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Valuing natural capital and its distribution in the Congo Basin forests.

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Abstract
Efforts to balance national economic development and global environmental sustainability in the forests of the Congo Basin can be informed by natural capital accounting. We contribute an initial estimate of the gross value of the Congo Basin forests (in 2019) for four provisioning services (industrial timber, artisanal timber, fuelwood, and bushmeat), one cultural service (tourism), and one regulating service (carbon sequestration). We estimate the distribution of ecosystem service values across land use categories, based in part on mapping customary tenures using a cumulative cost method, thus tying value production and associated incentives to the economic agents who manage forest natural capital. We find a total (i.e. regional) gross annual value for the Congo Basin forests of 2019 USD$ 7.8 billion (equivalent to 6.3% of regional GDP; comparisons with GDP are indicative only because our figures include the value of intermediate inputs). Total gross value is evenly split between lands under legally recognized statutory tenure and areas under alternative tenure arrangements. Values per unit land range from a high of $159.16/ha in community forests to a low of $0.10/ha in Pygmy areas. For carbon services, we compare three prominent approaches for estimating volumes. We find marked variation in both total volumes and the distribution of volumes across public and private economic agents, with significant implications for ongoing efforts to monetize carbon services in the Congo Basin. Our approach and results address critical issues not only of the value of forest assets in the Congo Basin (as well as attendant ambiguities), but also to whom this natural capital value might accrue if demonstrated value is aligned with value realization.

Keywords
Carbon, Congo Basin rainforest, Distribution, Ecosystem services, Natural capital accounting

JEL Codes
Q56, Q57

1. Introduction

Conserving the world's remaining tropical forests is a crucial bulwark of global environmental sustainability.[1] Conversely, resource extraction and land-use change are core features of economic development in forested countries. There remains an unresolved challenge in aligning conservation targets with economic development objectives, especially in low-income countries where tropical forest is located.

The tropical moist forests of Central Africa (see 2.1 for definition) exemplify this grand challenge. Colloquially known as the Congo Basin forests, these resources are distributed across six countries: Cameroon (CMR), the Central African Republic (CAR), the Democratic Republic of the Congo (COD), Equatorial Guinea (GNQ)[2], Gabon (GAB) and the Republic of the Congo (COG). Together, these countries are home to rapidly growing and urbanizing populations totalling 121 million persons. Intergovernmental reporting in the 7th *State of the Forests* report finds that forests "provide a livelihood" to 60 million, and "help to feed" a further 40 million in towns and cities (Dalimier et al. 2023:4). More precise assessments have been elusive, but the Congo Basin forests clearly play a central role in the economic lives of national populations.

This role is shaped by the integration of forest resources in daily life. Many people in the Congo Basin live in or amongst tropical moist forest: (Newton et al. 2020) find that COD has the highest population share living *proximate* (≤1 km) to forests among any tropical nation, at 60.2%. Our calculations in S.I.1.2, which use the forest and population datasets that underly our distributional analysis,[3] find that 13% of COD's population lives directly *in* forests. The figures are comparable in GNQ (34.57% proximate to forests vs 50.29% in forests), CMR (42.2% vs 12.01%,), and GAB (24.17% vs 30.26%). The situation is somewhat different in (more arid) CAR (34.49% vs 3.27%) and (highly urban) COG (3.71% vs 10.73%).

Clearly, *who* (i.e. which economic agents) interacts with forest resources and *how* (i.e. via which production and consumption systems) is of central interest for both scholars and practitioners of sustainable development in the Congo Basin. The picture that emerges from prior work is of a relatively massive agroforest economy oriented around household production (Mayaux et al. 2013; Shapiro et al. 2022), evidenced by the preceding population shares, which is now adapting to ongoing urbanization (OECD et al. 2025) in part via increased entrepreneurial supply of forest-derived fuels and protein to cities (Schure 2014; R. Nasi, Taber, and Van Vliet 2011). The expansion of smallholder agriculture via 'rural complexes' of roads, settlements, and fields is the primary (direct) cause of changes in forest extent and condition (*FRA 2020 Remote Sensing Survey* 2022; Shapiro et al. 2022), while over-harvesting for domestic and export markets is the most important threat to commercial timber species (Ceccarelli et al. 2022).

[1] Where environmental sustainability can be understood in the sense of conserving renewable natural capital (e.g. (D. Helm 2015) or reducing global environmental risks (e.g. (E.B. Barbier 2022).
[2] Severe data scarcity forces us to exclude Equatorial Guinea from analysis.
[3] The large differences between our figures and Newtown et al. (2020) should highlight the importance of data inputs and mapping standards in any natural capital accounting exercise, a point we partly explore in our examination of alternate forest cover maps in SI 2. As a trivial example, the apparent contraction our of competing figures for CAR is likely due to our use of a map of *moist tropical* forest, as opposed to the more general forest definition used by Newton et al.

One approach to the economic development challenges of the Congo Basin is to begin by conceiving of ecosystems as assets, with stocks producing streams of ecosystem services that are inputs to economies and so to human wellbeing. Natural capital accounting (NCA) then provides one building block for sustainable development, by establishing a statistical basis for making prudent decisions about economic development that may require sustaining the value of natural wealth. However, particularly in rapidly growing, low-income countries, whether natural capital values translate into tangible development opportunities, and for whom, are critical questions. Our contribution in this paper is thus two-fold.

First, we provide an estimate of the *gross value*[4] of the Congo Basin forests for a single year (2019). This comprises four provisioning services (industrial timber, artisanal timber, fuelwood, and bushmeat) and one cultural service (tourism). We additionally assess one regulating service (carbon sequestration). While the valuation of ecosystem services is now commonplace, primary data on forest values in Africa are extremely scarce (Archer et al. 2018).[5] Focusing on a single year 'snapshot' allows us to construct relatively detailed estimates from the available data, which often do not support repeated measures.

Second, we estimate the *distribution* of natural capital value among categories of land use both across and within our study countries. If natural capital (thus ecosystem services) has significant economic value, then the distribution of this value should also be of interest from a development perspective. Our contribution is to tie values, via land use, to the economic agents whose decisions will shape the future of the Congo Basin forests. In supplementary information to this paper (SI 1.1), we assess prior valuation estimates in forest landscapes in Africa. A marked disparity is evident in these studies between ecosystem services with a realized financial value (i.e. those which are transacted on current markets), which tends to accrue to local or national communities, and vastly larger global benefits which remain entirely nominal.

While natural capital studies such as (Platts et al. 2023) and (Oguge 2022) have focused on the consumption of ecosystem services when discussing distributional questions, our contribution is somewhat different. We build on Atkinson and Ovando (2022) and value distribution in the ecosystem services *supply* (i.e. production value). Our distributional analysis relies on identifying the ownership characteristics of land on which natural capital is located and managed. In the Congo Basin forests this necessitates several considerations (Section 2.5) regarding economic (as opposed to legal) ownership of land and a distinction between legal tenure systems and customary rights (e.g. (McDermott, Mahanty, and Schreckenberg 2013; Benra and Nahuelhual 2019).

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[4] Gross value is obtained by multiplying physical output volumes by (market) prices per unit output. Lack of reliable data prevent us from deducting the value of intermediate inputs, as in the Gross Ecosystem Product measure proposed by (Ouyang et al. 2020), meaning comparisons with GDP offer a comprehensible yardstick rather than a quantitative statement. A further complication arises because many ecosystem services should be treated as intermediates in GDP calculations, but harmonization is not (yet) practiced.

[5] For example, a comprehensive recent survey of the literature (Siikamäki et al. 2021) located estimates in Cameroon only. While large-scale valuation efforts often invoke "benefit transfer" to impute estimates for data-deficient regions (e.g.(Chiabai et al. 2009; Siikamäki et al. 2021) there are both theoretical and empirical reasons to be cautious about this approach (e.g. (Taye et al. 2021; Turpie et al. 2017). See SI 1.1.

Our key findings are as follows: for our four provisioning services and one cultural service, we find a total (i.e. regional) gross annual value for the Congo Basin forests of 2019 USD$ 7.8 billion, a value equal to 6.3% of regional GDP. This ranges from 5.2% of GDP in CMR to 8.1% in CAF. The regional value is evenly split between lands under legally recognized statutory tenure (domestic and foreign industrial forest concessionaires, community forests, and protected areas administered by national governments) and areas under alternative tenure arrangements (customary tenure, Pygmy habitation areas, and open access). On average, the per unit value[6] of customary tenures ($53.33/ha) is surprisingly close to that of industrial forestry concessions ($56.43/ha), and community forests have the highest values per unit land (2019 USD $159.19/ha).

These figures do not include the economic value of regulating services provided by the Congo Basin forests, in part because prices (USD$ / tCO_2^e) in a hypothetical regional-scale carbon market are unknown (thus *values* are speculative/incomparable). A more serious problem is that the *volume* of carbon services provided by forests can be measured in very different ways. One approach, most obviously consistent with NCA's focus on stocks of assets over time, is to estimate the volume of carbon services by comparing current-year carbon stocks against the prior years' stocks (e.g. $\Delta_{2019\text{-}2018}$). Using this "net flux" approach we find negative changes for all countries except GAB, with important distributional nuances: protected areas in all countries, Pygmy areas in COD and COG, and forest concessions in CMR generate positive carbon values under net flux accounting in 2019.

However, public and private sector efforts to monetize the value of regulating carbon services under Reducing Emissions from Deforestation and forest Degradation in developing countries (REDD+) have taken a very different approach to measuring carbon service volumes, based on accounting against a counterfactual (unobserved) baseline. We apply stylized versions of the two most popular methods: historical baseline accounting (comparing current year stocks against a lagged 5-year average) produces a regional supply estimate of *negative* 518.05 Mt C (i.e. a liability), whereas using a projected baseline (a 5-year nonlinear trend) finds a service volume of 24.28 Mt C in 2019.[7]

The significance of our results attaches to a number of interrelated issues in economic development. For example, our distributional approach focuses on spatial heterogeneity in ecosystem service value provision within countries: by identifying the economic agents exercising management control over the natural assets at issue (forests), our results may inform research and policy which target relevant incentives. But this effort also sheds light on questions about wealth distribution, which may arise from an equity perspective or from concerns about the sources of economic growth.

It is important to recognize that NCA (like any accounting system) exists to *demonstrate* natural capital value: the accounting structure and its alignment with the national accounts provide a

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[6] Note that converting per ha figures to land *asset* values would require assumptions about the pace and longevity of future extraction for each underlying ecosystem service.

[7] Because 'net flux' accounting compares stocks against the prior year, it may be viewed as a case of historical baseline accounting with a moving 1-year lag. This masks a fundamental difference: baseline accounting assumes that past performance predicts future performance, while net flux accounting does not.

pathway for NCA to inform policies that *realize* this value, but this is not guaranteed. At present, a clear 'implementation gap' is discernable where NCA and high-level policy commitments surrounding natural capital have generally not yet produced observable changes in policies (Brandon et al. 2021; Miteva 2019; Ruhl et al. 2021). One explanation, as found by (Willcock et al. 2016) in a survey of sub-Saharan Africa, is that stakeholders find current NCA data insufficient for policy-making (e.g. insufficient spatial resolution).

A different explanation for the 'implementation gap' arises from drawing a distinction between how the value of natural capital is actually distributed under current institutional arrangements, and how it could potentially be distributed in order to bring all relevant environmental costs and benefits into decision-making. Use-based estimates of natural capital value tend to illuminate the latter, for example by demonstrating the global value of regulating services provided by tropical rainforests. By contrast, our focus on the supply of marketed ecosystem services and the owners/managers of land aims to shed light on the incentives underlying decisions about forest management in the Congo Basin today. The obvious question is whether new institutional arrangements can bring realized and potential values into alignment.[8]

This tension between demonstrating and realizing value is acute for carbon services. Not only does the realization and distribution of value depend on principles assigning carbon rights (yet to be clarified even under legally recognized tenure arrangements), but the practical carbon accounting method used to assess value has strong implications. Our carbon results are intended to elucidate, in a preliminary way, the distributional implications of different accounting philosophies, and shed some new light on the challenges faced by policy-makers urgently seeking to mobilize climate finance for development in the Congo Basin.

A number of caveats characterize our study. Some of these relate to our omission of ecosystem services whose economic importance is increasingly recognized but either: insufficient data exist for spatializing value estimates, as in the case of Non-Timber Forest Products (NTFPs) (Ingram et al. 2011) and inland fisheries (Inogwabini 2014); or the scientific basis for estimating production volumes (per unit forest land) is immature, as in the case of rainfall provision to agriculture areas in the Sahel and Eastern/Southern Africa (Duku and Hein 2021; Nyasulu et al. 2024).

For those ecosystem services which we assess, while we have sought to discover and utilize all relevant information, the dearth of primary data forces the use of sometimes strong assumptions and precludes a statistical evaluation of the uncertainty of our results.[9] Our results may be contrasted to two recent regional studies: in the Brazilian Amazon (Strand et al. 2018) draw on a small constellation of regionally-specific ecosystem service models to produce spatially explicit

[8] We note that for forests under customary ownership regimes, there exists both a real value (from current economic activity) and a potential value if novel institutional arrangements formalized what currently implicit (with potential differences in value arising from changes in use under alternate assignments of rights, for example via collateralization).

