A mid-20th century estimate of global vegetation carbon stocks based on inventory statistics

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Abstract (< 150 words)

Biomass carbon stocks (BCS) play a vital role in the climate system, but benchmarked estimates prior to the late 20th century remain scarce. Here, by making use of an early global forest resource assessment and harmonizing information on land use and carbon densities, we establish a global BCS account for the year 1950. Our best-guess BCS estimate is 450.7 PgC (median of all modulations: 518.3 PgC, range: 443.9-584.6 PgC), with ecosystems in Southern America and Western Africa storing c. 27 and 16% of the total respectively. Our estimates are in line with land change emissions estimates and suggest a reduction in BCS of 8-29% compared to the median, with losses in tropical subcontinents partially offset by gains in northern subcontinents. Our study demonstrates an approach to reconstruct global BCS over the 20th century to complement carbon flux-based modelling efforts and identify emerging global land transitions.

Keywords

Global land use, global land change, carbon stocks, vegetation carbon, forest transition, forest carbon stocks, global forest inventory, FRA

1. Introduction

In the hypothetical absence of human activities, the global terrestrial biomass would store 900-950 PgC (Erb et al., 2018). Starting from their first signatures more than 12,000 years ago (Ellis, 2021), anthropogenic land cover change and land management have greatly impacted carbon dynamics in natural ecosystems. The extent and intensity of land use change has accelerated in the 20th century (Houghton et al., 1983; Ramankutty and Foley, 1999; Houghton and Nassikas, 2017; Kastner et al., 2021b). This acceleration is concomitant with increasing production, trade and consumption of biomass commodities (Krausmann and Langthaler, 2019; Kastner et al., 2021a) and a growth of resource use in general (Krausmann et al., 2013; Krausmann and Langthaler, 2019) over the last few decades.

To account for the carbon impacts of long-term land cover change and land management, existing vegetation modelling-based efforts span several decades (Houghton et al., 1983) or even millennia (Pongratz et al., 2009). These approaches focus on accounting for carbon flows between vegetation, atmosphere and societal use, without necessarily aiming to establish robust estimates of biomass carbon stocks (BCS). Two such major modelling approaches exist to assess long-term carbon fluxes: (1) book-keeping models (Houghton and Nassikas, 2017) and (2) process-based dynamic vegetation models (Yang et al., 2020). Book-keeping approaches quantify the impact of land use on carbon emissions, and therefore only quantify a fraction of BCS change, excluding the impacts of environmental change or legacy effects from management (Erb et al., 2013; Le Noë et al., 2020). Process-based models, in principle, account for environmental drivers and legacy effects as well, but their coverage of land management impacts is still relatively modest and imperfect, resulting in large uncertainties (Pongratz et al., 2018; Friedlingstein et al., 2019). In particular, the lack of observational constraints hampers the triangulation of results from these sets of analyses, hindering efforts to reduce the considerable uncertainties in historical BCS accounts (Li et al., 2017; Pongratz et al., 2021). Inventory-based approaches are well-placed to offer episodic (decadal, multi-decadal) reconstructions of BCS, especially across the 20th century (Brown and Lugo, 1984; Brown, 2002; Liski et al., 2006; FAO, 2018). However, recent global assessments based on field-based biomass observations and remote sensing data only start in 1990 (FAO, 2018) and mainly cover the start of the 21st century (Erb et al., 2018; Spawn et al., 2020; Xu et al., 2021). Other longer-term efforts are constrained by their regional focus (Richards and Flint, 1994; Gingrich et al., 2007; Le Noë et al., 2021b). In this background, a complementary approach focussed on estimating global BCS in a harmonized and integrative manner is required to not only better understand the dynamics of the carbon cycle over time (Houghton and Nassikas, 2017; Li et al., 2017), but also to contextualise estimates of carbon gains across regions (Griscom et al., 2017) and examine global land use transitions like the forest transition (Kauppi et al., 2006, 2020; Meyfroidt and Lambin, 2011).

Here, we start filling this research gap by constructing a global country-level BCS dataset for the mid-20th century. By combining historical records of biomass stocks with information on ecological potentials, we develop a closed-budget land use accounting approach to estimate global BCS based around the year 1950. This time point constitutes a vital signpost for long-term carbon budgeting studies (Klein Goldewijk et al., 2017; Hurtt et al., 2020) - it represents a time just after the end of World War II and just before the end of the colonial period across much of the tropics, with its accompanying changing dynamics on timber extraction and land use (Williams, 2006).

In this study, we aim to:

- Establish a global biomass carbon stock account for the year 1950.
- Conduct an uncertainty and sensitivity analysis.
- Discuss differences among world regions and land categories.
- Compare these estimates with assessments for the start of the 21st century.

In this way, we operationalise an approach to triangulate information from land inventories and other ecological datasets to establish CS accounts. This can be extended to cover the entirety of the mid and late-20th century.

2. Materials and Methods

We undertake a global country-level BCS assessment considering above-ground biomass and below-ground biomass, while excluding carbon stored in litter, deadwood, soil, and harvested wood products. We combine contemporaneous statistical information on global land use (FAO, 1957; Silva et al., 2011; Kastner et al., 2021b) *(Table 1)* to distinguish 8 major land categories, some of which are further sub-divided *(Figure 1)*, in a closed-budget vegetation approach, which allocates terrestrial land areas into considered land categories. To each land category, we assign country-level carbon density values either from available datasets or assign them typical values from the literature. Attributing carbon densities to land categories (for example, forests, rangelands, pastures) for each country is challenging because national land use statistics are neither consistently mapped nor linked to natural ecosystems. Further, no information is available for some ecosystems, in particular, other vegetated land. We address this challenge by developing a range of plausible estimates of carbon densities that enables us to quantify the uncertainty of BCS in each country.

We gather carbon density estimates derived from national-level inventories compiled by the FAO (FAO, 1957, 1960, 1963) or presented in other scientific studies, for example, for South and Southeast Asia (Richards and Flint, 1994), East Asia (Fang, 2001; Choi et al., 2002; Fang et al., 2005), the United States (Magerl et al., 2019) and some European countries (Gingrich et al., 2007; Le Noë et al., 2020) *(SI Table 3)*. We use standardized factors (Eggleston et al., 2006) and previously-used estimates from the literature (Haberl et al., 2007) for conversion of area and carbon density estimates into carbon stocks.

