies and to avoid free-riding behavior (Nie 2018). Evidence suggests that the presence of local institutions designed to match people’s preferences through participatory processes further enhances effective upholding of implemented policies (Schreckenberg and Luttrell 2009). These local institutions are characteristic of the current paradigm shift toward participatory natural resource management in most tropical countries (Schreckenberg and Luttrell 2009).

The observed negative relationships between charcoal production per capita, HDI and GNI may be explained by an increased capacity of countries and citizens to invest in alternative energy resources, like gas (Kojima 2011, FAO 2017, Broto et al 2018), which are more costly than locally sourced charcoal (Kojima 2011). Hence, with increased financial means, transitions may occur from charcoal to alternative energy sources (Kojima 2011), which may deter previously poor people from producing charcoal as increased access to alternative income sources becomes available (Zulu and Richardson 2013, Cotton et al 2021). This is illustrated by the clear separation between African countries and Asian and South American countries (figure 5). These results highlight the dependency of African countries on charcoal as a livelihood energy source, and the transition to charcoal as a global commodity in Asian and South American countries (FAO 2017).

Weak negative correlations between deforestation, GNI and HDI, furthermore, corroborate observations of reduced deforestation with human development (Jha and Bawa 2006), where nonlinearity may explain the weak relationship (Galinato and Galinato 2011). However, as charcoal production remains a vital livelihood diversification strategy and charcoal remains an accessible fuel for hundreds of millions (FAO 2017), energy transitions should be carefully anticipated (Zulu and Richardson 2013). Our study highlights countries that lead the way to higher governance quality (e.g. Botswana, Senegal, Costa Rica) and lower charcoal production and deforestation.
Figure 4. PCA of figure 3, where groups highlight: (a) number of governing bodies involved in tenure (tenure richness) and whether countries provide tenure rights to (b) regional, (c) local or (d) individual governing bodies, besides other governing bodies. The PCAs include charcoal production per capita (Charcoal) for FAO and UN data, deforestation rate, development indicators (GNI and HDI), and governance richness. WGI governance quality indicators include voice and accountability (GQ_VaA), political stability (GQ_PS), government efficiency (GQ_Eff), regulatory quality (GQ_RQ), rule of law (GQ_RoL), and corruption control (GQ_Cor) (see table 1 for an explanation of each development and governance quality indicator and why it is included in the analysis). We calculated the governance richness (GovRichness) of the entire governance system per country by summing the number of governing bodies with rights of tenure and enforcement. We have removed one outlier (Ivory Coast) to provide a better visualization.

(e.g. Cameroon, Zimbabwe and Botswana), which provides a starting point to identify governance that allows for continuous charcoal production without depleting forests in less wealthy countries (supplementary materials figure B2).

Significant positive relationships between forest governance, GNI and HDI agree with findings that show that HDI leads to an increase in forest governance quality (Nandha 2013). The relationship may, however, also suggest the opposite; governance quality may increase a country’s human development status and financial resources, potentially allowing countries to control charcoal production levels and efficiently implement policies that reduce deforestation (Umemiya et al 2010, Afawubo and Noglo 2019).

The limited effects of charcoal production per capita on deforestation may result from the multifaceted nature of tropical deforestation, caused by multiple drivers, e.g. wood logging for other purposes and agriculture (Hosonuma et al 2012, Houghton 2012). Additionally, charcoal production mainly occurs through selective tree cutting, a method resulting in forest degradation rather than deforestation (Woollen et al 2016, FAO 2017)—only 27%–34% of all woodfuel production causes deforestation (Bailis et al 2015).
Overall, our results suggest a limited influence of formal institutions on charcoal production and deforestation, potentially because informal institutions still exert a strong influence (Secco et al. 2014). This suggests the need to include the effects of informal institutions in forest governance impact assessments (Secco et al. 2014, FAO and UNEP 2020), which requires global data on informal governance systems and their governance quality. The weak effects of formal governance on charcoal production and deforestation contrast with the results of a recent review of 28 papers, which show positive impacts of governance quality on forests (Fischer et al. 2020). The reasons for the mismatch between our study and the review of Fischer et al. (2020) likely relate to differences in methodology and scope. Fischer et al. (2020) organize information on governance according to categories proposed by the World Resources Institute, which is used to assess the direct effects of forest governance on deforestation based on local, regional, national and multinational studies, which mainly originate from Asian and South American countries (only three studies regard the African continent). In contrast, we use global governance quality indicators and develop a typology based on USAID reports that provides relatively consistent country-level information, including information on the majority of African countries. It is likely that the weak effects of governance quality on deforestation we find on a global scale relate to the inclusion of countries from the African continent, which exhibit high deforestation. Nonetheless, and more importantly, our findings for Asian and South American countries are consistent with those of Fischer et al. (2020), indicating that high governance quality in these continents corresponds to low deforestation. The contrast in findings between our study and that of Fischer et al. (2020) highlights challenges in global scale assessments of forest governance effects on deforestation, as well as in the comparability of results from global studies of different scopes that utilize different approaches and sampling designs.

