Long-term effect of the COVID-19 lockdown on the dynamics of the bushmeat trade in West Africa (Côte d'Ivoire)

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Introduction

The wildlife trade is a major societal issue challenging both biodiversity conservation and global health (Bezerra-Santos et al., 2021; Hughes, 2021). At an estimated annual value of several US$ trillions, it also constitutes a crucial –often parallel– economy for countries, in which actors of the supply-chain source their revenues (Andersson et al., 2021). It is also an important food system for a number of rural households across the tropics (Fa et al., 2016).

The advent of the COVID-19 pandemic has generated a vivid debate on whether or not the wildlife trade should be banned. Contrasting calls from and within the scientific community, the political spheres and the public have been put forward (Fang et al., 2021), from an outright permanent ban (Sills et al., 2020) to maintenance of the wildlife trade for the sake of social development (Roe et al., 2020).

West and central African rainforests are a particular hotspot for the wildlife trade, where *bushmeat* –the terrestrial vertebrates hunted for food– has traditionally been a vital source of protein and income for rural communities (Ingram et al., 2021). With the globalization of the trade, bushmeat offtakes have become likely unsustainable for many species (reaching c. 5 million tons each year; Nasi et al., 2011), an extinction trend coined under the term "bushmeat crisis" (Bennett et al., 2002).

With the COVID-19 pandemic, the African continent was struck by national trade bans of various length and effectiveness (Harvey-Carroll et al., 2022; Meseko et al., 2020). However, because the bushmeat trade is a poorly regulated, parallel economy across most of Africa, the genuine economic stakes behind the trade are poorly known (van Vliet et al., 2017). Moreover, the impact of bans on trade activities has rarely been quantified (but see Funk et al., 2022), notably in terms of post-ban recovery.

We conducted long-term monitoring of bushmeat sites in Côte d'Ivoire (West Africa) that encompassed pre-, during, and post-COVID-19 lockdown. In Côte d'Ivoire, hunting has been illegal since 1974 (law n°94–442), but the bushmeat trade is openly tolerated, notably in major urban zones (Gossé et al., 2022). Quantitative data on the bushmeat trade are scarce and mostly outdated, but large levels of supply from protected areas has been observed recently (Bi Gonedelé et al., 2017; Bi Gonedelé et al., 2022). The trade seems non-selective in terms of species and strictly motivated by financial income (Gossé et al., 2022), highlighting both the likely unsustainability and important economic role of the national bushmeat trade network.

Controls of the bushmeat trade by Ivorian state agencies have been regularly implemented as conservation-oriented measures or public health emergencies after the earlier epidemic of Ebola virus disease in 1994 (Dindé et al., 2017). However, there is to date no information available on how such control measures have affected the market. Our main objective was to assess the dynamics of the bushmeat trade in Côte d'Ivoire as a response to the COVID-19 pandemic and explore post-lockdown recovery trends depending on market type. We posit that (i) bushmeat trade dynamics was negatively impacted by governmental measures, with trends being similar between market types (as a measure of the effectiveness of government interventions),

and that (ii) bushmeat trade activities quickly recovered after the lockdown –and the bushmeat ban– were lifted (as a measure of market network resilience).

Material and Methods

Data collection

The study covered five of the most active bushmeat sites in Côte d'Ivoire. It includes (i) four bushmeat markets in the district of Abidjan, namely Yopougon Siporex (5°21'N, -4°04'W), Abobo Grand Marché (5°26'N, -4°01'W), Abobo Mairie (5°25' N, -4°01'W) and Adjamé (5°21'N, -4°01'W), and (ii) the restaurants of Toumodi (6°33'N, -5°01'W) as a renowned hub for bushmeat trafficking in central Côte d'Ivoire (Dindé et al., 2017).

Bushmeat sites were surveyed from December 2019 to January 2021, including the period during which governmental measures were taken in response to the COVID-19 pandemic (Milleliri et al., 2021: see Fig. 1). We chose to measure the weekly effect of governmental measures from the first week of April 2020, i.e. the week following that of when the declaration of state of health emergency and of the closure of chop chop bars was announced. The end of governmental measures was fixed to the second week of October 2020, as there was no specific date associated to the final release of constraints.

Sites were visited by JKG, SGB and a trained field assistant twice per week between 08.00 am and 2.00 pm, every three days. An additional control survey was conducted in September 2021 (week 92 after survey start) in order to compare the observed number of sellers with that from predictive growth curve modelling (see below).