In this way, we reconstruct BCS for 140 countries, considering the political boundaries of 1950 *(SI Figure 1)*, and aggregate these estimates to 14 subcontinental units *(SI Table 1)*. We consider major administrative boundary changes but do not account for small-scale border adjustments (*SI Table 2*).

The derivation of land area and carbon density accounts is explained in greater detail for each major land category *(Sections 2.1-2.8)*. We perform a series of modulations of carbon densities in each land category based on different assumptions of the likely presence of woody biomass *(SI Table 6)*. We use all modulations to perform a comprehensive uncertainty assessment *(Section 2.9)*, select one modulation for a detailed analysis *(Section 2.10)* and identify which land category displays the highest sensitivity *(Section 2.11)*.

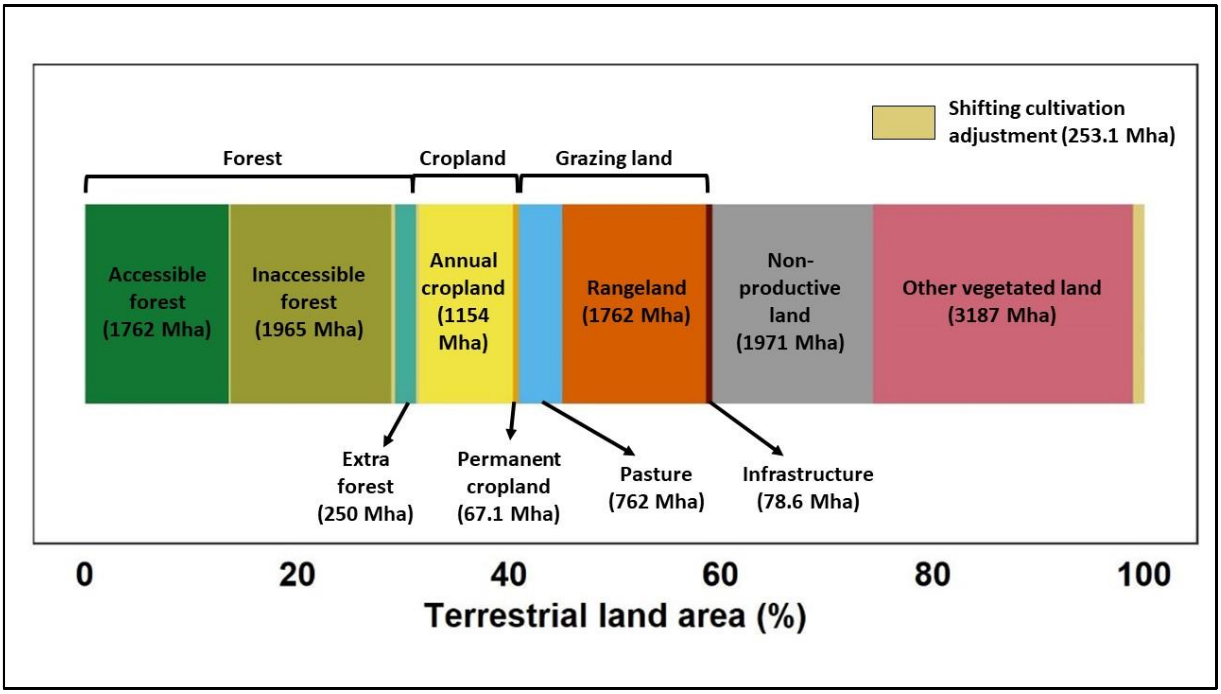

Figure 1: Land categories discerned in this study and their global distribution. Land areas mentioned in Accessible forest, Inaccessible forest and Other vegetated land represent areas without the shifting cultivation adjustment.

Table 1: Summary of the data sources used for estimating areas under each land category per country (n = 140). For more details on the categorization logic used for each land category, see text.

Land category	Land sub-category	Data source
Forest	Accessible forest	FAO World Forest Resources Assessment 1953
	Inaccessible forest	FAO World Forest Resources Assessment 1953
	Extra forest (n = 26)	FAO World Forest Resources Assessment 1953, Kastner et al. 2021
Cropland	Annual cropland	Kastner et al. 2021
	Permanent cropland	Kastner et al. 2021
Grazing land	Pasture	Kastner et al. 2021
	Rangeland	Kastner et al. 2021
Infrastructure		Kastner et al. 2021
Non-productive land		Kastner et al. 2021
Other vegetated land		Residual: Total land area minus all other land categories.

Shifting cultivation adjustment (n =41)	Shifting cultivation short fallows	Silva et al. 2011
	Shifting cultivation long fallows	Silva et al. 2011

2.1 Forest areas

We use forest area estimates from the FAO World Forest Resources Assessment 1953 (*hereafter, the 1953 Assessment*). The Assessment is the 2nd such assessment undertaken by the FAO (FAO, 1957, 2018), compiling data from country reports following an established forest area definition. According to the Assessment, forests are *'All lands bearing vegetative associations dominated by trees of any size, exploited or not, capable of producing wood or of exerting an influence on the local climate or on the water regime'* (FAO, 1957, 112).

According to recent reconstructions of global land-use dynamics (Klein Goldewijk et al., 2017; Kastner et al., 2021b), forest areas provided by the 1953 Assessment was under-reported for some countries. To quantify the extent of this underreporting, we compare forest areas reported by the Assessment with FAO-led Forest Resource Assessments of the early 21st century, and find an increase in forest areas in 26 tropical countries, despite there being no consistent evidence from other sources of an increase in forest areas. Rather, periodic assessments of the FAO (Lanly, 1982; Caravaggio, 2020) frequently identify high tropical deforestation rates in these countries across the 2nd half of the 20th century. We therefore introduce the additional sub-category of 'Extra forest', defined as the difference between forests (as provided in the Assessment) and the sum of the area under forestry and potentially forested wilderness areas in 1950 (Ramankutty and Foley, 1999; Kastner et al., 2021b) in these 26 tropical countries (*SI Table 4*). A total of 289 Mha was added to the forest category. The correction results in a 7.6% increase in the total forest area.