[9] Many of the published data on which we draw lack associated error estimates, preventing Gaussian quadrature, and the distributions of many key parameters are also unknown, implying that Monte Carlo simulation will be largely based on guesswork. We argue that error quantification would give merely an illusion of statistical rigour under these circumstances.

marginal values for ecosystem services, while in Tanzania's Arc Mountains (Platts et al. 2023) rely on ten years of fieldwork and model-building to perform ecosystem service accounting (as here). In our context, the absence of reliable cost data for most services necessitates our use of gross metrics (i.e. output volume times price per unit output) because data on costs, essential calculating streams of rental income, is simply not regionally available.

These caveats notwithstanding, the urgency of conservation and development problems demands an initial, if imperfect, assessment of the value of Congo Basin forests. Given the policy context of accelerating interest in monetizing natural capital in Africa (e.g. (*Natural Capital and Economic Productivity in Africa* 2024), our approach and results address the critical issues of *to whom* natural capital value might accrue if demonstrated value is aligned with value capture.

The remainder of this paper is organized as follows: Section 2 provides relevant details of our study region, while Section 3 overviews methods and data for valuing each service and our distributional analysis. Each subsection (3.1 – 3.7) has a corresponding SI entry containing ancillary information. Section 4 sets out results, and Section 5 concludes.

2. Study region

We analyze the distributional supply of gross output in 2019 from the tropical moist forests of Cameroon (ISO3 code: CMR), the Central African Republic (CAF), The Democratic Republic of the Congo (COD), The Republic of the Congo (COG), and Gabon (GAB). While Equatorial Guinea also contains tropical moist forests, we exclude it as statutory tenure data are not available.

2.1 Forest definition

We study the (distributional) natural capital value of Central African tropical moist forests (Fig. 1a), known colloquially known as the Congo Basin forests. Scientific understanding of the floristic and functional composition of these forests continues to evolve, with multiple classification schemes proposed (Dalimier et al. 2023). Recent work (Réjou-Méchain et al. 2021) has highlighted substantial diversity in both composition and vulnerability to climate change and anthropogenic disturbance, with the northern and southern forest margins, coastal (Atlantic) forests, and moist forests in the Democratic Republic of the Congo deemed most vulnerable. At present, structurally intact (i.e. undisturbed or "old growth") tropical rainforest in Africa appears to be a stable sink of carbon (Hubau et al. 2020), and carbon sequestration in regrowing secondary or degraded forests appears to be significant (Heinrich et al. 2023). Expert opinion focuses on agro-industrial plantations, subsistence agriculture, and timber harvest as the major driers of forest cover loss (Tegegne et al. 2016); analyses based on satellite imagery show that small-scale production by rural households is overwhelmingly the most important direct driver of forest cover change ((Tyukavina et al. 2018) find that 82.1 ± 1.8% of forest cover loss in the region is due to clearing for rotational agriculture by smallholders; (Shapiro et al. 2023) find that around 70% of deforestation and forest degradation results artisanal agriculture co-occurring with road and settlements in 'rural complexes').

We define Congo Basin forest area and analyze changes over time using the Landsat-based Tropical Moist Forest (TMF) dataset (Vancutsem et al. 2021). We use the TMF data because detection of small-scale disturbances (notably logging) appears to be significantly improved versus the widely-used Global Forest Change dataset (Hansen et al. 2013), change detection is consistent over our study period, and forest dynamics beyond loss (i.e. degradation, deforestation, regrowth) are tracked (thereby enabling more accurate carbon accounting). Any forest definition comes with trade-offs and should be made on a task-specific basis. Most of our estimates rely on undisturbed, degraded, and regrown landcover classes in the TMF 'Annual Change dataset'. Our forest area estimates are within 1.8 – 10.5% of official estimates collected by the Food and Agricultural Organization of the United Nations (except for CAR; see Appendix 2.1).

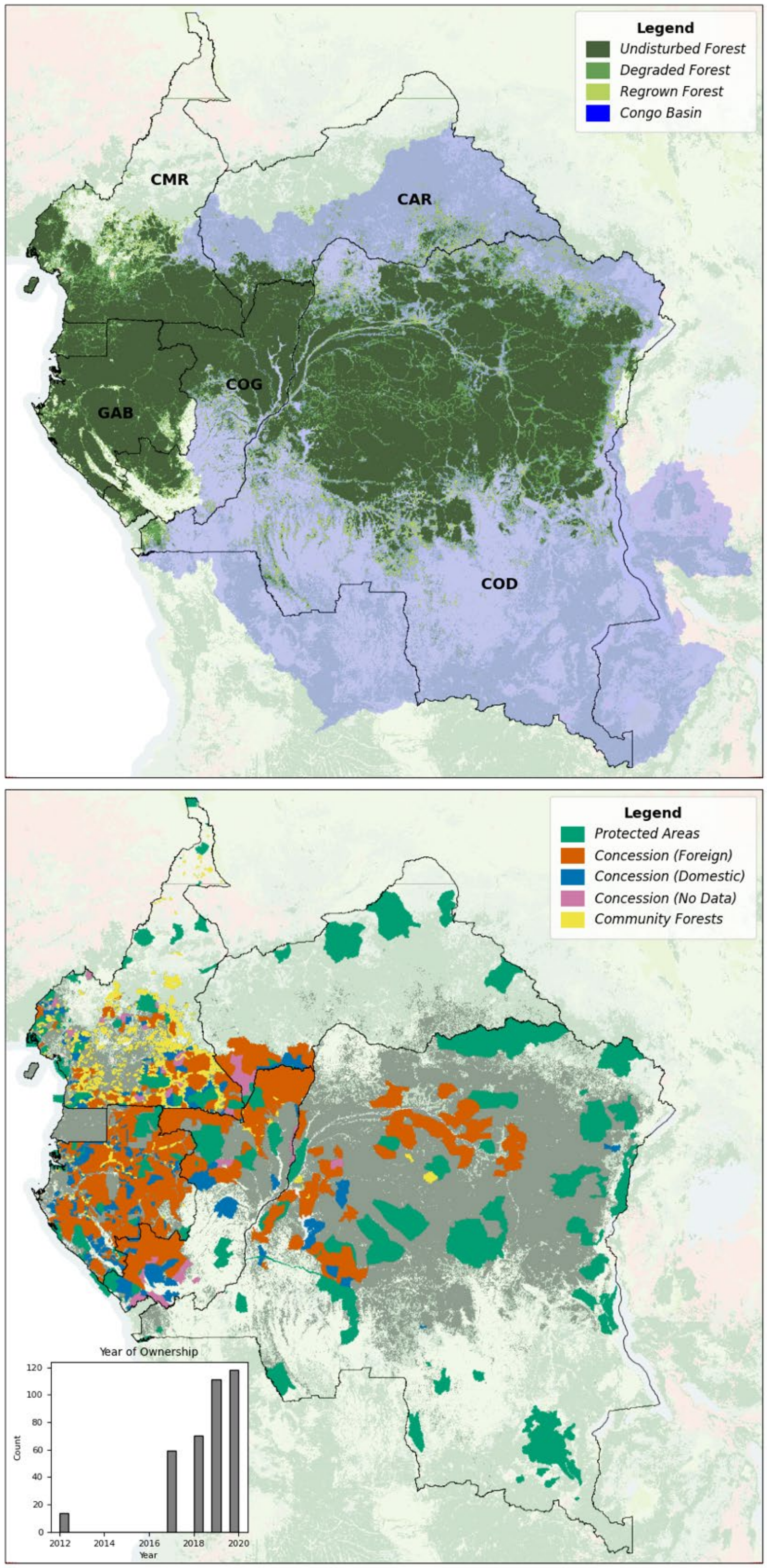

Figure 1. *Study area.* ***Top:*** *Tropical moist forests (Vancutsem et al. 2021) superimposed on the Congo Basin watershed (Linke et al. 2019). We follow common usage and use 'Congo Basin forests' to refer to the entire tropical moist forest area in our study countries.* ***Bottom****: Statutory tenure data used in our analysis; inset shows year at which industrial forest concession ownership was observed.*

2.2 Markets

Ecosystem services produced by Central African forests are consumed for subsistence and traded on local, regional, and international markets. Woody forest biomass is extracted for timber and fuel, with subsistence use of wood for energy potentially accounting for as much as 90% of woody biomass removals (Schure et al. 2012) (Masera et al. 2015). Fuelwood (especially charcoal) and artisanal timber are important domestic commodities with complex supply chains and probably a significant regional trade in border areas (Lescuyer et al. 2012; Ferrari and Cerutti 2023); despite well-developed markets, reliable data are scarce (Ferrari and Cerutti 2023; Masera et al. 2015). Industrial timber markets are better monitored via international reporting exercises, but statistics are often unreliable (Jianbang Gan et al. 2016; Bayol et al. 2022). Industrial production tends to concentrate in "flagship species" and is commonly reliant upon foreign capital (Bayol et al. 2022). There is substantial trade of intermediates between the artisanal and industrial sectors, with 9.6-50.7% of artisanal timber supply apparently originating in industrial scrap (Lescuyer et al. 2012); SI 3.4).

Congo Basin forests also provide significant quantities of bushmeat and edible or culturally/medically important plants and animals (NTFPs). The production and consumption of these services varies greatly with household composition (e.g. age/gender) and socioeconomic status, as well as location (e.g. rural/urban) (R. Nasi, Taber, and Van Vliet 2011; Ingram et al. 2011).[10] No systematic data are available and extrapolating from ad hoc studies is greatly complicated for NTFPs due to the wide variety of products harvested. Tourism production is similarly highly (spatially) variable and difficult to assess: unlike the high-profile international tourism sectors of Eastern and Southern Africa, access barriers in the Congo basin have been over overcome by only a few operators in few locations (Telfer and Reed 2021). While the potential of forest ecotourism has long recognized (Wilkie and Carpenter 1999) development has been slow. Data on national tourism revenues are available from the World Tourism Organization, but accuracy of these statistics and potential omissions (notable domestic tourism and foreign tourists arriving via land crossings) is unclear.

The physical dynamics of carbon storage and sequestration in the Congo Basin are increasingly well understood (e.g. (Hubau et al. 2020), but the monetary value of this service is hotly contested. It is important to recognize that monetary values attach to service volumes, which are defined by carbon accounting rules. These rules are novel institutional arrangements designed to incentivize climate mitigation by creating a scarcity price signal from a physically abundant resource. Choices about carbon accounting clearly could benefit some groups more than others, and carbon markets have not yet matured sufficiently to evolve a consensus solution. The Congo Basin hosted just one afforestation project under the Clean Development Mechanism (Louhisuo and Azuma 2024); currently, there are 31 Voluntary Carbon Market projects (Haya et al. 2025), for which 41.9/42.9 $MtCO_2^e$ total credit issuances are from REDD+ projects (and 28/31 are accredited by the VCS scheme).

[10] For example, rural households produce for self-consumption and sale; urban households consumer (often higher-valued products) bought at market; certain NTFP products may be preferentially produced by economically vulnerable persons (children, the elderly)

State-led REDD+ projects are also important (and increasingly implemented at jurisdictional scales): the ID-RECCO database lists 11 projects under development, with the first state-to-state payments (Norway to Gabon) having occurred in 2021. Despite sustained interest in harnessing forest carbon markets for REDD+, choice of accounting framework is problematic (see Section 3.2) and the impact of established projects is in serious doubt (e.g. (West et al. 2023); second-order policy issues include tensions between public (i.e. Paris Article 6) and private (i.e. Voluntary Carbon Market) approaches, as well as equity and benefit-sharing.

2.5 Tenure

While the distributional analysis in Atkinson and Ovando (2022) relies on a database of land ownership, necessitating a distinction between legal owners and the agents who manage natural capital (e.g. tenants), our approach focuses on land use categories (tenure types) associated with specific categories of economic agents. This is complicated by relatively complex and frequently contested tenure systems in the Congo Basin. The colonial-era imposition of European tenure systems in Central Africa arguably overlaid rather than replaced older institutions; as elsewhere in sub-Saharan Africa, customary (i.e. local- or community-based) tenure systems frequently remain the most important determinant of rights to manage and extract natural resources (Cotula 2007; Bruce 1998). Relatively rapid post-independence evolution of land tenure regimes further complicates the conceptual picture, and data availability remains a constant challenge. While progress has been made (notably by WRI's LANDMARK initiative), no reasonably complete spatial database of customary tenure is available for the Congo Basin forests.