We counted the number of sellers on each site as a proxy of the bushmeat activity. We systematically verified that each seller had his/her own stall(s), and was not a collaborator of another seller. We posit that the number of sellers –as one of the supply determinants of a market (Key et al., 2000)– is expected to positively correlate with the quantity of bushmeat supply. Weekly estimates per site were derived from the mean counts of sellers per week per bushmeat site (Appendix Table 1). Sellers were informed of the objectives of the study and participated to the survey on a voluntary basis.

Statistical analyses

All statistical analyses were conducted in the Rstudio interface of R v4.2.1 (Appendix 1).

A changepoint analysis was implemented with the package *changepoint* (Killick and Eckley, 2014) to identify the weeks at which the statistical properties of a sequence of observations for each trend changed in its mean seller counts. We used the PELT (pruned exact linear time) method with AIC values to identify multiple changepoints (Killick et al., 2012), and the AMOC (at most one change) method with the non-parametric CUSUM test statistic (penalty = 0.8) to identify the largest changepoint in each trend (Csörgő and Horváth, 1997). We used *imputeTS* (Moritz and Bartz-Beielstein, 2017) to undertake a time series imputation of missing data for Toumodi (January 2021) and Adjamé (April 2020).

We used a non-parametric two-sample Kolmogorov-Smirnov test (Marsaglia et al., 2003) to identify approximate significant differences between pairs of curves, both by the distance between curves and curve shape. These pairs included the comparison between the restaurants (Toumodi) and all markets through averaging the number of sellers across all four markets. To look more deeply into differences between pairs of curves, we calculated Fréchet distances using *kmlShape* (Genolini et al., 2016), which too account for the location and ordering of the points in each curve. We used a small 'timeScale' of 0.1 in order to measure differences of general curve shape across time (Dynamic Time Warping) and reduce the influence of time on the curve distance (Euclidean distance) (Genolini et al., 2016). Both the Kolmogorov-Smirnov and Fréchet distance tests were measured for the entirety of the study period and only during the period of governmental measures against COVID-19.

A growth curve analysis using *growthcurver* was conducted for each curve from the time governmental measures were enforced in order to determine relative rate of growth for the markets and restaurants under

a logistic regression model (Sprouffske and Wagner, 2016).

We used the Random Forest algorithm with the package *randomForest*(Breiman, 2001) to undertake a machine learning approach in order to predict what would likely happen in terms of bushmeat site growth after the main study period for each site (from January to September 2021, time of the control survey). Training and test datasets were divided into a ratio of around 80:20, while machine learning robustness was validated using a Root Mean Square Error (RMSE; better models have values closer to zero). We followed two scenarios for the evolution of the sites from January 2021 until when we revisited the sites in September 2021: (i) knowing the initial maximum number of sellers prior to COVID-19 (constraint by maximum capacity for each site), and (ii) not knowing any values post initial study period (no constraint on the predictions).

Results

Our study represented 60 weeks of continuous survey of 132 bushmeat sellers. The largest market was Yopougon Siporex (26 sellers before the COVID lockdown), whereas the smallest market was Abobo (Grand Marché; four sellers). From the two-sample Kolmogorov-Smirnov tests, all curves differed significantly from each other for the entire study period ($p < 0.05$). Fréchet distances also showed a certain level of heterogeneity among bushmeat sites, with Yopougon Siporex and Abobo Grand Marché curves having the greatest distance between each other (distance = 625.85) across the whole study period (Fig. 2).

The number of sellers was stable before lockdown enforcement and started decreasing more or less abruptly from the first week of April in all the bushmeat sites, except in Toumodi restaurants. This was mirrored by the changepoint analysis, as the biggest change in mean for all trends was at the first week of April 2020, except the Toumodi restaurants that had their most important change at the third week of March 2020, i.e. right after the announcement of the ban on bushmeat consumption (Fig. 1, Appendix Table 1). Bushmeat site re-opening was first visible in Abobo Grand Marché and Toumodi (June 2020), before the end of state of health emergency (30 June 2020). Adjamé started reopening in July 2020 (concomitantly with end of lockdown in Abidjan), whereas Abobo Mairie (September 2020) and Yopougon Siporex (October 2020) reopened later, once sanitary measures were lifted. Growth curve analysis suggest that Toumodi restaurants saw the most rapid, but non-significant, growth rate ($r = 0.927 \pm 0.67$, $p = 0.2$), followed by Yopougon Siporex market ($r = 0.508 \pm 0.143$, $p = 0.001$). Adjamé market had the slowest growth rate ($r = 0.105 \pm 0.043$, $p = 0.02$), followed by Abobo Grand Marché market ($r = 0.128 \pm 0.072$, $p = 0.08$). Toumodi restaurants, Abobo Grand Marché and Adjamé markets had relatively high levels of standard error in the growth rate estimates.