2.2 Forest carbon densities

We place particular emphasis on the derivation of carbon densities in forests because forests store manifold times more aboveground biomass carbon per unit area than all other land categories (Pan et al., 2013).

The Assessment provides a detailed categorization on forest types based on extent of use and its volumes (FAO, 1957). Being primarily a timber assessment meant to estimate timber flows to service post-War economies (Chazdon et al., 2016), the Assessment distinguishes ‘accessible’ and ‘inaccessible’ forests based on physical and economic accessibility. ‘Accessible forests’ are defined as *‘Forests which are now within reach of economic management or exploitation as sources of forest products, including immature forests and managed forests where fellings are prohibited’* and ‘Inaccessible forests’ as those *‘which are not yet managed or exploited, owing to inaccessibility’* (FAO, 1957, 112).

We interpret this distinction in terms of the likely presence/absence of forest management regimes involving significant wood harvest. We consider ‘Accessible forests’ as secondary forests under active management regimes, while ‘Inaccessible forests’ are considered to match the average potential vegetation in a country *(SI Text 2)*.

For accessible forests, we derive average forest carbon densities based on growing stock information from global assessments which compiled inventory information from individual countries (FAO, 1957, 1960, 1963). Where possible, we used information derived from the 1953 Assessment, and used information from subsequent assessments when necessary to make up for data gaps.

We convert growing stock volumes to BCS estimates by considering (1) wood density values classified per continent and biome-type, (2) region-specific biomass expansion factors (BEFs), (3) a root-to-shoot ratio classified per biome-type (Haberl et al., 2007) and (4) a constant carbon fraction of 0.5 (Eggleston et al., 2006).

For 17 countries, we use independent assessments of forest carbon densities for South and Southeast Asia (Richards and Flint, 1994), East Asia (Choi et al., 2002; Fang et al., 2005), United States (Magerl et al., 2019) and some European countries (Gingrich et al., 2007; Le Noë et al., 2020) derived from local forest inventories (*SI Table 3*). Combining these assessments, we obtain forest carbon density estimates for a total of 100 countries, which cover 87.2% of all forests in the world (*SI Figure 2*).

For the 40 countries lacking growing stock information, we derive subcontinental-averaged estimates of CS densities to combine with the reported country-level forest area estimates. This approach is similar to IPCC ‘Tier 2’ methods (Eggleston et al., 2006) that apply region-specific carbon density values to the country-specific forest areas.

We assume that ‘Inaccessible forests’ and ‘Extra forests’ were undisturbed by management or harvest activities and allocate them per-country carbon density values for “potential forests”, i.e. forests in the absence of human intervention (Erb et al., 2018). See *SI Table 6* for all modulations performed for this land category.

2.3 Cropland

We obtain cropland areas from a long-term study of global land use (Kastner et al., 2021b), which is based on historical statistical records from the FAO and the HYDE long-term land use dataset (Klein Goldewijk et al., 2017). We consider this dataset to be authoritative since the FAO has a long tradition in compiling agricultural statistics and remains the only standardized database available on the global scale since the mid-20th century.

Available cropland estimates combine areas under annual croplands (including multi-cropping) and permanent croplands. We distinguish these two subcategories by estimating the permanent crop fraction, ie. the proportion of permanent crops in total cropland per country, using FAOSTAT data for the years 1961-1965 as the value for the year 1950 *(SI Text 2)*. These years represent the first years of consistent and harmonized data collection by the FAO. We consider the categories ‘Land under permanent crops’ and ‘Cropland’ to make this distinction.

We assume that each country only belongs to one biome type - tropical, temperate or boreal, and consider the biome type as a fixed conditioning variable. For annual crops, we allocate an average carbon density equivalent to their climatic-zone averaged NPP (Krausmann et al., 2013). For permanent crops, we allocate an average carbon density of 22.5tC/ha, assuming an equal mix of tree-bearing and shrub-bearing permanent crops per country, in line with established estimates (Erb et al., 2018).

2.4 Grazing land

Grazing land is an umbrella term for many different land categories that can potentially be used for grazing or mowing (hay, silage) with very different land use intensities. Some of this land may even be irrigated and regularly fertilized.

Information on this land category remains scarce despite its vast geographical extent.

Furthermore, data quality varies greatly among the individual nations as many ambiguities related to definitions exist (Erb et al., 2007; Fetzel et al., 2017).

We delineate two kinds of grazing land based on the Aridity Index and population density, namely (1) permanent pastures and (2) rangelands (Klein Goldewijk et al., 2017), and allocate carbon densities based on the nature and temporal duration of vegetation.

Pastures

We consider pasture areas from Kastner et al. 2021 and allocate an average carbon density equivalent to their subcontinental-averaged NPP to account for their yearly use (Kastner et al., 2021b).

Rangelands

We consider rangeland areas from Kastner et al. 2021. We allocate a carbon density of twice the subcontinental-average NPP to account for the likely turnover times in these ecosystems (Kastner et al., 2021b). Since information on carbon densities in this land category remains relatively scarce, we also perform a set of modulations relying on existing literature (Xia et al., 2014; Kastner et al., 2021b). See *SI Table 6* for all modulations performed for this land category.

2.5 Infrastructure

We consider infrastructure areas from Kastner et al. 2021. In the absence of reliable datasets and due to the small extent of this land category, carbon densities are calculated as one-sixth of potential mean carbon densities at the country level, derived from a spatially-explicit FAO-based potential carbon stocks map for the year 2000 (Erb et al., 2018).

2.6 Non-productive land

Non-productive areas (for example, hot and cold deserts), by definition, are assumed to be devoid of any CS (Kastner et al., 2021b).

2.7 Other vegetated land

Land area in this land category is estimated in a subtractive approach, ie. this land category encompasses all land use and land cover types not addressed so far. We allocate carbon densities to this land category based on the likely presence of woody biomass, building on estimates and approaches from previous literature to determine carbon densities of sparse tree-bearing ecosystems (Erb et al., 2018). See *SI Table 6* for all modulations performed for this land category.