Given these challenges, we proceed as follows. We first consider statutory tenure (i.e. those rights which flow from the state, which may largely embody an inherited European apparatus), collecting existing maps of forest concessions, protected areas, and community forests at the most recent date available. We then produce new maps of customary tenure following a proximity-based approach (Section 3.1.2), combining spatialized population density estimates with satellite observations of the extensive margin for small-holder agriculture ((Newton et al. 2020) discusses the challenges - and necessity - of this proximity-based approach). We then map 'ecosystem service supply areas' in a similar fashion for two services (fuelwood and bushmeat) whose production is not restricted to agricultural tenure boundaries. In a final step, we identify areas inhabited by Pygmy peoples using published maps of potential habitat, acknowledging that this exercise is demonstrative and that Pygmy tenure claims may not be widely recognized. These steps are described in detail in Section 3.1 and Appendix 3.1 (see Table S.3.1.2 for the rules used to reconcile overlapping tenures); in the remainder of this section, we elaborate key conceptual information about the allocation of rights in the Congo Basin forests.

While there are many differences in detail and context, national governments are the ultimate owner and custodian of the Congo Basin forests. Relatively little forest land is owned privately, primarily in COD and GAB (< 15% of total in both cases). All study countries demarcate their forests as belonging to either the permanent (PFE) or non-permanent forest estates (NPFE) (Forest Legality Initiative, 2013; The Rainforest Foundation, 2013), although terminology for this sometimes differs.[11] NPFE land is legally eligible for conversion to non-forest land uses, as development needs require. Within the PFE, sub-categories of zoning are often specified. For example, in CAR, PFE may be demarcated for production, plantation, or conservation. In CMR, PFE must constitute at least 30% of national territory – but this total may include both protected areas (where forest use is highly circumscribed) and forest concessions.

The continuity of colonial-era legislation in our study countries is a matter of extent, with GAB arguably exhibiting the most explicit retention of pre-independence land laws. All countries have undertaken significant reforms to existing forest codes or established entirely new codes over the past two decades. We refer to the resulting formal means of awarding forest tenure as 'tenure types' (from 6 in CAR to 11 in GAB). These govern the award of land tenure and circumscribe related matters such as duration, rights, and responsibilities across the PFE and NPFE, collectively providing the legal basis for awarding tenure to private agents (enterprises and individuals) or establishing community forests and recognizing customary rights across the forest estate (PFE and NPFE). It is these instruments for assigning tenure that, in turn, distribute rights most notably related to timber and non-timber forest products and, in some cases, carbon rights. Table 2 summarizes the resulting allocation of rights across our study countries.

Rights relating to timber harvest are the most prominently and consistently defined in the tenure types we reviewed, which typically clarify several qualifying criteria. These may include maximum holding sizes to which the tenure arrangements apply, the eligibility of certain classes of agents to hold tenure, the character of the application process, and various responsibilities and obligations subsequently imposed. For example, in CMR, large timber concessions are subject to a competitive bidding process in which both individual citizens (or naturalized residents) and companies registered within the country can participate, with awardees required to prepare detailed management plans over the 30-year lifetime of the concessions and update them every 5 years. Short-term logging permits (not exceeding 3 years and 2,500 ha) is awarded through a competitive process to CMR nationals only, without scrutiny of detailed management plans. Fiscal responsibilities attached to tenure types awarding timber rights often include taxation revenue-sharing between the state and local communities affected by logging activity: in CMR, a portion of forest tax revenues collected from large concessions is earmarked for local development purposes, while in DRC, concession holders in permanent production forests pay into a specific development fund, and in GAB a portion of concession revenues must be shared with local communities in order to fund projects of local collective interest (Forest Legality Initiative, 2014).

In contrast to timber extraction, the assignment of rights to NTFP across tenure types is less well defined. In GAB, these entitlements are explicitly excluded or limited by all tenure types across the forest estate except community forests in NPFE. In COG, the Forest Code (Government of Congo, 2000) primarily covers rights to timber: rights to other forest resources, notably NTFP,

[11] In DRC where forest resources demarcated in terms of: classified forests (conservation areas in undisturbed areas); protected forests (where some limited production activities are permitted); permanent production (where timber concessions can be awarded); and private (a relatively small area of forest which has private legal owners). In GAB forests are distributed between the PFE and what is termed the rural forest domain (where the latter is roughly equivalent to NPFE).

are generally not defined. In some cases, however, timber concessions may also entail entitlements to use NTFP. In CAR, commercial use is permitted following consultation with relevant stakeholders. In DRC, timber concessions in forests designated for permanent production do not include rights to extract NTFP but such rights can be established via special harvesting permits in certain circumstances. In CMR, rights to NTFP are unclear for large concessions but community (or council) forests confer rights to access these resources for commercial or subsistence purposes by the local title holders.

Rights relating to carbon are a novel, but increasingly important, category of property. To the extent that these rights are defined in our study countries, they are retained by the state and transferred to other parties only via the definition of distinct tenure types (rather than tied to, for example, timber concessions). This is presently the case for DRC, COG and GAB, while the assignment of carbon rights in CAR and CMR remains unclear.[12] In general, institutional novelty likely explains a lack of clarity in the practical exercise (and transfer) of carbon rights.

As an illustration, in DRC, this has manifested in an observed lack of clarity on how rights to use carbon might be transferred or granted to those with tenure on forested land (Rights Resources Initiative, 2021). Nonetheless, this does not appear to have prevented agreements to be established with private agents who have established concessions on permanent production forest for sharing revenues from sequestrating and storing carbon (Nhantumbo and Samndong, 2013). Clarifying critical details is a work-in-progress with legislative developments in 2018 establishing the broader principle that the state can transfer its right to carbon units to private agents (Streck, 2020).

In GAB, another illustration of this evolving picture, a carbon credit can be owned and transferred (inter)nationally (UNEP, 2022). Similarly, in COG, carbon rights can be assigned by the state to other (non-state) agents. Notably, the 2020 Forest Code, however, makes explicit reference to the participation of local communities and indigenous peoples in initiatives such as REDD+. This is not without practical challenge, however. These entitlements refer to carbon in forests over which such local communities and indigenous peoples have customary rights. This appears currently to be at odds with existing land laws given that very little land is held in this way, a point to which we turn below.

It is worth noting that while all statutory tenure types specify detailed rules, governance challenges remain. For example, in CAR, there is some evidence that artisanal logging activities have been awarded to foreign-based economic agents despite this being formally restricted to CAR citizens (Global Witness, 2015). So called ‘illegal’ or ‘informal’ logging is another prominent example. In CMR, it is estimated the physical volume of timber that is illicitly harvested is perhaps around 30-70% of legal exports. In the CMR, there is also evidence that efforts to support local development, arising from concession revenues, are only weakly enforced and implemented (Hoare and Uehara, 2022).

[12] Loft et al. (2015) note that this leaves it unclear whether, in existing REDD+ initiatives in CMR, local and indigenous peoples have formal rights to the monetary flows arising.

Finally, the treatment of customary rights (i.e. rights not codified by statute) varies meaningfully between our study countries. In DRC, the 2002 Forest Code (Art. 38) attempted to allocate non-commercial resource use rights to local populations in accordance to custom and tradition. In CAR, such rights are limited (Kone and Pichon, 2019) but not absent; customary rights are circumscribed to subsistence use and relate to resource extraction rather than land access (Rainforest Foundation, 2019). In CMR, while the 1994 Forest Code sought a basis for restoring customary rights post-independence, serious practical challenges prevent local communities from formally proving entitlements (Walters, 2023). In COG, by contrast, customary tenure has largely been downplayed since independence (Bruce, 1998), at least until more recent developments in the 2020 Forest Code (Preferred by Nature, 2021). In GAB, pre-independence land laws have largely been retained and traditional (i.e. pre-colonial) land occupation is generally not recognized, although the 2001 Forest Code makes some provision for the exercise of customary rights in the rural domain relating to individual or collective needs of local communities.

Table 2. Statutory assignment of forest rights in Congo Basin countries.

	Timber					NTFPs					Carbon				
	CAF	**CMR**	**COD**	**COG**	**GAB**	**CAF**	**CMR**	**COD**	**COG**	**GAB**	**CAF**	**CMR**	**COD**	**COG**	**GAB**
Protected areas	✓	✓	✓	✓	✓	✓	(✓)	✓	×	×	U	U	(✓)	(×)	(?)
Indigenous areas	(✓)	U	U	U	U	(✓)	U	U	U	×	U	U	U	U	(?)
Unallocated forest estate	(?)	(?)	✓	✓	U	(?)	(?)	✓	✓	×	U	U	✓	✓	(?)
Forest concessions	✓	✓	✓	✓	✓	✓	(?)	×	✓	×	U	U	✓	U	(?)
Community forests	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	U	U	U	(?)	(?)
Customary tenure	(✓)	(✓)	(✓)	(✓)	(✓)	✓	(✓)	(✓)	(✓)	(✓)	U	U	(?)	(?)	(?)

Notes:
1. Country abbreviations: CAF – Central African Republic; CMR – Cameroon; COD – Democratic Republic of Congo; COG – Republic of Congo; GAB – Gabon.
2. Key to symbols: ✓ – yes, full legal entitlement to landholder apparently exists; (✓) – legal entitlement probably exists; × – full legal entitlement apparently ruled out; (×) legal entitlement probably ruled out; (?) – legal entitlements unclear; U – legal entitlement currently undefined.
3. Reported rights for unallocated forest estate are based on rights associated with private forest ownership.
4. Forest concessions includes both foreign and domestic producers.

3. Methods and data

We use best available information to produce distributional estimates for 2019 for five marketed ecosystem services (industrial timber, artisanal timber, wood fuel, bushmeat, and tourism) and carbon storage/sequestration. Ideally, natural capital accounting produces either asset values (defined as the net present value of a future stream of rents), which are useful for aggregate stock-takes to inform large-scale policy efforts, or model-based marginal values, which are useful for evaluating local trade-offs. Due to data deficiencies in the Congo Basin forests our analysis focuses on gross output, defined as production volumes times output prices: our valuations therefore include payments to all factors required to produce a particular ecosystem service at the point of sale, such as labour and transport costs, because data do not exist to isolate the (Ricardian) rent attributable to forest land.

Since our results rely on price and volume data collected in different ways at different times, care is required to maximize comparability between services. Industrial timber and tourism are valued using official national statistics (national export values and in-country tourism expenditures, respectively). Assigning industrial timber export values to statutory tenure holders in concessions and community forests effectively assumes complete vertical integration of firms, while assigning tourism expenditures to customary tenure holders where tourist activity is observed makes the much stronger assumption that institutions exist to transfer value at all such locations. By contrast, our results for fuelwood and bushmeat are valued using prices at rural markets; allocating this value to tenure holders makes the (often plausible) assumption that the producer is also the seller. This is clearly not true for artisanal timber, for which values are collected at urban markets and multi-tiered supply chains are well documented; we therefore utilize detailed survey data to adjust unit values for artisanal timber to exclude payments made outside rural areas (e.g. transport, urban labor costs, mark-ups/profit by resellers). For carbon services, unit prices are entirely speculative at the scale of assessment we employ and we consequently emphasize physical volumes in our results.

We arrive at estimated values using either 'top down' methods (industrial timber, fuelwood, and tourism) or 'bottom up' methods (artisanal timber, bushmeat, and carbon). Our 'top down' calculations start with trusted national data on output (in physical volumes, e.g. FAO estimates) and define a (service-specific) spatial allocation rule to assign fractions of this output to each of our distributional categories (e.g. using shares of TMF degraded forest). We then price each unit of allocated output in various ways. To price industrial timber, we exploit species-product fidelity and combine species-product prices with potential habitat maps to capture potentially important differences in the unit price of output across tenures. To price fuelwood, we interpolate unit prices collected throughout Sub-Saharan Africa by the Millennium Villages Project. For Tourism, uniquely, we begin with a monetary measure of output and allocate monetary values rather than physical volumes.

Our 'bottom-up' calculations for artisanal timber and bushmeat are based on estimates of per capita consumption. Our total national volumes are therefore new estimates and we compare these against prior work whenever possible. We adjust per-capita estimates to account for urban versus rural populations, first producing an estimate of national output before proceeding to allocate fractions of this output amongst our distributional categories (via satellite-based data products, as before). We obtain unit prices for artisanal timber from a series of national studies by CIFOR, and interpole bushmeat unit prices from data collected by the Poverty Environment Network. To estimate carbon volumes, we combine satellite observations of forest condition with (variously) carbon stock density and carbon flux, relying on regional emissions factors (as per IPCC Tier I guidance) rather than (scarce) country-specific data to enable clear cross-country comparisons of the distributional implications of three alternate accounting methods.

To define distributional categories, we rely on published maps of statutory tenure and Pygmy potential habitat, and generate new maps of customary tenure using cumulative cost methods as described below. The aim of our distributional allocations is to make the best guess possible given variation in the available spatial data: thus for industrial timber we use range maps of commercial species because there exists significant variation in species distributions across concessions (see Appendix 3.3), while for bushmeat we assume each pixel produces an identical amount because the most important game species are widely distributed habitat generalists (Nasi et al. 2011). Such choices attempt to balance the precision of the available data with national-scale policy relevance: because we aggregate results for each distributional category at the country level, some detail is unnecessary.