During the period under governmental measures, two-sample Kolmogorov-Smirnov tests indicated that Toumodi restaurants significantly differed from the combined bushmeat markets ($D = 0.57$,p -value < 0.001), with the markets being completely closed following the first months of lockdown and the restaurants only closing for a period c. two months and a half. This period saw significant differences across most comparisons, except between the Toumodi restaurants and Adjamé market ($D= 0.2$, p -value$= 0.379$), as well as Yopougon Siporex and Abobo Mairie markets ($D= 0.14$,p -value$= 0.524$) trends. Fréchet distances suggested Yopougon Siporex market and Toumodi restaurants were the most divergent (distance = 130.88), while Yopougon Siporex and Abobo Mairie markets were the most similar (distance = 30.42; Fig 2).

In January 2021 (end of the survey), all the bushmeat sites exhibited lower numbers of sellers than before lockdown, whilst the control survey in September 2021 yielded the same result with the exception of Abobo (same as before lockdown) and Toumodi (higher than before lockdown). In all cases and models (with or without constraint), forecasting predictions after 76 weeks since the beginning of lockdown were inferior to the initial numbers of sellers (Fig. 3), with unconstrained models yielding lower estimations. Both models yielded predictions of number of sellers inferior to observed values after 76 weeks for Abobo Mairie and Grand Marché markets, and Toumodi restaurants. The number of sellers in Adjamé market was over-predicted by both models, while for Yopougon Siporex market the unconstrained model yielded inferior predictions and the constrained model higher predictions relative to the observed number. The two models yielded the most dissimilar predictions for Adjamé market (unconstrained model yielded simulated value closer to

observed value) and Toumodi restaurants (constrained model yielded simulated value closer to observed value). Toumodi predictive models had the highest averaged RMSE values (0.47) and lowest proportion of variance explained (50.47%), while Yopougon Siporex had the lowest averaged RMSE (0.16) with high levels of variance explained (92.51%) (Table 1).

Discussion

Our study encompassed a large timespan (60 weeks) and a variable spectrum of bushmeat site categories including small to large urban bushmeat markets and chop chop bars (*maquis*). Although more accurate proxies of the trade dynamics were not investigated (e.g., trends in biomass and income), our unprecedented survey design allows, for the first time, to assess African bushmeat trade dynamics during and after a national ban.

Trade dynamics in Côte d'Ivoire as measured per number of sellers was strongly, negatively impacted by the COVID-19 lockdown and bushmeat ban, as all bushmeat sites went down to a null number of sellers right before or after the first governmental decisions were taken. This is in line with our original expectation on the efficiency of governmental measures. A significant reduction in carcass numbers was also observed in Nigeria after lockdown (Funk et al., 2021). The COVID-19 pandemic has shown that African states can be efficient in mitigating the bushmeat trade when resources are duly mobilized, a notable point considering the ongoing bushmeat crisis and the zoonotic outbreaks to come (D'Cruze et al., 2020; Reynolds et al., 2019).

However, we observed significant differences in the dynamics of bushmeat sites both during and after the strongest measures taken against the COVID-19 pandemic, deviating from our posited expectation on trends being similar between market types (as a measure of the effectiveness of government interventions). We speculate that bushmeat trade dynamics are affected by a combination of intrinsic market characteristics and dissimilar levels of governmental interventions. For instance, Toumodi restaurants were first to be fully closed (mid-March 2020, concomitantly with the announcement on the bushmeat ban) and first to start re-opening, at a time when all the bushmeat markets in Abidjan were closing (early June 2020). This suggests that predicting bushmeat trade dynamics under bans or restrictions is geographically and typologically (i.e., type of market) dependent. State authorities may have been more zealous in Toumodi by quickly applying the bushmeat ban before the decision on closing *maquis* one week later, but prompt to release pressure on sellers from a zone not affected by the lockdown (which was restricted to Abidjan).

The Ivorian state was permissive with the resumption of the bushmeat trade, as we observed a progressive return of sellers on the bushmeat sites before the sanitary measures were lifted. Although global trajectories among bushmeat sites were similar throughout the survey period, significant trend differences were observed during the constrained period. This reinforces our view that the dynamics of the bushmeat trade are site-specific and shaped by multiple factors. In our case, small (Abobo Grand Marché) or poorly accessible (Adjamé) markets could have been less controlled than the largest bushmeat market of Abidjan, Yopougon Siporex. The latter is clearly identified as the main hub of the bushmeat trade in Côte d'Ivoire (Gossé et al., 2022) and was the last to show sign of resumption, after the end of the sanitary measures against COVID-19 (October 2020).