2.8 Shifting cultivation adjustment

Shifting cultivation, or swidden agriculture, is a rotational mode of smallholder agriculture essentially restricted to the tropics since the start of the 20th century (Heinimann et al., 2017). Information on its spatial extent remains limited (Houghton, 2010). The rotational form of agriculture practiced means that landscape-averaged carbon densities is lower under shifting cultivation than in forests but larger than in permanent croplands (Houghton et al., 2012; Mertz et al., 2021).

We adjust for the presence of shifting cultivation fallows by performing two sets of modulations which accounted for their extent and carbon density *(SI Table 6)*.

In the first modulation, we assume that the effects of shifting cultivation are reported in existing inventory accounts for 1950. In these cases, no modifications to carbon densities are made.

In the second modulation, which we use in the best-guess estimate *(Table 2)*, we assume shifting cultivation fallows as a separate and additional land category. In the absence of datasets that describe the extent of shifting cultivation in the mid-20th century, we consider a more recent pantropical estimate for the year 2000 (Silva et al., 2011). The study describes a total area under shifting cultivation, ie. the area of currently-cultivated fields and fallows, to be 253 Mha. This likely represents a modest under-estimate for the mid-20th century *(see SI Text: Notes for each land category)*. We assumed that any land with the presence of shifting cultivation that is not recorded as cropland would exist in one of two land use-land cover states: (1) short fallows (cultivation of 2 years followed by fallows of 4 years) or (2) long fallows (fallows of more than 6 years) (Fearnside, 2000). This modulation is considered in our best-guess estimate.

We gather country-level information on the total shifting cultivation areas and aboveground biomass densities for short and long fallows (Silva et al., 2011) as well as average fallow lengths (Fearnside, 2000) for a total of 41 countries under the administrative boundaries of the year 1950. We assume a root-shoot ratio of 0.24 and a carbon fraction of 0.5 to convert aboveground biomass densities into total CS densities (Eggleston et al., 2006).

In this scenario, the land under long and short fallows is subtracted preferentially from ‘Extra forest’, ‘Other vegetated land’ and then ‘Inaccessible forests’ in each country. Here, we follow the logic that since the Assessment defined accessibility under physical and economic terms for servicing post-War economies (Chazdon et al., 2016; FAO, 2018), areas under shifting cultivation would likely not be considered suitable for ensuring continuous timber flows and may even not be reported at all. Only in the case of Colombia are shifting cultivation fallows subtracted from ‘Accessible forests’ because of a lack of land in the other land categories.

2.9 Uncertainty analysis

To improve the understanding of the role of considered modulations on the overall BCS estimates, we perform a sensitivity and uncertainty analysis by varying carbon densities for each land category.

For accessible forests, we derive an uncertainty scale based on the reporting capability of the country and the kind and volume of information available in historical FAO datasets, assuming that the capacity of the country, with its administrative and economic status as a proxy, impacts the certainty and accuracy of the presented data (Romijn et al., 2015; Carter et al., 2018). This approach aligns with the uncertainty scale presented in another established global assessment from the 2nd half of the 20th century (Persson, 1974), and is consistent with the tier approach of recent FAO Forest Resource Assessments (FAO, 2020). The uncertainty scale is used at the country-level for accessible forests, distinguishing countries in the boreal, temperate, and tropical climatic zones. These are informed, best-guess categorizations based on conventions followed by similar studies of a global nature (Persson, 1974; Pan et al., 2011).

For temperate and boreal countries either covered by the FAO assessments or where forest carbon densities are derived from individual country-level studies, an uncertainty of ±25% is considered in the carbon densities of accessible forests. For temperate and boreal countries where continental averages are used as a measure for forest carbon densities, an uncertainty of ±40% is considered in the carbon densities of accessible forests. For tropical countries either covered by the FAO assessments or where forest carbon densities are derived from individual country-level studies, an uncertainty of ±40% is considered in the carbon densities of accessible forests. For tropical countries where continental averages are used as a measure for forest CS densities, an uncertainty of ±50% is considered in the carbon densities of accessible forests.

Due to a lack of direct observations of carbon densities for all other land categories, we use different permutations of possible carbon densities derived from the literature (Xia et al., 2014; Erb et al., 2018) in a scenario-based approach as a means of addressing uncertainties *(SI Table 6)*.

In this way, we develop 1728 BCS estimates per subcontinent by systematically combining and aggregating all the modulations performed for each land category. *SI Table 6* summarises all the modulations performed in this study.

2.10 Presentation of results

Out of the total of 1728 modulations performed by combining modulations within each land category *(SI Table 6)*, we choose one particular BCS estimate as the ‘best guess’ estimate for detailed analysis based on three criteria: (1) the quality of input data sources, (2) the reasonableness of assumptions, and (3) comparisons of empirical evidence to later available estimates for the early 21st century. This best-guess estimate is based on carbon densities derived from available forest inventory-based datasets to the extent possible and includes shifting cultivation as a separate land management practice in the tropics, which is a key determinant of tropical carbon fluxes (Hurtt et al., 2011) (*Table 2*). In addition, we use the median and inner quantiles to describe the spread of all 1728 modulations.

Table 2: Carbon stock accounting approaches for the best-guess case considered in the study.

Land category	Best-guess estimate	Data source
Accessible forest	Growing stock-derived from the Assessment (n = 83); independent studies (n = 17); subcontinental averages (n = 40)	See Section 2.3
Inaccessible forest	Average potential forest carbon stock densities	Erb et al. 2018
Extra forest (n = 26)	Average potential forest carbon stock densities	Erb et al. 2018
Shifting cultivation short fallows (n = 41)	Average shifting cultivation short fallows carbon stock densities	Silva et al. 2011
Shifting cultivation long fallows (n = 41)	Average shifting cultivation long fallows carbon stock densities	Silva et al. 2011
Rangeland	2 x NPP	Kastner et al. 2021
Annual cropland	NPP	Kastner et al. 2021
Permanent cropland	Equal mix of shrub and tree-bearing crops	Erb et al. 2018
Pasture	NPP	Kastner et al. 2021
Infrastructure	1/6th of average potential carbon stock densities	Erb et al. 2018

2.11 Sensitivity analysis

We pair the description of this best-guess case with a sensitivity analysis, quantifying the range of results from all modulations (*Section 2.11*). We identify which of the land categories contribute most to the observed range of values, both at the global level and at the subcontinental level. To do this, we start from the best-guess estimate (*see Section 2.10*) and pair-wise change carbon densities in only a single land category to calculate the impacts of these differences on the aggregate *(SI Table 6)*. Sensitivity of each chosen pair of values for each land category, both at the global level and at the subcontinental level, is calculated as the difference of the resulting estimate of total and land category-specific BCS from the corresponding best-guess estimate.