3.1 Distributional analysis

The distributional analysis of natural capital values relies on a spatial analysis of where ecosystem services are produced (their "supply areas", for example the area accessible for hunting) and where heterogenous agents hold rights (tenures, for example national parks). Since more than one ecosystem service can be produced at a single location, ecosystem service supply areas can overlap. Such overlap may be the rule rather than exception: in our study region, (Shapiro et al. 2022) detect multiple economic uses of forest land at more than 80% of examined sites. However, partitioning the supply of services across distributional categories requires that the assignment of rights for each specific service is exclusive. Our mapping rules (Appendix 3.1) therefore result in mutually exclusive tenure areas, but allow overlapping ecosystem service supply areas. The supply area for artisanal timber is an exception: we clip this area to exclude the fuelwood supply area, which is located closer to settled areas and is assumed to be denuded of merchantable timber. Ecosystem services supply areas that do not overlap with any tenure category are recorded as open-access. Following the System of National Accounts (SNA) concept of an 'accounting boundary' forest outside *any* ecosystem service supply area is irrelevant to our analysis, with the exception of carbon assessed using the net flux method (under which the atmospheric regulation service of all forest within a national boundary has economic value). We do not map a supply area for tourism, since our distributional analysis approach (based on mining the Flicky photo database) allows us to allocate shares of value to directly to our distributional layers.

Statutory tenure

We map industrial forestry concessions and community forests using extracts from the Congo Basin Forest Atlases,[13] published by the World Resources Institute (WRI) in collaboration with

[13] Downloaded from https://www.wri.org/data/forest-atlas-congo or (updates only) provided via email by WRI. Our labelling of industrial concessions into foreign- and domestic-owned in 2019 relies on information from 2012 to

national governments. Concession attributes include the country of origin of each concession licence holder at the time of publication, which we use to distinguish foreign-held versus domestic-held concessions. This information was missing for 14% of records (concessions) in the original dataset; we used supplementary data (Holmes, Billings, and Powell 2007a; 2007b) and web searches to update ownership information and reduce missing-data records to 9%. For concessions licensed to domestic firms, we assigned foreign ownership if our investigation determined that the licensee was a subsidiary of a foreign firm. To map protected areas, we rely on WRI 'snapshots' from the *World Database of Protected Areas*, since the main *Database* contains only most recent-data.

Pygmy tenure areas
(Olivero et al. 2016) estimate an upper bound of ~900,000 Pygmies in central African forests, and employ an environmental favourability model estimated using known locations of Pygmy camps from 1984-2014 to map areas of *potential* Pygmy habitation. We hand-digitise this map to represent zones of Pygmy tenure, clipping polygons to subtract overlaps with all other tenure areas because Pygmy population densities are low and Pygmy people are generally unable to enforce claims on land that conflict with those of other ethnic groups (Olivero et al. 2016). We remove polygon shards created by clipping using a minimum threshold size of 989 km^2, which is one standard deviation below the mean subsistence area (1079.38 ± 90.0 km^2.) of a Pygmy population unit (camp) as reported by (Olivero et al. 2016).

Cumulative cost mapping approach
We map customary tenure boundaries and ecosystem service supply areas using cumulative cost mapping, i.e. using thresholds of cumulative travel time on a 2019 global friction surface (Weiss et al. 2020); units are minutes/meter to traverse each pixel) and an appropriate set of source locations (see Figure S3). Compared to traditional spatial buffers, our cumulative cost approach offers improved accuracy by taking account of spatial features that determine access (e.g. roads/tracks, rivers, slope, etc…). By defining ecosystem service-specific supply areas, our approach allows for idiosyncratic and overlapping assignment of rights under customary tenure regimes. However, our approach does not take into account cultural factors determining service areas (e.g. ethnic divisions) and remains an imperfect proxy of customary tenure.

We build cumulative cost surfaces using Google Earth Engine's `cumulativeCost()` algorithm. We set cumulative travel time buffers (which define customary tenure and ecosystem supply areas on the cumulative cost surface) using either hand-labelled forest change plots collected from 2015-2020 satellite imagery by (Shapiro et al. 2022) or values reported from fieldwork by various authors. When using forest change plot labels, we sample the relevant cumulative cost surface at each label location to obtain a distribution of travel times per label per country (see Table S3.1.3). We use the 75% percentile of these distributions to define temporal buffers. Cumulative cost mapping used a resolution of 0.1 km for rasterized source locations and 1 km for the input friction surface; vector outputs were simplified with a 200m error margin. Note that, for maps using human populations as source locations, our approach does not distinguish rural versus urban populations. However, because our cumulative cost maps measure

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2019. For community forests, we consider that discrepancies between the year of record creation and 2019 are relatively less important because community forest tenures are predicated on the legal recognition of *long-established* customary rights.

distances to the *nearest* source pixel we view as reasonable the implied assumption that populations at the 'rural edge' of peri-urban areas use forests in similar ways to their rural counterparts.

Customary tenure

Our cumulative cost mapping defines customary tenures as the extensive margin for artisanal agriculture. We obtain 3,324 plots containing Artisanal Agriculture in 2020 (defined as "small irregular fields, generally less than 5 ha") from (Shapiro et al. 2022) and use the GHS-POP spatial population product (Schiavina et al. 2023) as source areas for cumulative cost mapping, constraining population rasters to retain only pixels with a population density > 2 persons per kilometre squared (hereafter "population locations"). Rounding results to the nearest minute of travel time, we map customary tenure (at the 75th percentile of observed travel times) using the following values: CAF – 44.9 (minutes), CMR – 18.2, COD – 36.0, COG – 75.5, GAB – 14.7. We clip resulting polygons to exclude all forms of statutory tenure (see Table S.1.3.2).

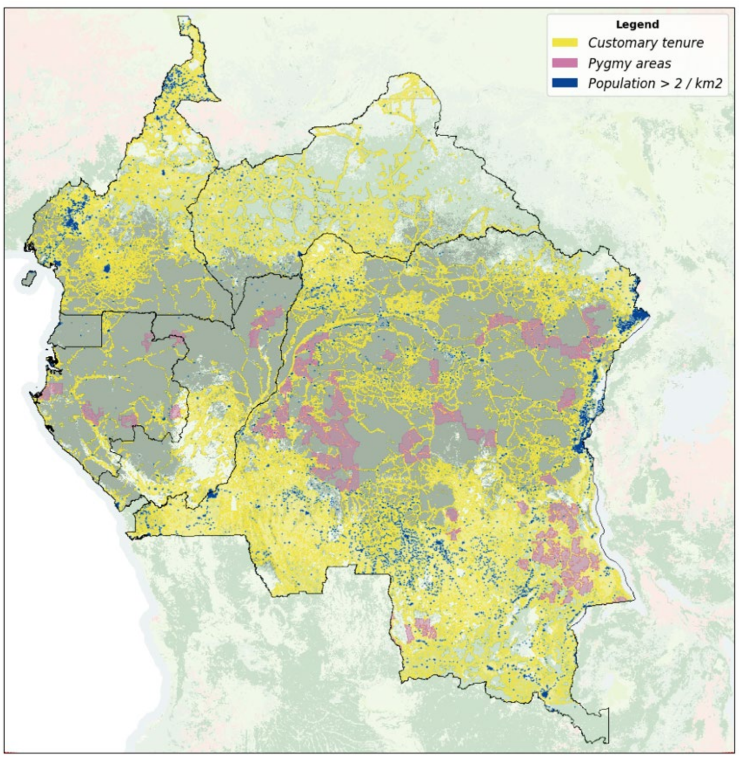

Fig. 2 Mapped customary tenure areas and Pygmy areas in the Congo Basin. Grey shading indicates Tropical Moist Forest extent. Customary tenures are equivalent to spatialized population maps (Schiavina et al. 2023) with a population density floor (2ppl/km^2) and country-specific travel time buffers applied. Because of the order of precedence applied to distributional mapping (Table S3.1.2), Pygmy habitation areas overlapping with other tenure regimes do not appear on this map (e.g. Pygmy settlements in Dja National Park, CMR).

Artisanal logging supply area

We map the ecosystem service supply area for artisanal logging using 1,984 plots labelled as containing Artisanal Forestry (defined as 'forest with small canopy gaps or perforations and felled trees') by (Shapiro et al. 2022). Since logging depends on proximity to transport networks, we use rivers and roads as source areas for cumulative cost mapping. We map rivers using the HydroSHEDs Free Flowing Rivers 2019 product (Grill et al. 2019), selecting rivers with at least 10-100 m^3 sec^{-1} long-term average discharge and excluding river segments with waterfalls. We map roads using 2023 OpenStreetMap (OSM) data.[14] OSM is a crowdsourced project, but assessments have found it be reasonably accurate and complete in West Africa (Kim-Blanco, Bogdan-Mihai Cîrlugea, and Sherbinin 2018) and much better than official roads data in Burundi (Campalani, Pittore, and Renner 2022). We retain road classes for analysis based on class descriptions and tabulating codes for all road features that intersect industrial forestry concessions.[15] We merge river and road data, and define the artisanal logging service area using the 75th percentile of observed travel times (in minutes) to transport networks as follows: CAF - 47.1 (minutes), CMR – 18.8, COD – 38.0, COG – 52.6, GAB – 5.9. We report supplementary information about artisanal harvest distances in SI 3.4.

Wood fuel supply area
We map the supply area for wood fuel using population locations as source areas, applying travel time buffers based on survey data from the Millennium Villages Project (average roundtrip distances and speeds of travel for fuelwood collection from Table 7 of (Adkins, Oppelstrup, and Modi 2012); see Table S.2.3.4). We use data from 4/10 Millenium Villages with ≥1200 mm/yr of precipitation (and therefore most similar biological productivity to our TMF forest layer, which is characterised by >2000mm annual rainfall (Vancutsem et al. 2021)), obtaining an average one-way travel time for fuelwood collection of 67.6 minutes. Since fuelwood collection is typically not mechanized, we construct a cumulative cost surface using Weiss et al's 'walking only' friction surface. Prior work in Africa suggests that collection distances for wood products (including fuelwood) by rural populations rarely exceeds a few km (Ceccarelli et al. 2022; Bailis et al. 2015); of course, this should vary by resource abundance and usage (population) pressure as well as the type of wood fuel in question. For example, (Schure 2014) finds that fuelwood for Kinshasa (COD) and Kisangani (COD) is sourced up to 101.7km and 25.3km away, respectively (134.8km and 36.8km for charcoal), and the WISDOM model of (Bailis et al. 2015) applies a 12-hour (one-way) travel buffer for commercial producers.

Bushmeat supply area
We map the supply area for bushmeat population locations as source areas, applying a 14-hour roundtrip hunting distance (thus a 7-hour buffer) using a 'walking only' friction surface (as for fuelwood). Our choice of buffer attempts to represent day-length hunting trips by household producers, though some hunters will clearly travel further (e.g. commercial producers). We find no data with which to refine our hunting buffer; a study by (Ziegler et al. 2016) does offer a map of hunting pressure for comparison (Fig S3.1.2.2) which is qualitatively similar to our bushmeat supply area.

[14] Downloaded from https://download.geofabrik.de/. Guidance is available here and class definitions are available here.
[15] We tabulate n = 44,751 OSM road segments that intersect industrial forestry concessions, finding that 53.6% are classed as "track – for agricultural use, in forests, etc.: and 15.8% are classed as "roads in residential areas". Both categories are retained as source locations.

Table 3. Distribution (percentage) of 2019 Tropical Moist Forest area by distributional layer. **Panel A**: Statutory tenures (Protected Areas, industrial forestry concessions (by ownership), community forests), customary tenures, and Pygmy areas. Unallocated or "open access" forest is derived as a residual since tenure types are mutually exclusive by construction; this is the area of (state-owned) forest not under economic management. **Panel B**: Ecosystem service supply areas (Artisanal timber, fuelwood, and bushmeat; note that supply areas for bushmeat can overlap with supply areas for artisanal timber or fuelwood). Tropical Moist Forest is defined as all pixels classes as 'undisturbed', 'degraded', or 'regrown' by (Vancutsem et al. 2021).