The COVID-19 lockdown and bushmeat ban had a long-term impact on the bushmeat trade dynamics, as three months after the end of governmental measures all the bushmeat sites in Côte d'Ivoire exhibited lower numbers of sellers than before (c. 63 to 91% of the initial numbers). This effect was still prevailing in three of the bushmeat markets from Abidjan during our control survey eight months later (c. 56 to 91% of the initial numbers), despite stronger growth rate in large markets such as Yopougon Siporex. This clearly violates our initial assumption of market network resilience to the lockdown.

Forecasting predictions after 92 weeks since the start of sanitary measures in Côte d'Ivoire showed contrasting outputs relative to observed number of sellers. Most of the bushmeat sites were not optimally modelled due to their heterogeneity in growth, especially Toumodi restaurants. Random Forest algorithms performed better in the case of Yopougon and Abobo Mairie markets, where predicted values from both models converged closer to observed values. Convergence between constrained and unconstrained models may serve as an additional

confidence estimate of model performance, coupled with the intrinsic estimates already available (RMSE and variance). Further investigations on Random Forest algorithms as applied to bushmeat trade dynamics over longer periods of time will have to be undertaken before the benefits of such predictive approach can be considered (e.g., as in finance research; Ghosh et al., 2022).

We conclude that neglecting the socio-geographical specificities of the different types of bushmeat sites could lead to erroneous projections of bushmeat trade dynamics. Eleven months after the end of governmental measures in Côte d'Ivoire, most of the bushmeat sites had not fully recovered in terms of number of sellers. Whether regular controls have slowed down the resumption of the trade requires further investigations. The social and economic implications behind the lack of the full recovery of certain markets at the time of our study, including that of the largest bushmeat market of Côte d'Ivoire, is unknown. Given the possible precariousness of certain bushmeat sellers (see Falola et al., 2015), it is likely that some could not economically support the consequences of a national ban for several months. However, with the data at hand, it remains hazardous to discuss the deleterious economic shockwave foreseen by some authors in relation to wildlife trade bans (e.g., McNamara et al., 2020), especially since future disease outbreaks and reduction in resources through over-harvesting will likely influence market dynamics under the current tolerated market scenario.

Understanding bushmeat trade dynamics in the context of mitigation measures will require a multi-dimensional approach where the characteristics of the different markets (e.g., type of markets, socio-demography of vendors, ban record, species hunted and places sourced) are clearly identified. Our study showed that wildlife trade bans can have a long-lasting impact on bushmeat trade dynamics, and that state power when guided by a clearly defined objective can efficiently setup trade mitigation, at least in the short-term. Actual mitigation of the bushmeat trade, whether conservation- or health-driven, will depend on a comprehensive understanding of its specific dynamics and the economic reliance of involved actors. To reach this objective, less talk, and more on-the-ground data with comprehensive modelling will be required.

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Table 1. Input variables and model fit results for the predictive models per bushmeat site.

The models were either constrained (grey row) by the highest number of sellers prior to COVID-19 for each site, or not constrained (no color). They were run under a machine learning approach using the Random Forest method in which we provided a training and testing dataset (ratio of around 80:20 of data, excluding missing data). Model fit was determined by percentage of variance explained and the Root Mean Square Error (RMSE), which was standardized by number of sellers per site (RMSE closer to zero equals more confidence).

Market	Ratio training:test datasets	Number of sellers (September 2021)	% variance explained	% variance explained (averaged per site)	RMSE	Standardized RMSE (averaged by n sellers)
Yopougon	35/10	22	92.43	92.51	0.63	0.09403
Yopougon	35/9	22	92.59		1.5	0.223881
Abobo Mairie	35/10	10	96.93	96.28	1.42	0.367876
Abobo Mairie	35/9	10	95.63		0.7	0.181347
Abobo Grand Marché	35/10	4	71.21	68.975	0.56	0.254545
Abobo Grand Marché	35/9	4	66.74		0.41	0.186364
Adjamé	32/8	9	83.93	79.725	1.45	0.239669
Adjamé	32/7	9	75.52		1.22	0.201653
Toumodi	33/	25	46.56	50.465	2.49	0.559551
Toumodi	33/7	25	54.37		1.73	0.388764

Figure legend

Figure 1. Variation in the number of sellers at the five bushmeat sites surveyed in Côte d'Ivoire before, during and after the governmental measures against the COVID-19 pandemic. X-axis represents 60 weeks of survey.