2.12 Comparison with recent estimates

As a final step, we compare the estimates developed in this study with recently-developed global BCS estimates from the literature for the 21st century. We use three recent studies to consistently compare BCS estimates at the subcontinental level for the years 2000, 2010 and 2019 (Erb et al., 2018; Spawn et al., 2020; Xu et al., 2021). We use two best-guess BCS estimates from the Erb et al. dataset which describe BCS for the year 2000 (Erb et al., 2018): one based on the FAO Forest Resource Assessment (FAO, 2001) and the other based on a study on global forest carbon fluxes (Pan et al., 2011). The Spawn et al. dataset is based on the harmonization of vegetation-specific remote sensing analysis for the year 2000 (Spawn et al., 2020). The Xu et al. dataset is also based on high-resolution satellite imagery analysis through 2000-2019 (Xu et al., 2021); we use their estimates for the years 2000, 2010 and 2019.

3. Results

3.1 Total carbon stocks in the mid-20th century

In 1950, global vegetation stored 450.7 PgC, according to our best-guess estimate *(Table 3)*, while the median of all modulations performed was 518.3 PgC, with inner quartiles of 443.9-584.6 PgC.

Tropical subcontinents across Africa, America and Asia contributed 299.5 PgC, or two-thirds, to total global BCS *(Figure 2)*. South America and Western Africa were the two regions with highest CS, with 124.71 PgC (27.6% of the total) and 74.47 PgC (16.5% of the total) respectively. Outside of the tropics, Soviet Union and North America made the biggest contributions. These two regions contributed around one-tenth of the total BCS each, with 57.38 PgC and 47.12 PgC respectively.

We find significant differences between the best-guess estimate and the median of all modulations across subcontinents. In 8 of the 14 subcontinents, the best-guess estimate is lower than the median, including in the 3 subcontinents with highest BCS (Southern America, Western Africa and the Soviet Union). This indicates the uncertainties that exist in BCS reconstructions and the relatively conservative nature of the best-guess estimate.

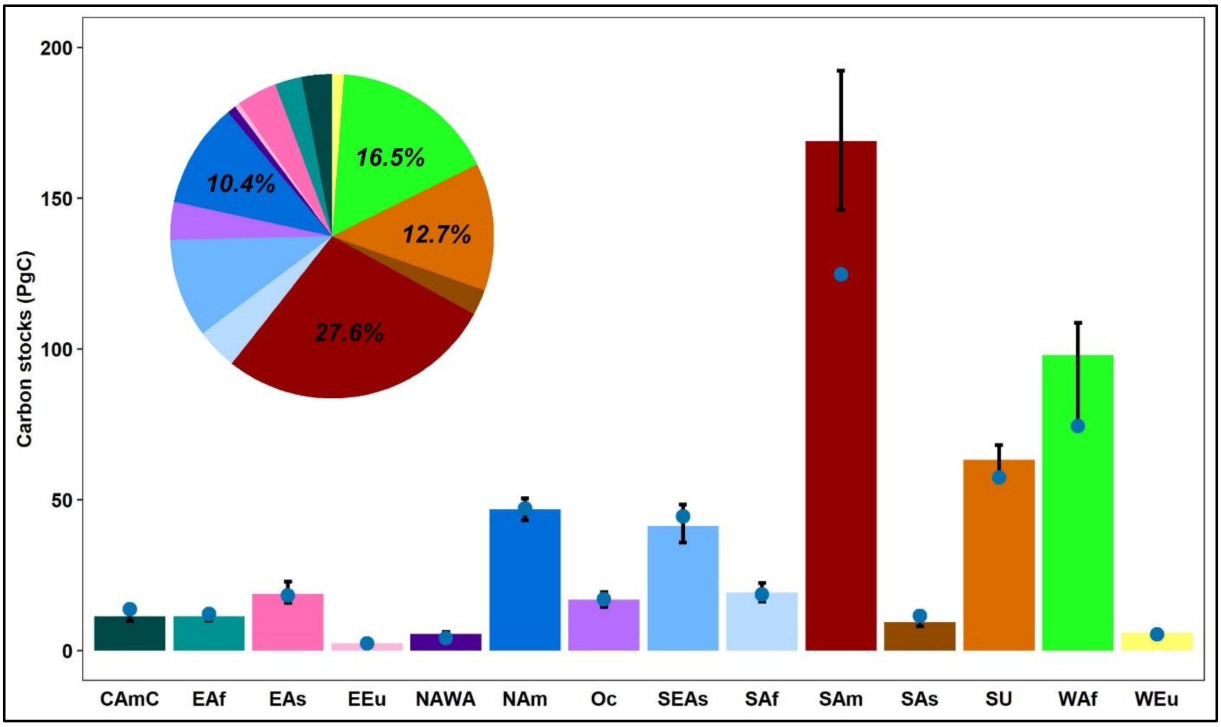

Figure 2: Global and subcontinental biomass carbon stocks. The best-guess estimate (blue dots) includes the presence of shifting cultivation in the tropics. The bars represent the median and the whiskers represent the inner quantiles of all modulations. The pie chart in the inset represents the contribution of each subcontinent to the best-guess estimate. Numbers on the pie chart are only denoted for those subcontinents where the contribution to total carbon stocks > 10%. Here, CAmC = Central America & the Caribbean; EAf = Eastern Africa; EAs = Eastern Asia, EEu = Eastern Europe; NAWA = Northern Africa & Western Asia, NAm = Northern America, Oc = Oceania; SEAs = Southeastern Asia; SAf = Southern Africa, SAm = Southern America; SAs = Southern Asia; SU = Soviet Union; WAf = Western Africa; WEu = Western Europe.