A.	**PAs**	**Industrial concessions**			**Community forests**	**Customary tenures**	**Pygmy areas**	**Residual**
		foreign	*domestic*	*no data*				
CAF	2.77	20.83	4.05	6.49	0.00	16.18	0	49.66
CMR	14.08	17.91	7.08	2.98	14.5	20.34	0	23.11
COD	14.11	8.53	0.93	0.10	0.19	20.31	8.54	55.81
COG	13.03	40.03	7.77	2.63	0.31	8.27	3.09	27.96
GAB	8.93	52.19	8.91	0.00	1.27	5.8	4.03	22.9
B.	**Artisanal timber**	**Fuelwood**	**Bushmeat**					
CAF	9.08	25.57	81.85					
CMR	2.68	39	86.6					
COD	9.97	29.06	79.15					
COG	6.25	16.05	70.02					
GAB	3.56	16.14	79.73					

3.2 Forest carbon accounting

Climate regulation by carbon sequestration and storage in the Congo Basin forests is globally significant (Hubau et al. 2020; Saatchi et al. 2011) and the rationale for accounting for the economic value for this regulating service is much discussed (e.g. (Bulckaen et al. 2024). Sustained efforts have been made to monetize carbon values via both public- and private-sector REDD+ mechanisms, but defining a marketable unit of forest carbon has proven contentious (e.g.(Pande 2024; Delacote et al. 2024; Filewod and McCarney 2023)). REDD+ mechanisms exist to incentivize forest conservation (thus climate regulation service provision) by altering development paths in forest landscapes; to do so, baseline scenarios are constructed from which deviations in forest cover dynamics are quantified. Deviations from baselines produce marketable units of carbon, but the methods used for baseline construction in carbon markets (either historical averages or projections of historical trends) lead to wildly varying estimates of carbon volumes (Haya et al. 2023) and diverge markedly from estimates in the research literature using *ex poste* baseline methods (Guizar-Coutiño et al. 2022; West et al. 2023). Because baseline methods are debated, we assess the distributional implications of three stylized approaches to baseline construction.

We implement two baseline methods which represent current practice in carbon markets (i.e. relying on counterfactual scenarios constructed *ex ante* from historical data) and one alternate approach based entirely on *ex poste* observations. In our *average baseline* approach, we assign credits or debits for forest carbon by comparing the carbon stock in year *t* to the mean of stocks in the prior five years (*t-5 … t-1*). This represents the 'historical average baselines' used under the UN-REDD+ mechanism and by some Voluntary Carbon Market (VCM) protocols. In our *trend baseline* approach we fit a second-degree polynomial curve to stocks in *t-5 … t-1* and compare the observed stock in *t* to its predicted value. This represents the 'projected baselines' used in Voluntary Carbon Markets, using a simplest-possible projection that still allows for increasing or decreasing rates of carbon stock loss over time (Barbier, Delacote, and Wolfersberger 2017). Our use of a 5-year lagged period for both approaches is intended to focus attention on the distributional implications of competing approach across countries; in practice, the time period used for average baseline construction or making projects is case dependant.[16]

In our *net flux* approach we depart from current practice in carbon markets and simply compare stocks in *t* to stocks in *t-1*, i.e. evaluate the net sequestration or emissions in the assessed area for a given year. Net flux accounting has been promoted by so-called High Forest – Low Deforestation (HFLD) countries, in which standing forests sequester significant amounts of carbon that has no value under REDD+ mechanisms relying on counterfactual baselines. Because net flux accounting relies only on physical quantities observed *ex poste*, problems caused by the inherent uncertainty in (counterfactual) baseline construction do not arise; conversely, defining marketable units of carbon in this way may direct carbon revenues to the owners of remote forests facing no credible threat of loss or degradation.

All carbon accounting approaches are implemented per spatial unit: baselines and carbon stocks are assessed individually for each forestry concession, protected area, customary tenure within GAUL ADM2 polygon, etc…, and results are then aggregated nationally (by distributional category). We record emissions as positive (+), and sequestration as negative (–), i.e. as changes in atmospheric stocks. We use the TMF dataset to quantify changes in the area of undistributed, degraded, or regrown forest for each spatial unit, and multiply areas by appropriate continental[17] carbon stock or sequestration factors obtained from the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Domke 2019). We restrict attention to aboveground biomass only, since data on other important aspects of forest carbon dynamics are generally unavailable in our study region (e.g. (Dalimier et al. 2023), noting that our results are consequently most interesting as relative rather than absolute values. Compared to prior efforts relying (e.g. the assessment of pan-tropical forest sequestration by (Harris et al. 2021)) our use of the TMF dataset captures potentially important dynamics in degradation and regrowth, though we stress that statistical validation of change class areas and nationally-accurate emissions factors are obvious areas for improvement. Full details of each approach (including alternate emissions factors taken from national *Forest Reference Emissions Level* (FREL) submissions) are given in Appendix 3.2. We view unit prices as speculative (and therefore of little interest) for any regional-scale forest carbon market scenario; we therefore report results in physical volumes only.

[16] For example, Forest Reference Emissions Levels submitted by our study countries to the United Nations Forum on Climate Change use the following periods for calculating average baseline stocks: COD – 2000 to 2014, COG - 2000 to 2012, GAB- 2000 to 2009.
[17] Our approach can therefore be described as IPCC Tier 1.

3.3 Valuation of industrial timber

Timber harvest in the Congo Basin can be differentiated into a domestic or artisanal sector, operating generally without effective regulation and producing sawnwood via chainsaw milling for national and regional markets, and an industrial sector, operating with legal tenure (i.e. in recognized forestry concessions and community forests) and producing primarily logs but also sawnwood, veneer, and plywood for overseas export (Lescuyer et al. 2012). Analysis of the industrial sector is complicated by the presence of firms operating outside of legal frameworks, the output of which is unrecorded and may be large (ATIBT 2023; Global Witness 2015), and by the diversion of a portion of industrial harvest to the domestic sector (Lescuyer et al. 2012)). We obtain data on volumes and prices for the industrial timber sector from the International Tropical Timber Organization's (ITTO) *Biennial Review*[18] and define industrial timber output as the sum of ITTO exports (valued at export prices) plus artisanal timber sourced from industrial operations (valued at domestic prices; see Section 3.4).

Our analysis of the (legal) industrial timber sector relies on ITTO data on export volumes and prices, which we allocate to concessions and community forests using tenure-level shares of national satellite-observed degradation in all concessions/community forests (see SI3.3 for details, including the empirical basis for this approach). For each country, we select the degradation product for which total area degraded best predicts aggregate physical exports in time-series (Fig. S3.3.5). We additionally attempt to identify differences in value accruing to tenures of different types (foreign- versus domestic-owned industrial concessions, community forests) by exploiting ITTO data on species-product export volumes. The ITTO data distinguishes four product aggregates (logs, sawnwood, plywood, and veneer) and gives production per aggregate product by commercial timber species for some combinations of year and country. We use recent maps of timber species potential habitat (Ceccerelli et al., 2022) and calculate shares of total national degradation (in concessions and community forests) per timber species, using these shares to aggregate production per aggregate product to specific tenures. Thus for each country i and aggregate product j and spatial unit n (concession or community forest) and species s we calculate:

$$export\ value_{j,n} = \sum_{s} export\ volume\ (m^3)_{j,i} * \ spp.share_s * \ unit\ price\ (\$/m^3)_{i,j,s}$$

We then aggregate over n by distributional category. *Spp.share* gives the average share of export volumes (in m^3) attributable to each timber species in our study region in any year, since reporting is erratic and shares are roughly stable across countries and years. Unit prices are country-specific and are obtained by adjusting the most recent price data using various export price indices compiled for West Africa by the ITTO.

Note that we treat ITTO data on total export value as given (i.e., our approach is 'top-down'). Summing the left-hand side of the preceding equation over j and n and subtracting the result from national export values gives a residual value (not traceable to the production of specific

[18] ITTO data are sourced from the Joint Forest Sector Questionnaire; this is the same data source used by FAOSTAT forest sector reporting, but each organization applies unique harmonization and cleaning rules. Note that export data should be reliable since dual-entry book-keeping is possible.

aggregate products by specific tenures); we allocate this residual using shares of total degradation. Comparing results per aggregate product to ITTO-reported export value and averaging over countries provides an indication of the information content of our approach: we are able (on average) to allocate 62.1% of reported sawnwood value, 52.1% of veneer value, 38.2% of log value, and no (1%) plywood value; these differences arise in the share of export volume (m^3) attributable to individual species in the ITTO *Biennial Review* data (Fig. S.3.3.3; results per aggregate product in 2019 $USD are given in Table S3.3.2).

3.4 Valuation of artisanal timber

In our study countries, small-scale production by artisanal producers was the primary source of timber supply to some 128.7 million people in 2019. No official statistics are collected on the artisanal sector, but fieldwork (Lescuyer et al. 2012) suggests that artisanal production volumes are 2.5× industrial export volumes in CMR, 1.2× in COG, 5× in COD, and 1.6 × in CAR (Gabon is the exception, at 0.5×). Data on the scale of artisanal production are restricted to a few difficult-to-compare studies and one major regional data collection effort by the Center for International Forestry Research (CIFOR), which monitored 1,240 timber depots for 10-12 months in 2009-2011 (CMR, GAB, COD, COG) and 2010-2011 (CAR). We rely on 2009-2011 per capita consumption estimates (m^3/person) from the CIFOR data to estimate 2019 production volumes (Table S3.4.1; we compare estimates from an alternate approach based on industrial export volumes). We recognize several limitations to this approach (see S3.3), including biases in CIFOR data collection protocols,[19] but note that CIFOR's data constitute the only systematic study of the artisanal timber sector undertaken to date.

We then spatially allocate national volumes using shares of observed TMF degradation (Annual Change Collection: Class 2), selecting this degradation product due to the plausibility of implied yields (m^3 artisanal timber output per ha degraded) versus alternatives (Table S3.4.2). Importantly, a significant share of domestic artisanal timber supply apparently originates from low-quality timber and scraps from industrial operations: (Lescuyer et al. 2012):Table 4.3) report that 50.7% of industrial timber volumes are sold on the domestic market in CAR, 28.6% in GAB, 23% in CMR and 9.6% in COG (no data are available for COD). We do not attempt to assign industrial-origin artisanal production to specific industrial concessions, instead adding this value to aggregate output for the industrial forestry sector for each country (no fraction of this value is assigned to community forests).

Table 4. CIFOR data on volumes and prices of artisanal timber by origin (artisanal or industrial sector). Data were collected in 2009-2009 except for CAF (collected in 2010-2011).

	Artisanal origin (m^3)	Industrial origin (m^3)	Artisanal price (CFA)	Industrial price (CFA)
CAF [1]	212,944	219,430	*26924*	101544.8
CMR	1,429,056	427,343	*48273*	41313
COD [2]	4,305,788	1,673,020	103450.1	210544.3
COG	236,715	25,109	*47557*	79322
GAB	102,529	41,009	*53798*	75000

[1] CIFOR data do not include industrial-origin prices for CAF; reported price is average of CMR, COG, and GAB price (we exclude COD prices because of exchange rate distortions).
[2] CIFOR price data for COD are reported in current $USD and converted to CFA here using official exchange rates (World Bank).

[19] CIFOR data are collected at urban timber markets/deports near major population centers. Depot selection is non-random and cross-country differences in data collection protocols are sometimes important (e.g. monitoring of night-time shipments); rural markets and international trade at border crossings are not monitored.

Unlike our industrial timber analysis, we do not attempt to trace artisanal production by species because the specific areas in which artisanal production occurs is unknown (see SI 3.4; in Fig. S3.3.5 we show that the sum of degraded pixels in industrial concessions correlates with industrial timber output to substantiate the analysis of the potential species composition of these specific forested pixels). We therefore use average prices from the CIFOR data rather than species-specific prices. Since CIFOR prices are collected at urban markets, we adjust artisanal-origin prices for comparability with other assessed services (specifically, we include the element of total price that accrue in rural areas, i.e. wages paid to producers, payments to customary owners, and informal payments in rural areas, taking volume-weighted averages across producer sub-categories where necessary). We use World Bank CPI to inflate prices for artisanal-origin timber (chainsaw milling) to 2019 values; for artisanal supply originating in the industrial sector, we adjust prices using the ITTO West African Roundwood Export Price index.

3.5 Valuation of fuelwood

Despite the importance of fuelwood production, few developing countries collect fuelwood production statistics. We rely on FAO estimates of fuelwood production volumes (which include downstream products, e.g. charcoal); these are generally derived from linear (multiple) regressions of per capita consumption rates on national-level variables such as income, climate, forest cover, land area, oil production, and rural population fraction (Whiteman, Broadhead, and Bahdon 2002).[20] Because our study countries also produce fuelwood from non-TMF forests, we adjust FAO (national) estimates downward using fractions of national population located in GAUL-AMD2 administrative units that contain (TMF) forest-dwelling population (see SI:1). We allocate fuelwood production using shares of satellite-observed degradation per distributional layer and using a single unit price per country. We acknowledge a number of important limitations to this approach (SI:3.5) which lack of data prevent us from overcoming. To convert between kg and m^3 of fuelwood, we apply a mean wood density value for tropical African species of 598.5 kg/m^3 calculated using the Global Wood Density database (Zanne et al. 2009).

While fuelwood prices should vary spatially with demand, supply, and consumption preferences (product type), data do not exist to account for these important complexities. Instead, we derive country-level unit prices interpolating what data do exist on producer prices as a linear function of PPP GDP per capita. We lack data to address urban versus rural price disparities. Our unit prices are based on $n = 17$ village or site-level observations (averages) of fuelwood prices per kg paid by households across Africa from the Millenium Villages Project (Adkins, Oppelstrup, and Modi 2012), all records in the Poverty Environment Network database (Angelsen et al. 2014) for which convertible mass units are recorded, and a review study for CMR (Eba'a Atyi et al. 2016). We aggregate observations to site or village-level to avoid pseudoreplication. Since our unit prices are based on rural data, they are consistent with our efforts to value supply accruing to primary producers and thus to the distributional owners of forest land.