4.2. Impact of governance systems characteristics on charcoal production and deforestation

Our observation that certain countries that provide tenure rights to regional governing bodies have relatively lower charcoal production per capita is in line with theoretical and empirical studies indicating that regional scale governance is most appropriate to tackle natural resource governance, because it strengthens governance networks, provides equal access to decision making, enables more voices to be heard, and distributes power (Campbell 1996, Sedlacek and Gaube 2010). It is, furthermore, in line with literature that indicates that decentralized governance is more effective than centralized governance (Campbell 1996, Ribot et al. 2006, Morrison 2014), and supports theories of polycentricity, which argue for redundancy in governance systems to increase collaboration between governing bodies (Ostrom 2001, Carlisle and Gruby 2019). As the majority of countries that assign tenure rights to regional/sub-regional governing bodies are located in Asia and South America (supplementary materials figures B2 and B3; figure 5), the relatively lower charcoal production per capita can be explained by mixed effects of relatively higher governance quality related to decentralization and higher development status, which fosters energy transitions and causes charcoal makers to refrain from production. It also indicates a commodification of charcoal.

Our observation that local tenure may potentially be associated with deforestation based on separation between governance systems with and without local tenure in the PCA space contrasts with literature that highlights the importance of local tenure rights in the adoption and implementation of sustainable forestry (Arnot et al. 2011). However, the results are in line with literature that finds variable effects of decentralization on forest outcomes, which affects the success of forest policies, such as REDD+ (Larson and Petkova 2011), as well as with studies that show better outcomes for forest conservation in state-owned forests (Robinson et al. 2011). An alternative explanation of the results may be a mismatch between the
formal distribution of tenure rights and the ability of governing bodies to exercise those rights (i.e. tenure security) (Robinson et al. 2014). A recent meta-analysis shows that tenure security is associated with lower levels of deforestation in any form of tenure because it reduces the incentive of governing bodies to tend forest resources (Robinson et al. 2014). Therefore, our results might indicate that local governing bodies may have inadequate tenure security to exercise tenure despite formal distribution of tenure rights, which could explain the on average slightly enhanced deforestation and charcoal production observed for those governance systems that provide tenure rights to local governing bodies.

Potential negative effects of local tenure on deforestation and the control of charcoal production could also indicate that local formal and informal institutions do not operate independently. Previous studies suggest that informal institutions may substitute formal ones in case of dysfunction (Osei-Tutu et al. 2015). In these countries both formal and informal institutions may remain non-functional, causing an institutional gap that allows for illegal forestry practices (Osei-Tutu et al. 2015), which may explain the higher deforestation levels observed. This may result from limited funding transferred by national to regional/sub-regional governing bodies (Agrawal and Ribot 1999, Andersson et al. 2006), and other forms of elite capture (Persha and Andersson 2014).

Our observation that distribution of tenure, rather than enforcement rights, may potentially influence the outcomes of forest governance is in line with studies that highlight the importance of tenure right distribution for effective forest governance (Larson 2011, Larson and Dahal 2012) and local participation (Schreckenberg and Luttrell 2009, Nie 2018). The low effect of enforcement may relate to influences of informal institutions, suggesting that enforcing governing bodies currently may not have the implementation power they need to ensure percolation of formal institutions. Reconciling polycentricity with the need for percolation of formal institutions requires further examination and research (Osei-Tutu et al. 2015). Our results also highlight the need to further examine whether regional/sub-regional governing bodies can serve to bridge formal and informal institutions to foster bidirectional percolation of institutions bottom-up and top-down.