Table 3: Biomass carbon stocks in the mid-20th century.

	Best-guess estimate (PgC) (% of total)	**Median of all modulations (PgC) (inner quantiles)**
Global	450.77 (100%)	518.3 (443.9-584.6)

Central America & the Caribbean	13.69 (3.0%)	11.28 (9.71-13.14)
Eastern Africa	12.05 (2.6%)	11.35 (9.90-13.14)
Eastern Asia	18.17 (4.0%)	18.68 (15.70-22.89)
Eastern Europe	2.25 (0.5%)	2.29 (2.12-2.59)
Northern Africa & Western Asia	3.99 (0.9%)	5.45 (4.75-6.13)
Northern America	47.12 (10.4%)	46.76 (43.22-50.37)
Oceania	16.99 (3.7%)	16.78 (14.53-19.38)
Southeastern Asia	44.49 (9.8%)	41.34 (35.76-48.43)
Southern Africa	18.6 (4.1%)	19.14 (16.26-22.35)
Southern America	124.71 (27.6%)	168.83 (145.95-192.16)
Southern Asia	11.49 (2.5%)	9.44 (8.04-11.14)
Soviet Union	57.38 (12.7%)	63.24 (57.37-68.15)
Western Africa	74.47 (16.5%)	97.93 (75.29-108.60)
Western Europe	5.28 (1.1%)	5.71 (5.25-6.23)

3.2 Contribution of land categories to total carbon stocks

Forests were the dominant land category for biomass carbon stocks. In the best-guess estimate, forests contributed more than 75% (341.3 PgC) on only a third of the global terrestrial land mass *(Figure 3)*, the median of all modulations being 72.7%, or 377.8 PgC (inner quantiles 319.1-443.1 PgC) of the total CS.

Forests in tropical regions across America, Africa and Asia contained 249.1 PgC, or 72.9%, of the global forest BCS. These forests, which represented 55.2% of the global forest areas and 17.5% of the terrestrial land mass, stored 55.2% of the total BCS. Forest BCS were also high in Soviet Union and North America, storing 37.4 PgC and 31.9 PgC respectively.

Forests stored the highest proportion of total BCS in tropical subcontinents *(Figure 3)*. Their contribution was highest in Western Africa (89.4%), Southeastern Asia (85.4%) and Southern America (84.6%). It was the lowest in Eastern Asia, where forests stored about a third (33.2%) of the total BCS.

In the best-guess estimate, non-forest ecosystems had BCS of 109.43 PgC, while the median of all modulations was 130.32 PgC (inner quartiles 108.5-165.42 PgC). This was dominated by other vegetated lands, where CS were 76.17 PgC. BCS in other vegetated lands were highest in the Soviet Union (17.75 PgC) followed by Southern America (12.44 PgC) and Northern America (12.19 PgC) respectively. The share of BCS in this category as a proportion of total was highest in Eastern Asia (51.2%), Soviet Union (30.9%) and Oceania (30.2%). In these regions, large areas remain under different kinds of sparse trees, shrubs and productive grasses with diverse land management intensities, which have a fraction of the carbon densities reported in forests in the same country. These ecosystems store large parts of their carbon in soil (Scharlemann et al., 2014; Smith et al., 2016), whose estimation is outside the scope of our assessment.

The contribution of rangelands was highest in Oceania (11.4%), while it remained below 10% for all other subcontinents. The contribution of crop, pastures and infrastructure lands was the highest in Western Europe (15.5%) and Eastern Europe (15.4%). For other subcontinents, the contribution of these land categories remained below 10%. The contribution of shifting cultivation was highest in Southeastern Asia (6.4%) but remained well below 10% at the global level as well as for all other tropical subcontinents.