[20] 90.49% of FAO data entries for woodfuel in Africa are model estimates from in the period 1961-2018 and 75% thereafter (Steele et al. 2021); current efforts focus on revising estimation methodology to use "machine-learning" models. The leading alternative data source is the WISDOM model (Bailis et al. 2015), which makes spatially explicit estimates of woodfuel supply using a cumulative-cost mapping approach.

3.6 Valuation of bushmeat

Bushmeat is produced for subsistence and trade, increasingly by semi-professional hunters (Petrozzi et al., n.d.). Consumption levels vary with cultural preferences and the price of substitute proteins, but consumption per capita is generally much lower in urban areas (where bushmeat may be a luxury item, e.g. CMR, GAB) compared to rural areas (where bushmeat is a dietary staple, e.g. DRC, CAR) (Nasi, Taber, and Van Vliet 2011). Given scarce data, we follow prior work in estimating total (national) bushmeat production as the product of average per-capita consumption (kg $person^{-1}$ yr^{-1}; taken from Nasi, Taber, and Van Vliet 2011) and current population. We use the GHS-MOD year 2020 product to estimate consumption separately for rural populations (Class 11-13; consuming 51 kg $person^{-1}$ yr^{-1}) and urban populations (class 21-23, 30; 7 kg $person^{-1}$ yr^{-1}). Because bushmeat may be produced from non-forest areas, we restrict attention to populations in GAUL2-AMD2 containing 'undisturbed' TMF forest.

To allocate production, we intersect our bushmeat supply area (defined as a 7-hour travel buffer around human populations) with each distributional layer and apply shares of total TMF undisturbed and regrown forest (see SI 3.6). We count all forest pixels irrespective of patch size because the majority of bushmeat harvest (mass basis) relies on a small set of forest-dependant habitat generalists (Petrozzi et al., n.d.; R. Nasi, Taber, and Van Vliet 2011), such as blue duiker, and hunting pressure on forest fragments is thought to persist until stocks are depleted (Fa and Brown 2009). We obtain unit prices for bushmeat from African data in the Poverty Environment Network database (Nielsen et al. 2017). We extract n = 731 price observation, which include only two of our study country (CMD: n = 320, COD: n = 3). To interpolate prices for our study countries in 2019, we inflate prices to 2019 local currency units, convert to 2019 $USD, and regress on 2019 GDP per capita (see SI 3.6).

3.7 Valuation of tourism

Uniquely, our top-down approach to the distributional analysis of tourism revenues allocates *monetary* output volumes. We use in-country expenditures from inbound tourists obtained from the United Nations Tourism Statistics Database (Jan 31 2024 update; SI 3.7), and follow the approach of the Stanford InVEST toolkit in mining the Flickr database of geotagged photos to construct a Photo User Day (PUD) metric (Wood et al. 2013) to allocate national tourism expenditures amongst distributional layers (i.e. via shares of PUDs; see Table 5). We stress that this approach assumes characterizes where tourism value is produced (i.e. the location of tourist activity) rather than were such values are captured (e.g. lodges, hotels, tour operators).

Flickr records consist of a single image with metadata. PUDs are defined using image metadata as the unique combination of user, date, and site and have been shown to reliably correlate with site-level observed visitation rates in a global sample (Wood et al. 2013), including at sites with relatively very few records. Because our analysis focuses on national aggregates, we take (national) distributional layers as sites (e.g. a user visiting two protected areas in one day produces 1 PUD for the 'protected areas' class). Our distributional analysis is based on n=11,088 all-time records from 351 unique Flickr users occurring ≤ 100m from a (undisturbed, degraded, or regrown) forest pixel and spatially coincident with a distributional layer. To account for in-country tourist activity not associated with tropical moist forests, we scale total tourism expenditures by the share of forest-adjacent Flickr records in total records per country before allocating using PUD shares.

Table 5. Shares of Photo User Days (%) per distributional layer, calculated from all-time Flickr records located ≤ 100m from TMF forest.

Country	*Industrial concessions*	*Community Forests*	*Protected Areas*	*Customary Tenures*	*Pygmy Areas*	*Total records*
CAR	35.7	0	49.8	14.5	0	255
CMR	0.6	3.8	7.3	88.3	0	2579
COD	3.3	0	36	58.8	1.9	5081
COG	27.4	1.8	36.2	34.5	0.1	1181
GAB	15	6.1	16.7	60.2	2.1	1992

4. Results

Our main result is a set of distributional supply tables, modelled after (Atkinson and Ovando 2022): Table 5b). Output volumes and unit prices underlying these results are given in this section and in SI as appropriate. We give country level results in Table 6, and a regional summary in Table 10. Because output volumes for carbon vary dramatically with accounting method and unit prices are speculative, we do not report valuation reports for carbon in the country tables.

Table 6. Country-level distributional supply tables for 2019, in millions current $USD. The symbol "–" indicates that a service is not produced by a distributional unit by definition.

Central African Republic (CAF) — 2019 GDP[4], current $USD, millions: 2,221.30	ind. Timber[1]	art. Timber[2]	fuelwood	bushmeat	tourism[3]	total	% GDP
Public							
- of which:							
Protected areas	–	0.17	0.03	1.15	3.65	5.00	0.2%
Indigenous areas	–	–	–	–	0.00	0.00	0.0%
Open access	–	10.51	2.25	23.36	–	36.12	1.6%
Private							
- of which:							
Domestic-owned forest concessions	7.21	4.38	2.92	26.28	2.61	113.23	5.1%
Foreign-owned forest concessions	31.54	19.25					
Community forests	0	0	0	0	0	0.00	0.0%
Customary tenure	–	4	11.27	9.95	1.06	26.29	1.2%
TOTAL	52.53	43.57	16.46	60.74	7.32	180.63	8.1%

Congo (COG) — 2019 GDP, current $USD, millions: 13,976.64	ind. Timber[1]	art. Timber[2]	fuelwood	bushmeat	tourism[3]	total	% GDP
Public							
- of which							
Protected areas	–	1.47	1.12	17.66	8.38	28.63	0.2%
Indigenous areas	–	–	–	–	0.02	0.02	0.0%
Open access	–	9.98	0.75	52.03	–	62.76	0.4%
Private							
- of which:							
Domestic-owned forest concessions	110.78	1.19	19.89	142.44	6.34	632.60	4.5%
Foreign-owned forest concessions	303.07	2.64					
Community forests	10.74	0.13	0.54	0.94	0.42	12.77	0.1%
Customary tenure	–	12.71	17.06	22.37	7.99	60.12	0.4%
TOTAL	470.29	28.67	39.35	235.44	23.15	796.90	5.7%

Cameroon (CMR) — 2019 GDP, current $USD, millions: 39,667.76	ind. Timber[1]	art. Timber[2]	fuelwood	bushmeat	tourism[3]	total	% GDP
Public							
- of which							
Protected areas	–	15.86	1.51	50.84	22.81	91.02	0.2%
Indigenous areas	–	–	–	–	0.00	0.00	0.0%
Open access	–	76.8	27.28	143.27	–	247.35	0.6%
Private							
- of which:							
Domestic-owned forest concessions	137.58	6.42	3.00	170.99	1.88	607.58	1.5%
Foreign-owned forest concessions	243.57	9.08					
Community forests	428.07	24.08	15.21	95.90	11.88	575.12	1.4%
Customary tenure	–	49.27	89.05	116.11	275.95	530.38	1.3%
TOTAL	843.05	182.74	136.05	577.10	312.51	2,051.45	5.2%

Gabon (GAB) — 2019 GDP, current $USD, millions: 16,874.41	ind. Timber[1]	art. Timber[2]	fuelwood	bushmeat	tourism[3]	total	% GDP
Public							
- of which							
Protected areas	–	0.94	0.79	10.25	3.33	15.31	0.1%
Indigenous areas	–	–	–	–	0.42	0.42	0.0%
Open access	–	6.23	8.75	54.32	–	69.30	0.4%
Private							
- of which:							
Domestic-owned forest concessions	65.57	0.98	12.02	154.87	2.99	751.96	4.5%
Foreign-owned forest concessions	510.01	5.51					
Community forests	48.61	0.49	1.42	3.57	1.22	55.31	0.3%
Customary tenure	–	4.53	26.34	15.25	12.02	58.14	0.3%
TOTAL	624.20	18.68	49.32	238.26	19.98	950.44	5.6%

Democratic Republic of the Congo (COD) — 2019 GDP, current $USD, millions: 51,775.83	ind. Timber[1]	art. Timber[2]	fuelwood	bushmeat	tourism[3]	total	% GDP
Public							
- of which							
Protected areas	–	60.98	57.83	213.88	15.94	348.62	0.7%
Indigenous areas	–	–	–	–	0.84	0.84	0.0%
Open access	–	229.95	144.48	1180.35	–	1,554.78	3.0%
Private							
- of which:							
Domestic-owned forest concessions	6.12	31.33	67.54	240.11	1.46	659.86	1.3%
Foreign-owned forest concessions	62.30	249.7					
Community forests	0.60	2.07	0.62	6.05	0.00	9.34	0.0%
Customary tenure	–	62.28	787.96	379.33	26.04	1,255.60	2.4%
TOTAL	69.26	637.37	1,058.43	2019.71	44.28	3,829.05	7.4%

[1] Concessions without ownership data are not seperately reported; values generated in 'no data' concessions are added to the appropriate row or column totals.

[2] Artisanal timber values are the sum of industrial scrap-origin artisanal timber (produced in concessions and community forests) plus chainsaw-origin artisanal timber (produced in the artisanal timber supply area).

[3] Only partial tourism values are available for COD ('travel' sub-item only); for GAB, data are from 2015.

[4] 2019 GDP measured at purchaser's prices (downloaded from https://data.worldbank.org/indicator/NY.GDP.MKTP.CD)

Carbon

The three stylized accounting systems we examine have very different distributional results (Table 7). Our used of IPCC Tier 1 emissions factors implies that these differences arise in the trajectories of forest degradation, loss, and regrowth in our mapped distributional units. Convexity matters (Fig SI3.2.1): at regional aggregation, our average baseline approach assigns carbon *debits* (i.e. liabilities) to all distributional units, while our trend baseline approach mostly assigns credits. This is because rates of forest cover loss and degradation were decreasing over the 2014-2019 accounting period in the TMF dataset, consistent with statistical evaluations of regional forest cover trends. (Mayaux et al. 2013; *FRA 2020 Remote Sensing Survey* 2022; Shapiro et al. 2022). Different emissions factors (e.g., higher sequestration in regrowth) could locally alter this result. The net flux approach gives mixed results, tending to assign credits to industrial concessions, protected areas, and Pygmy areas, and debits to community forests and customary tenure areas. This pattern is consistent with extraction rates (biomass per unit area) increasing in proximity to (forest dependant) human settlements.

Differences between results are dramatic. In COD, average baseline accounting results in a national debit of 386.53 Mt C, while a trend baseline gives a credit of 15.08 Mt C and net flux accounting gives a debit of 34.86 Mt C.[21] To shed light on the sources of divergence, we compared our results against two alternate national[22] estimates for Congo Basin forest carbon. For average baseline accounting, Gabon's Forest Reference Emissions Level (FREL) submission to the UNFCC uniquely provides sufficient data to recreate our analysis for evaluation year 2018. We re-run our analysis pipeline for 2018, finding a debit of 35.8Mt CO_2^e (our data) versus 6.4 CO_2^e (FREL data[23]) and note Gabonese development of country-specific activity data and emissions factors as a likely source of divergence. For net flux accounting, prior work by (Harris et al. 2021) gives a national sequestration estimate for COD of -350 Mt $C0_2^e$ (credits) on average each year from 2001-2020, whereas we record net emissions of 127.8 Mt $C0_2^e$ (debits) in 2019.[24] Major potential causes for this (net flux) divergence are the use of different activity data (e.g. Harris et al. use GFC binary gain/loss, without degradation; GFC and TMF products may disagree), our omissions of residual TMF from our net flux calculations, and deviations in 2019 conditions from the 2001-2020 average. In general, choices we make to enable cross-country comparisons (using TMF forest areas, IPCC default emissions factors, and tracking aboveground biomass only) will produce marked deviations from nationally determined accounting results (which may use national forest definitions and statistically validated area estimates, locally accurate emissions factors, and track multiple biomass pools).

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[21] Our net flux results do not include sequestration in Tropical Moist Forest falling outside any distributional layer (i.e. generally remote and undisturbed forest), constituting ~56% of total TMF area in COD (see Table 3).