Main governmental measures and relaxes (following Milleliri et al., 2021): A - 16 March 2020: suspension from entry into Ivory Coast of foreigners, closure of teaching establishments, prohibition of people gathering, suspension of cultural events, application of barrier measures, strict ban on the consumption of bushmeat (*Communiqué du Conseil National de Sécurité du 16 mars 2020*); B- 23 March 2020: declaration of state of health emergency, establishment of a curfew, lockdown of Abidjan, closure of *maquis* (chop chop bars) and restaurants (*Décret n°2020-351 du 23 mars 2020*); C- 9 April 2020: obligation to wear masks in Abidjan, mandatory confinement for vulnerable people, implementation of telework, reduction of the number of passengers in public transports; D- 15 May 2020: end of the curfew in Abidjan; E- 25 May 2020: reopening of teaching establishments; F- 30 June 2020: end of state of health emergency.; G- 1 July 2020: end of suspension from entry into Ivory Coast of foreigners; H- 15 July 2020: end of lockdown of Abidjan; E- October 2020: end of sanitary measures.

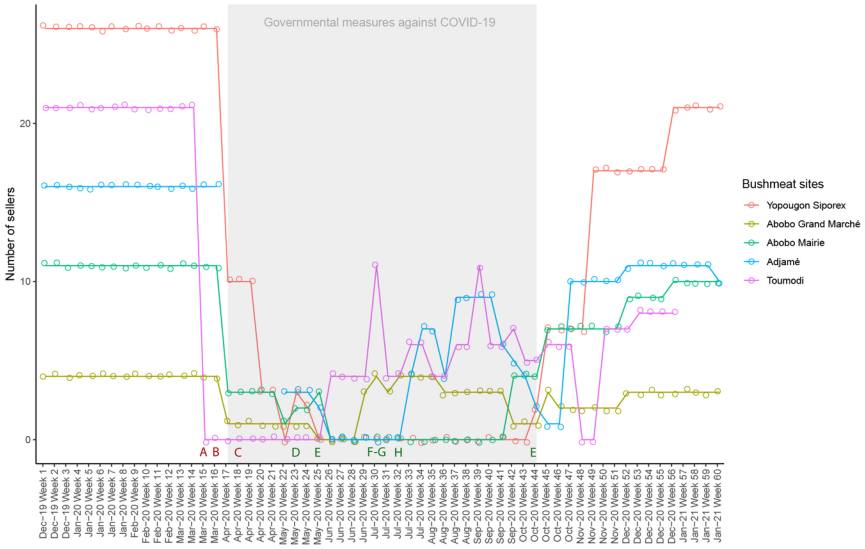

Figure 2. Heatmap of Fréchet distances between trend curves of seller numbers for the five bushmeat sites surveyed in Côte d'Ivoire.

A: whole survey period. B: period of governmental measures only. Below grey diagonal (red tones): sum of the distances. Above the grey diagonal (blue tones): maximum distance found across all sites.

A	Toumodi	All Markets	Yopougon Siporex	Abobo Grand Marché	Abobo Mairie	Adjamé
Toumodi	x	7,33	13	17	10	5
All Markets	238,84	x				
Yopougon Siporex	327,78		x	22	15	11
Abobo Grand Marché	357,18		625,85	x	7	12
Abobo Mairie	261,96		361,72	245,12	x	5,02
Adjamé	166,72		329,26	355,9	141,38	x
B	Toumodi	All Markets	Yopougon - Market	Abobo Grand Marché	Abobo Mairie	Adjamé
Toumodi	x	7	10	7	7	4
All Markets	104,36	x				
Yopougon Siporex	130,88		x	9	7	7

A	Toumodi	All Markets	Yopougon Siporex	Abobo Grand Marché	Abobo Mairie	Adjamé
Abobo Grand Marché	57,24		71,86	x	3	5
Abobo Mairie	77,37		30,42	46,36	x	5
Adjamé	41,81		82,96	53,22	41,39	x

Figure 3. Modelled trends in number of sellers at the five bushmeat sites surveyed in Côte d'Ivoire after the end of the survey period. Red line indicates the modelled growth curve during the survey period and stops at week 60 (survey completion). Blue line indicates post-survey predictions without model constraint, while green line indicates predicted values with model constrained by maximum number of sellers prior to COVID-19 (ultimate circle on the top right of each graph). Point "x" refers to the numbers of sellers during the September 2021 control survey.

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Appendix Table 1. Number of sellers observed at the five bushmeat sites surveyed in Côte d'Ivoire before, during and after the COVID-19 lockdown. [Excel table]

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Appendix 1. R scripts related to the analyses conducted as part of this study [R document]