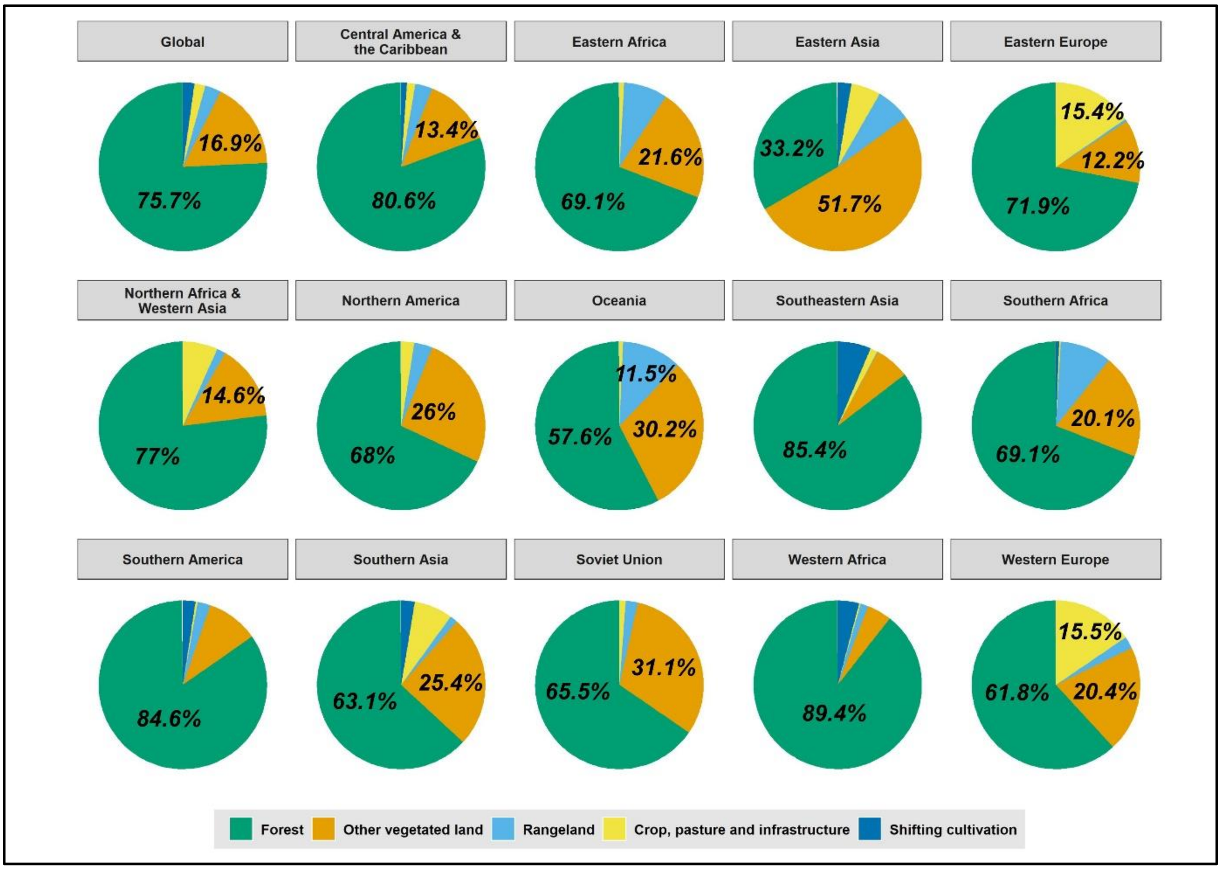

Figure 3: The contribution of each land category to total biomass carbon stocks in each subcontinent for the best-guess estimate. Numbers on the pie chart are only denoted for those land categories where the contribution to total carbon stocks > 10%.

The distribution of forest BCS differed between accessible and inaccessible forests for each subcontinent *(Figure 4)*. In Western and Eastern Europe, accessible forests stored more forest BCS than inaccessible forests, while inaccessible and extra forests stored significantly more forest BCS across the Americas and across Western and Southern Africa. Inaccessible forests and other vegetated lands demonstrated the highest uncertainty and sensitivity to different carbon densities due to a lack of direct measurements for these ecosystems in available inventory or modelling-based assessments *(SI Figures 5 and 6)*.

Distinctions between different categories of forests allowed us to explore the impacts of forest management on BCS. In the best-guess estimate, we found that forest management decreased BCS by more than a quarter globally, with significant regional differences. The impacts of management were particularly high in Eastern Asia, Western Europe and Eastern Africa. These regions had management-induced BCS losses in accessible forests of 4.7 PgC, 4.5 PgC and 4.74 PgC, or 65.2%, 60.5 and 60.3% of their potential forest BCS respectively. In comparison, accessible forests in other tropical regions covered only a fraction of the total forest area, reflecting the comparatively lower extent of forest use *(SI Figure 3)*. In Southern America, Western Africa and Northern Africa, management impacts could not be adequately disentangled because growing stock-derived CS densities were close to, or even exceeded average potential forest CS densities for some countries in these three subcontinents *(SI Table 5)*. Such cases where forest carbon densities in accessible forests exceeded the average potential forest carbon densities indicated that accessible forests in these countries were preferentially located in carbon-rich forests, in line with ensuring maximum timber flows.

In general, forests had the highest carbon densities among all land categories *(SI Figure 4)*. However, differences in the relative distribution of accessible, inaccessible and extra forests led to significant differences in subcontinental carbon densities.