4.3. Data limitations and lessons learned
We obtained different results between charcoal production estimates provided by the UN and FAO. This variability may result from different definitions, data collection methods and sets of countries that submit the UN Energy Statistics Questionnaire and the annual survey by FAO Forestry Division. Although we found a significant positive relationship between charcoal production data from the UN and FAO, we also found substantial differences between countries. Thus, we suggest caution when interpreting global charcoal production data. A range of other factors are known to impact charcoal production, such as export (Proskurina et al. 2019), demand, and policy instruments and programs, including financial investments to promote alternative energy sources (FAO 2017) and alternative income sources for forest-adjacent communities (Zulu and Richardson 2013, Cotton et al. 2021), which may overshadow the impacts of formal forest governance. Additionally, charcoal is mainly produced by rural citizens but mainly consumed by urban citizens (FAO 2017), indicating that the ratio between urban and rural citizens may affect relative measures of charcoal production per capita, either enhancing them (in the case of large rural populations who do not depend on charcoal) or lowering them (in the case of large urban populations who depend on charcoal). Finally, the governance data used in this study do not directly reflect forest governance quality, and GNI and HDI may not directly correspond to financial investments and knowledge in forestry, while other socio-economic factors, such as infrastructure, may also affect development (Fan et al. 2016) and governance (Houballah et al. 2020). We recommend that future studies explore the effects of indicator choice and their relationships.

We acknowledge that some aspects of governance systems may not have been mentioned or may have been left out entirely from the USAID reports we based our forest governance typology on (USAID 2020). We were only able to retrieve information on tenure right distribution across governing bodies from the USAID reports, and we acknowledge that additional factors besides tenure distribution affect governance outcomes, such as access of governance bodies to finances and tenure security (Robinson et al. 2014, Asaaga et al. 2020). Additionally, the typology does not regard country-specific nuances. For instance, in Tanzania, no specific individual enforcement or tenure rights exist for charcoal production (National-Assembly 1982), and although regional governing bodies are involved in forest governance, they derive limited funding (Milledge et al. 2007). Hence, decentralization may not automatically result in equitable distribution of rights and financial resources to involved governing bodies, potentially explaining disparities in the governance quality of decentralized countries. Additionally, governing body richness does not provide complete insight into the polycentricity of governance systems, as governing bodies may have been assigned completely different tasks, potentially resulting in fragmentation rather than redundancy. A complete assessment of fragmentation and polycentricity requires full knowledge of the overlap and complementarity of governance tasks among all governing bodies involved, calling for a more detailed assessment of countries’ forest acts.
and a more advanced typology of forest governance systems. Thus, country/continent-specific (informal) governance aspects may have inhibited us in finding clear patterns in governance and further research is necessary to understand their effects on charcoal production, deforestation and governance quality. Finally, we did not specifically regard the wellbeing of people involved in the charcoal value chain (Ece 2017), which may be influenced by governance systems and should be considered when designing them (van’T Veen et al 2021). Our data exploration can, however, be used to inform future local studies and policy projects on global effects of forest governance by providing indications of important governance and development factors, which influence charcoal production and deforestation.

5. Conclusion

Charcoal production causes up to 7% of annual deforestation and forest degradation, while providing energy for hundreds of millions of livelihoods. High levels of charcoal production and consequent loss and degradation of forests may be mitigated through high-quality and effective governance, which requires large financial investment. We explore the relations between forest governance, development, charcoal production and deforestation. Our results to date suggest that countries’ development status affects charcoal production rather than their governance quality. We also find indications that regional/sub-regional governing bodies may potentially serve as levers to foster transitions to decentralized, polycentric or regionalized governance, which could lower charcoal production levels. These results may be explained by mixed effects of high governance quality related to decentralization and development, fostering energy transitions and commodification of charcoal in Asian and South American countries. Our findings should be regarded with caution because of the strong effects of informal governance on charcoal production. However, our study highlights countries that lead the way in higher governance quality and lower charcoal production and deforestation, and we see a potential opportunity for regional/sub-regional governing bodies to act as a bridge between formal and informal institutions.

Data availability statement

No new data were created or analysed in this study.

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