[22] Our data support sub-national comparisons, i.e. versus specific REDD+ projects offering credits on the Voluntary Carbon Market (VCM). We do not make such comparisons, primarily because our interest lies in national-level accounting choices and their distributional implications. A secondary issue is that REDD+ projects on the VCM are known to use widely varying methodologies which are easily gameable (West et al. 2023; Filewod and McCarney 2023) and exhibit variation in estimated mitigation impacts across methodologies of over 1400% (Haya et al. 2023).

[23] Extracted from main report Figure 29 and source workbook tab 10:AT43.

[24] While net sequestration should diverge (vs Harris et al 2021) because we do not assess the carbon services of forest land located outside the distributional categories in Table 7, emissions estimates should be more comparable (if little forest disturbance occurs outside the ecosystem service areas we map, any different would be mostly due to activity associated with the 'open access' area in Tables 6 and 10). Other sources of divergence include Harris et al.'s use of average (2001-2020) values and disagreement in the TMF vs GFC datasets (S.I. 2).

Table 7. Carbon volumes (Mt C) per distributional layer in 2019. Positive (+) values are emissions/debits, negative (-) values are sequestration/credits.

	Average baseline	*Trend baseline*	*Net flux*		*Average baseline*	*Trend baseline*	*Net flux*
	CAF				**CMR**		
All TMF forest	**24.92**	**-2.17**	**3.01**		**60.74**	**-12.27**	**3**
...concessions	8.89	0.95	0.82		4.3	-1.35	-3.1
...community forests	0	0	0		10.91	-2.47	0.44
...protected areas	0.64	-0.24	-0.08		1.77	-0.81	-1.81
...customary tenure	15.39	-2.88	2.27		43.76	-7.65	7.46
...Pygmy areas	0	0	0		0	0	0
	COD				**COG**		
All TMF forest	**386.53**	**-15.08**	**34.86**		**35.81**	**5.61**	**1.13**
...concessions	38.32	-2.93	1.11		19.74	3.62	0.05
...community forests	0.22	-0.04	-0.1		0.53	-0.02	0.1
...protected areas	36.73	-4.48	-4.15		1.42	0.26	-1.4
...customary tenure	299.7	-6.84	41.96		14.01	1.79	2.81
...Pygmy areas	11.56	-0.8	-3.97		0.11	-0.03	-0.43
	GAB						
All TMF forest	**10.05**	**-0.37**	**-8.98**				
...concessions	4.48	-0.19	-7.36				
...community forests	0.25	0	-0.11				
...protected areas	0.29	-0.1	-1.26				
...customary tenure	4.62	-0.28	0.3				
...Pygmy areas	0.4	0.2	-0.54				

Industrial and artisanal timber

Summing across countries, our approach to species-product tracing allows us to allocate 47.1% of ITTO reported export values in 2019 to specific industrial concessions using species-specific degraded areas, with the remaining share allocated using total degraded area (validated as a predictor of physical output in S3.3). We find that domestic-owned concessions generate more value per unit area (2019 USD $50.9/ha versus $36.3 for foreign-owned concessions), a difference that may be driven by harvesting intensity or species (thus products) produced. Community forests are important producers of industrial timber in CMR and play a small role in GAB and COG. Scrap-origin artisanal timber, while less valuable on a per unit basis, is also significant, with an estimate regional output of USD$ 338.6 million in 2019. However, the majority of artisanal timber is produced by smaller operators (i.e., chainsaw-origin), with open access lands regionally the most important source (producing $USD 333.5 million) followed by customary tenures ($USD132.8 million). The boundary between these two categories (defined via the 75th percentile of the artisanal agriculture frontier) is questionable: customary tenure arrangements may cover most or all of the 'open-access' area, a possibility supported by the ubiquity of ‘rents to customary owners’ as a production cost in the CIFOR data. This pattern is consistent across countries, indicating similar (spatial) distributions of forest degradation across the artisanal timber supply area. Our estimate of $USD 79.42 million of artisanal timber production in protected areas ($USD 60.98 million of which arises in COD) must be considered in light of our inability to estimate enforcement for individual areas: our method assigns this value based on observed forest cover degradation occurring with protected areas boundaries and within the artisanal timber supply area (i.e. always less than 1 hour’s travel time from transport networks) without attempting to distinguish natural versus anthropogenic causes of the underlying spectral phenomena.

Fuelwood

Although fuelwood has low unit values, the importance of wood for cooking and domestic heating in the Congo Basin (Steele et al. 2021) supports the relatively large fuelwood values we estimate (roughly $1.3 billion in 2019). Most fuelwood (61% on average) is sourced from customary tenures (i.e. close to settlements), with industrial concessions and community forests being nationally important sources of supply. We stress that both the total volume of estimate fuelwood production and its distribution are uncertain,[25] but our results are compatible with the (very limited) available evidence. Pan-African results from the Millennium Villages Project (Adkins, Oppelstrup, and Modi 2012) show that 51% of fuelwood is sourced from own (household) lands, with another 44% from “Roadside/other’s field/community land/forest”; the corresponding categories in our analysis are customary tenures (61%) and the residual area (13.4%) and excluding COD (in which concessions are unusually proximate to settlements) increases the average share attributable to either categories (from 74.4% to 81.7%, versus 95% in the MVP data). (Eba’a Atyi et al. 2016) provide a second point of comparison, finding (in CMR) a national net profit of CFAF 393.5 billion in 2016. A back-of-the-envelope conversion with our data (using 900kg per stacked meter and $USD 1 = FCAF 585.8) gives a value of CFAF 219.7 billion from out data. Both analysis rely on FAO data but we adjust production to consider TMF forests only; our gross output metric is comparable to net profit assuming most production is by household ‘owner operators’ (i.e. zero labor cost).

Table 8. Fuelwood production shares (%) by distributional layer.

	Community forests	Concessions	Customary tenures	Protected areas	Residual	Production[1] (m3)	Price per kg (2019 USD$)
CAF	0	17.7	68.5	0.2	13.6	948,604	0.029
CMR	11.2	2.2	65.5	1.1	20.1	6,314,182	0.036
COD	0.1	6.4	74.4	5.5	13.7	58,948,839	0.030
COG	1.4	50.5	43.3	2.9	1.9	1,529,156	0.043
GAB	2.9	24.4	53.4	1.6	17.7	1,070,000	0.077

[1] Production values are based on adjusting FAO estimates using forest-dependent population fractions (see Section 3.5)

[25] Major sources of uncertainty include the original FAO estimates, which are themselves outputs of an imperfect relatively crude modelling strategy, the lack of independent data to test our allocation rule, considerable variation in regional conversion factors (e.g. kg/m^3), and order-of-operations choices in unit price interpolation.

Bushmeat

We estimate a bushmeat value of $USD 3.13 billion across our study countries; this is the largest value of any ecosystem service we assess. Roughly 2/3 of the total value originates in COD[26], chiefly in the open access area. While we stress the uncertainty of our bushmeat estimate, we see few opportunities for improvement absent new price or volume estimates, except refinements to our price interpolation method. Our regional estimate for 2019 is roughly 2 million metric tonnes; the authority on which we base our (per capita) estimates (Nasi, Taber, and Van Vliet 2011) gives 3.2 million tonnes produced in the Congo Basin in 2011 (our lower estimate results form downwards adjustment of national populations to isolate production from TMF forests only). The (very high) value we assign to this output may be partly due to an out-of-sample problem in our unit price interpolation,[27] as well as the scarcity of price evidence in general. We note at least one, very different, estimate of bushmeat values: (Ingram et al. 2011) suggest a value of $USD 2.8 million for bushmeat in CMR (versus our we find $USD 577 million), alongside a value of $USD 612 million for fish and $USD 12 million for *Gnetum* ('wild spinach'). While at odds with prior work (e.g. the Nasi et al. review), Ingram et al.'s result clearly demonstrates the need for increased investment in data collection.

Table 9. Bushmeat production shares, total production, and prices

iso3	Community forests	Concessions	Customary tenures	Protected areas	Residual	Production (kg)	Price 2019 USD /kg
CAF	0	43.3	16.4	1.9	38.5	48,430,375	1.253017
CMR	16.6	29.6	20.1	8.8	24.8	293,657,399	1.967198
COD	0.3	11.9	18.8	10.6	58.5	1,495,694,520	1.349003
COG	0.4	60.5	9.5	7.5	22.1	90,890,444	2.590335
GAB	1.5	65	6.4	4.3	22.8	41,004,040	5.810717

Tourism

Our allocation approach assigns the vast majority of regional tourism revenues (79%) to customary tenures, with the obvious sites for tourist activity (protected areas) accounting for merely 13% of regional revenues (with relatively more importance in Congo and Gabon). Distributional results are driven by the tourism sector in CMR, which creates 77% of total regional value. While the drivers of tourist activity are not clear (e.g. the role of protected areas versus national cultural life in attracting foreign tourists), geo-tagged photos consistently suggest a surprisingly small role (29% on average) for high-profile protected areas in generating tourism revenues; customary tenures (and sometimes forest concessions) are relatively much more important. However, the spatial location of tourist activity clearly does not imply a corresponding allocation of tourism receipts: absent institutional arrangements for collecting and

[26] This represents roughly $USD 2 billion of bushmeat, or roughly 4% of the GDP of COD. We arrive at this substantial figure by taking the national population living in forested districts (some 60.97 million persons in 2019), assuming that each rural person consumers 51kg of bushmeat per year and each urban person consumes 7kg, and applying an estimated price of $USD 1.34 / kg.

[27] Our price estimates are based on data collected by the Poverty Environment Network (PEN). Mean 2019 GDP per capita in PEN study countries was $USD 1175, whereas 2019 GDP per capita was $USD 7524 in Gabon. Regressing unit price on GDP per capita consequently predicts a price of USD $5.81 per kg in Gabon (2019 CFA 3405). PPP adjusted price estimates for 2011 give a unit price of CFA 5638 in Gabon, whereas work by Abernathy and Ndong Obian (2010) reports contemporaneous prices ranging from CFA 663-1207. However, GDP per capita in COD, by far the largest contributor to our regional bushmeat value, are more similar to PEN study countries.

distribution payments, tourist revenues may accrue almost exclusively to service provide (hotels, tour operators) with international exposure, rather than the distributional agents who supply the sites of tourist attraction.

5. Discussion & Conclusions

We find that the supply of marketed ecosystem services from the Congo Basin forests (excluding non-timber forest products) is equal to roughly 6.3% of regional GDP in 2019, with the highest national importance in CAR (8.1% of GDP) and the lowest in CMR (5.2%). GDP comparisons are indicative only: beyond the many limitations discussed in Section 3, the services we measure are partially included in headline GDP and our inability to robustly exclude the value of intermediate products when valuing ecosystem services implies our results would be better compared against a reliable measure of Gross Output. While this should tend to overestimate the contribution of specific services to GDP, we view our aggregate results as (rough) lower bounds on the economic role of Congo Basin forests: significant flows are likely missing from both official statistics (industrial timber, tourism) and field studies (artisanal timber), while indirect effects (so-called "output multipliers") are not assessed and likely to be large. More holistic views of forest wealth may also highlight the reliability and 'insurance' value of forest services, particularly to the rural poor. Finally, we do not attempt to value unpriced ecosystem services, such as climate regulation and rainfall provision, despite their potentially transformative social value.

Table 10. A regional distributional supply table for marketed ecosystem services in the Congo Basin forests in 2019 (millions 2019 USD$).

	ind. timber	art. timber	fuelwood	bushmeat	tourism	total	% GDP	forest area	$/ha
Congo Basin (n = 5 countries)				*2019 GDP [1], current $USD, millions:*			124,515.93	ha, millions	2019 $USD,
Public									
- of which:									
Protected areas	–	79.42	61.28	293.77	54.11	488.58	0.39	27.2	$17.96
Indigenous areas	–	0.00	0.00	0.00	1.28	1.28	0.00	12.8	$0.10
Open access	–	333.47	183.50	1,453.34	0.00	1,970.31	1.58	71.4	$27.60
Private									
- of which:									
Domestic-owned forest concessions	327.26	44.30	105.36	734.69	15.29	2,765.23	2.22	7.3	$56.43
Foreign-owned forest concessions	1,150.50	286.18						39.6	
Community forests	488.01	26.77	17.78	106.46	13.51	652.54	0.52	4.1	$159.16
Customary tenure	–	132.79	931.68	543.01	323.05	1,930.53	1.55	36.2	$53.33
TOTAL	2,059.33	911.03	1,299.60	3,131.26	407.25	7,808.47	6.27	198.6	$39.32

The major weaknesses of our study flow from scarce primary data. Some guesswork is unavoidable, and idiosyncratic assumptions make validation-by-comparison difficult. At the time of writing, the most prominent alternate estimate of forest natural capital in the Congo Basin is the World Bank's national time series of forestry sector rents (as percent of GDP, i.e. the NY.GDP.FRST.RT.ZS series), which are frequently cited in a policy context (e.g. (African Natural Resources Center 2018). These rent estimates are sometimes much higher than our estimates of sectoral gross output,[28] although our respective estimates converge in countries where forest-sector statistics may be more reliable. At root, differences arise because these

[28] World Bank forestry rents vs our gross ecosystem service value for industrial timber, expressed as percent of GDP in 2019: CAR - 9.7% vs 3.67%, CMR - 2.6% vs 1.09%, COD - 8.5% vs 0.68%, COG - 3.0% vs. 3.32%, GAB - 2.2% vs 3.45%.

estimates are built from different assumptions (and sometimes different data) for different purposes[29]. New primary data are needed to advance the argument.

As in (Atkinson and Ovando 2022) our results suggest a central role for distributional concerns in natural capital accounting. We find marked variations in the value of (marketed) ecosystem services supplied by different groups of rightsholders, ranging from (regional averages) a high of USD $159.16/ha in community forests to a low of $0.10/ha in remote and relatively unpopulated Pygmy areas. Customary tenures provide nearly as much value (per unit land) as industrial forest concessions ($53.33/ha versus $56.43/ha). Foreign owned-tenures have lower values per ha than domestic-owned ($36.28/ha versus $50.90/ha), possibly because of larger tenure sizes or rights-holding in expectation of future profits.

These distributional differences, and many others evident in our country-level results (Table 6), should be of interest to development planners managing investment programmes, to analysts interested in the sources of economic growth, and of course to policy-makers seeking to design novel mechanisms to compensate the suppliers of ecosystem services (for example, attempts to estimate a supply curve for carbon via the opportunity cost of forest land as in (Busch and Engelmann 2017)). Some of our distributional results match expectations, such as the economic importance of industrial forestry tenures (2.22% of regional GDP). Others are more surprising.

A striking feature of our results is the economic importance of customary tenures (1.55% of regional GDP, and as high 2.04% in COD). The figures we report would be even higher if the contributions of “open access” land (1.58% of regional GDP) were added, which could reasonably be done on the assumption that land we map as “open access” is in fact largely subject to service-specific customary tenure arrangements that extend beyond the extensive agricultural margin. Most of the value of customary tenures arises in informal markets for fuelwood (48% of total customary tenure value) and bushmeat (28%). The basic needs met by these services (heating/cooking and protein provision) represent a critical, and massive, economic role for the forests of the Congo Basin.

Given that these values are currently captured (at least in part) by rural households, where does recognizing value lead? One set of responses relates to the common policy suggestion to formalize customary rights via legal statute, thereby increasing access to credit (via collateralization of realized ecosystem services values) and lowering the risk of investment. Another set relates to the informal nature of much of this activity (e.g. bushmeat or fuelwood production). As urbanization continues these activities may be increasingly professionalized, in which case understanding their current distribution is an essential step for training and for regulatory measures. A final set of responses relates to uncaptured value. We find (noting imperfections in our method) that the majority of tourism services originate in customary tenures, but few mechanisms exist for rural households to retain a correspondingly large share of

[29] The World Bank approach (Siikamäki and Santiago-Ávila 2014) is designed for rapid global application and assumes FAO-reported (estimated) roundwood production is fully sold at product and price ratios for a representative country (in this case, Ghana), with a cost structure observed in logging operations in the United States Our approach is designed to analyze distributional supply in a single region and can therefore make use of more detailed country data, and assumes ITTO-reported exports and CIFOR observations of consumption per capita are reliable volume estimates – not the FAO roundwood statistics.

tourism revenues. CMR has been uniquely successful in developing a tourist industry linked to global appreciation of cultural activities occurring in customary tenures, but our analysis of Flickr data (Table 5) reveals a comparable pattern of tourist activity in GAB and a promisingly large share in COD and COG.

Our results for protected areas are also noteworthy, though our methods may be (correctly) criticized in relation to specific protected areas for which effective enforcement is known. Most of the protected area value we estimate originates in bushmeat production (60%) rather than tourism (11%), a finding corroborated by (Nlom 2011). Given the proximity of many protected areas to forest-dependent rural populations with customary claims to forest access, the advisability of strict protection in a European model is questionable. (Wilkie and Carpenter 1999) ask whether nature-based tourism can finance Protected Areas establishment and maintenance: our results suggest that it might be more productive to seek institutional arrangements that link the value that rural households derive from Protected Areas to conservation goals.

Given currently high interest in harnessing natural capital for economic growth in Africa, we suggest three cross-cutting priorities based on our distributional analysis. First, opportunities for financialization (i.e. integration of the financial services sector with the ecosystem services markets we quantify) are abundant. Much of the value we estimate originates in informal markets with little access to financial services. Codifying customary tenure within statutory tenure systems and formalizing the economic activities of household entrepreneurs are daunting tasks, but could make capital and insurance markets more available to drive economic growth in what are *de facto* important sectors of the national economy. Of course, given concern about the pace of forest resource extraction (Robert Nasi 2008; Hiemstra-van der Horst and Hovorka 2009), increased access to financial capital may have undesirable effects. Can recognizing the economic value of informal markets lead to financial instruments compatible with more sustainable development paths?

Second, natural capital policies must take political economy into account. Recognizing the value produced by forests in Pygmy areas, for example, might have serious negative consequences if Pygmy claims to land right are ignored. Distribution trade-offs are complex and involve vulnerable segments of society: for example, NTFP production may be a vital source of income for children and elderly people, which trades off with logging income for working-age men. Equity in access to the services that flow from natural capital has received significant attention (e.g. McDermott, Mahanty, and Schreckenberg 2013; Berbés-Blázquez, González, and Pascual 2016), but despite recognition that distribution matters in an accounting context (e.g. Benra and Nahuelhual 2019) and occasional attempts to include it in applications (e.g. Adekola, Mitchell, and Grainger 2015), there has been little consideration of how natural capital accounting should consider distributional issues. These may play out very differently in a developing country context, and we hope that our initial distributional estimate for the Congo Basin helps guide future work in this direction.

Arguably, the development of NCA as a field is transitioning from an earlier phase aimed at demonstrating the value of ecosystems, to a later phase where this value is taken seriously and impacts decision-making. Our third priority is therefore to rigorously demonstrate the distribution of currently captured natural capital values, thereby accelerating the uptake of NCA information in near-term decisions. NCA analyses frequently focus on demonstrating the value of open-access ecosystem services for which suppliers lack sufficient power to enforce payment by consumers.[30] These are essential for motivating institutional innovation, but more 'near sighted' studies of (currently) captured value will help mainstream uptake.

In a developing country context, institutional innovation may be relatively more important. At issue is whether (or not) recognizing the economic contributions of nature will lead to net capital inflows (as is implicit in valuing supra-national regulating services, for example via REDD+), and whether these inflows are required to meet development goals. NCA may lead to more sustainable or more efficient domestic institutional arrangements (although sufficient institutions for this need not depend on valuation (Ostrom 1990)), but increasing the available capital stock in the Congo Basin countries via forest natural capital requires either: competitive opportunities for profit for foreign capital (currently limited to the industrial forestry sector, although formalizing value capture in other sectors could attract investment), credible risk to the supply of open-access ecosystem services to foreign countries, or altruism.

In principle, institutional innovation to capture carbon service values is tied to the risk of (globally significant) tropical moist forest loss. The contribution of our analysis here relates to the details of these institutional arrangements. We stress that while the underlying ecosystem service traded in carbon markets is climate regulation, the markets themselves exist to reduce the risk of ecosystem service losses. Marketed units of tropical forest carbon are therefore generally conceived as representing *avoided* emissions or *new* sequestration. Both these concepts require measurement against an unobservable counterfactual to demonstrate that a change has taken place.

Table 11. Comparison of carbon service value under alternative accounting approaches (all values in millions 2019 $USD). These results flow from an extremely simple model of aboveground forest carbon dynamics that ignores nationally most-accurate data in order to make methodological comparisons across countries.

	2019 GDP	All marketed ecosystem services		Carbon service value at USD$5 per t CO2e: average		trend		flux	
		value	*%GDP*	*value*	*% GDP*	*value*	*% GDP*	*value*	*% GDP*
CAF	$2,221.30	$180.63	8.1%	-$456.87	20.6%	$39.78	1.8%	-$55.18	2.5%
CMR	$39,667.76	$2,051.45	5.2%	-$1,113.57	2.8%	$224.95	0.6%	-$55.00	0.1%
COD	$51,775.83	$3,829.05	7.4%	-$7,086.38	13.7%	$276.47	0.5%	-$639.10	1.2%
COG	$13,976.64	$796.90	5.7%	-$656.52	4.7%	-$102.85	0.7%	-$20.72	0.1%
GAB	$16,874.41	$950.44	5.6%	-$184.25	1.1%	$6.78	0.0%	$164.63	1.0%

The first point made by our carbon analysis (Table 11) is that current REDD+ accounting methods do not produce robust estimates of the volume of carbon services. This is now well known at the project level in the Voluntary Carbon Market, but the considerations from a national point of view are somewhat different. In our analysis, a simple methodological choice changes both sign and magnitude of measured C services. Even within one baseline accounting

[30] For example, a recent study of a recent study of transboundary landscapes in East Africa (Oguge 2022) reported global benefits (USD $32,000/ha to $56,000/ha) which are orders of magnitude higher than the benefits accruing to the countries in which these landscapes are located ($260/ha to $2700/ha). Only 1.8% of total value originates in economic activity in-country, and most of this is due to assigning prices to regulating services for which routes to monetization do not yet exist.

approach, there is no way to prove that a particular past period best represents future performance (the choice of which period to use may therefore be best understood as a price negotiation between buyer and seller). While many other counterfactual methods have been proposed,[31] the basic problem of measuring against an unobservable counterfactual introduces some irreducible uncertainty into carbon volume estimates built around an avoided risk concept. Despite high promise at *project* scales, it seems unlikely that quasi-experimental (causal inference) methods can reduce this uncertainty to manageable levels if all forests in a globally unique biome participate (as is hoped) in institutions designed to realize carbon value.[32]

The results in Table 11 corroborate previous findings, for example work by (Haya et al. 2023) showing that choice of REDD+ method can vary estimated mitigation services volumes by >1400%. Recognizing uncertainty may lead to (downward) unit price adjustments. Alternatively, institutions may be structured around uncertainty in carbon service volumes (Filewod and McCarney 2023), most notably by preventing their substitution for relatively certain emissions reductions in carbon accounting systems.

Our second point relates to net flux accounting, which offers the possibility of arbitrarily high certainty by restricting attention to physically observable phenomena. Deploying net flux accounting to maintain standing forests in countries with low risk of conversion is a persistent policy interest (e.g. (Paltseva et al. 2023; Mitchell and Pleeck 2022); in the Congo Basin, Gabon has advocated for this accounting approach (Pilling 2021). However, net flux accounting has severe distributional consequences that block widespread uptake: literally attaching a price to carbon emissions penalizes countries that will draw down forest stocks to develop (Table 11), as has been done by nearly every forested nation throughout history (Barbier, Delacote, and Wolfersberger 2017), and (in our context) concentrates these penalties upon the rural poor (Table 7).[33]

In closing, we offer some methodological observations. Our results provide a demonstration of a data-driven approach to natural capital accounting. While our findings are severely constrained by data deficiencies, we believe they constitute an informative (if imperfect) advance. One key area for improvement lies in better mapping of customary tenure arrangements: our approach relies on satellite observations of small-holder agriculture, and could clearly be enriched by new primary data. Our distributional approach to tourism valuation could be improved by paid access to social media data.

Looking ahead, we see high promise for improving Congo Basin natural capital by combining new field data collection with spatial predictions from machine learning models. In our study, we assume that values (e.g. outputs per unit land, prices) collected in a few places can be applied regionally. However, an increasing number of spatial covariates are now available to predict both

[31] For example, the use of stylized facts (Paltseva et al. 2023), empirical spatial models (e.g. (Vieilledent et al. 2022), structural models (e.g. (Golub, Hertel, and Sohngen, n.d.) and the matching-based quasi-experimental methods currently in favour (e.g. (Roopsind, Sohngen, and Brandt 2019; Groom, Palmer, and Sileci 2022).
[32] i.e., if all comparable forest is enrolled in a REDD+ program, no quasi-controls exist. Other methodological issues of concern in this context are the role of subjective choices about model construction (Mitchard et al., n.d.) and possible leakage contamination of quasi-controls (Filewod and McCarney 2023).
[33] Lack of additionality is an equally important concern given that global carbon accounting is oriented around deviations from projected emissions pathways.

output volumes and prices, and more flexible interpolation between primary observations is a logical next step. We are hopeful that the necessary stratified sampling campaigns that would be required to provide training data for such an approach need not be onerous, and look forward to the implementation of innovative statistical production for African natural capital that – as with the rapid uptake of mobile phones and e-payments in the global South – may perhaps leapfrog established methodologies elsewhere.

Data Availability Statement

[as of April 30 2025] Google Earth Engine (GEE) and R scripts used to perform the geospatial analysis for this paper are available on request from the corresponding author and will ultimately be archived at a public repository. A self-contained Supplemental Information directory is available with copies of all public datasets and GEE outputs required to reproduce the analysis.

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