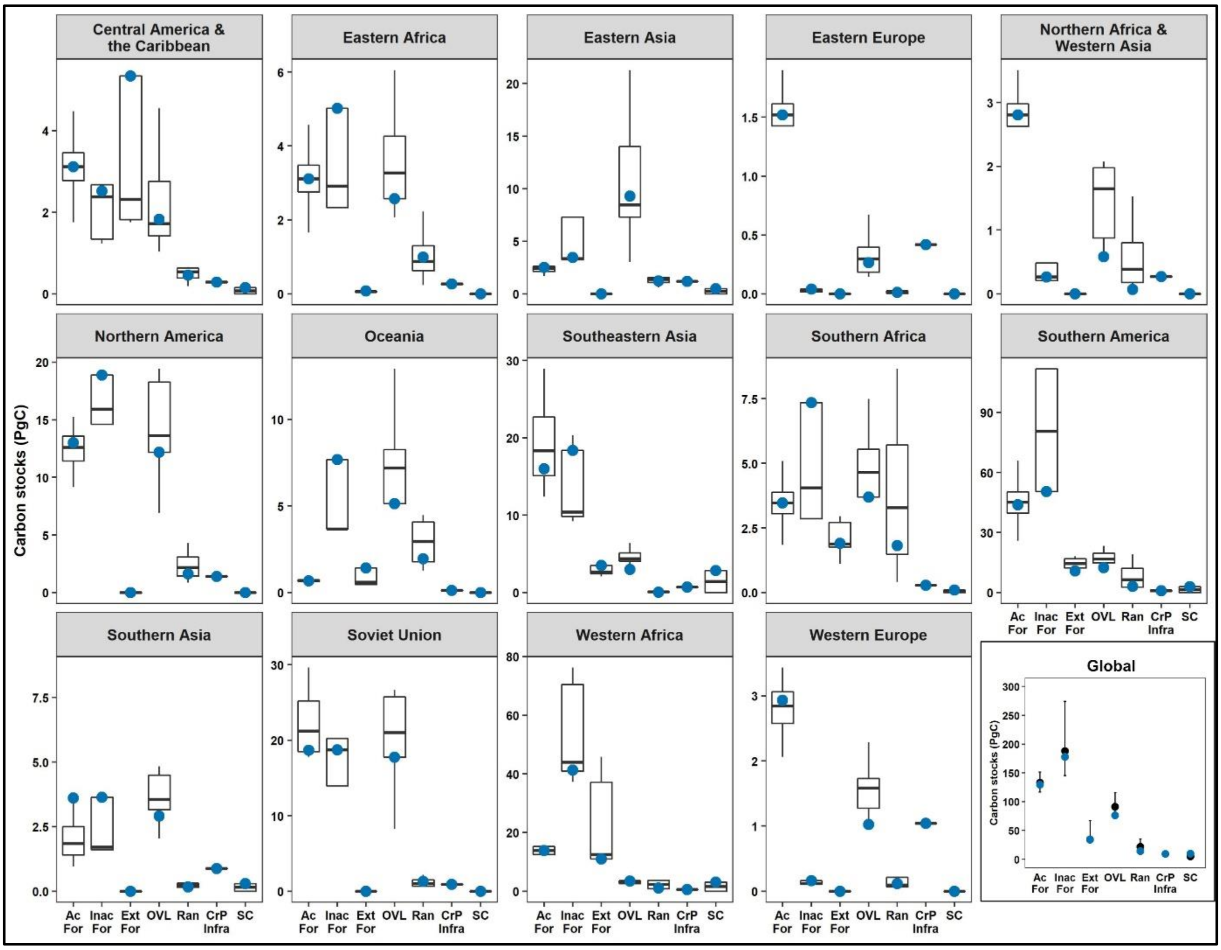

Figure 4: Distribution of carbon stocks among land categories across all subcontinents and globally (bottom right inset). The blue dots represent the best-guess estimate (see text). Here, AcFor = Accessible Forests, InacFor = Inaccessible Forests, ExtFor = Extra Forests, OVL = Other Vegetated Lands, Ran = Rangeland, CrPInfra = Crop, Pastures and Infrastructure. For information on land categories, see Materials and Methods.

3.3 Relative contributions of areas and carbon densities to total carbon stocks

Comparing the extent of forest in each subcontinent with forest CS densities revealed the relative role of forest areas and forest carbon densities in determining total CS *(Figure 5)*. We find that tropical regions had the highest average forest carbon densities and had the largest fractions of land area as forest. In the best-guess estimate, forest carbon density was highest in Southeastern Asia (140.5 tC/ha). This region also had the highest share of forests in the total land area – more than 60% of the land area in this region was under forest cover. Other regions with a high share of forests were Southern America (51.2%) and Western Africa (41.7%). Forest carbon densities were also high in Western Africa (140.1 tC/ha), followed by Southern America (116.3 tC/ha) and Central America (109.6 tC/ha). Forest carbon densities were comparatively lower in Eastern Asia (40.9 tC/ha) and the Western Europe (30.0 tC/ha). However, tropical regions did not necessarily contribute the highest to total BCS *(SI Figure 7)*. Despite high forest carbon densities in Southeastern Asia, its contribution to total CS was lower than the Soviet Union and Northern America, even though these two regions have lower forest carbon densities (50.4 tC/ha and 48.5 tC/ha, respectively). Southern America contributed the highest to global BCS because of large areas under forest cover and high carbon densities.

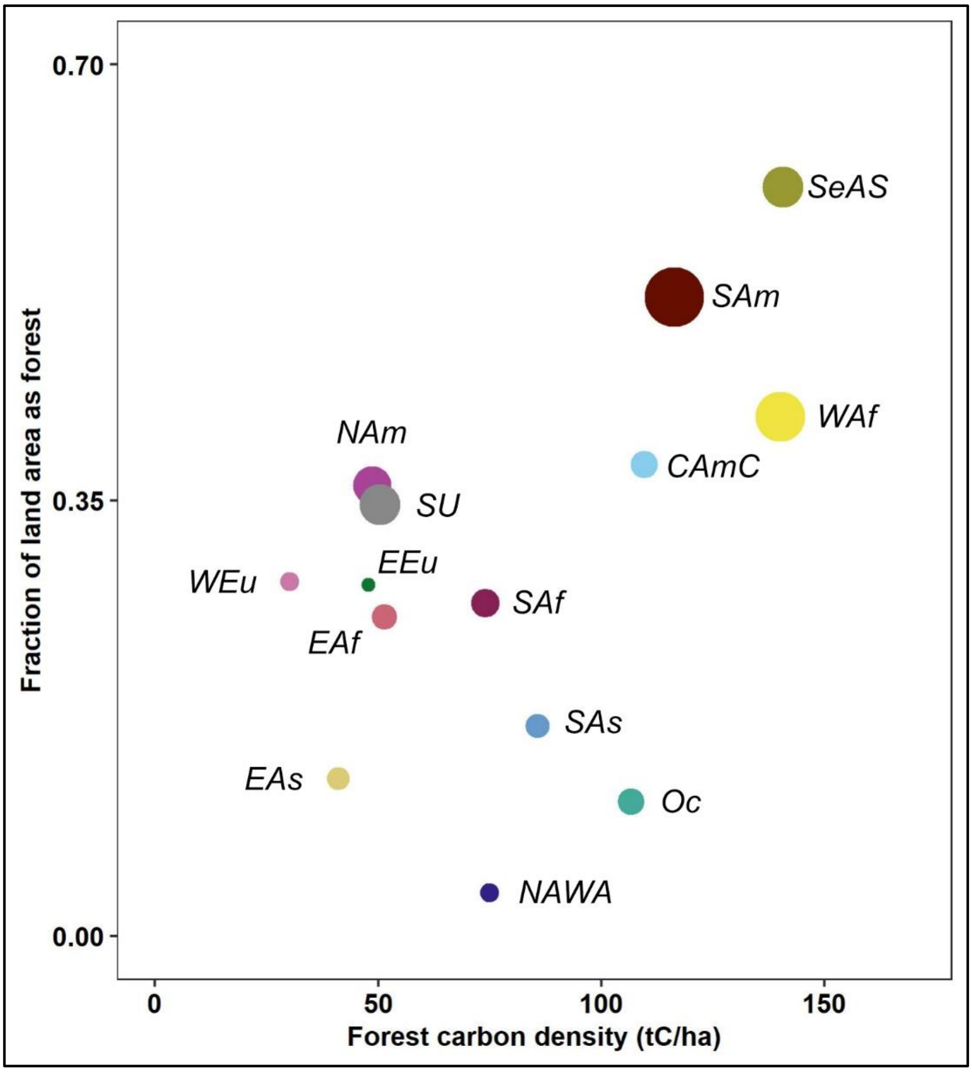

Figure 5: The contribution of each subcontinent to total carbon stocks as a function of its forest area fraction and average forest carbon density for the best-guess estimate. The size of the circle indicates the forest biomass carbon stocks in that subcontinent. Here, CAmC = Central America & the Caribbean; EAf = Eastern Africa; EAs = Eastern Asia, EEu = Eastern Europe; NAWA = Northern Africa & Western Asia, NAm = Northern America, Oc = Oceania; SEAs = Southeastern Asia; SAf = Southern Africa, SAm = Southern America; SAs = Southern Asia; SU = Soviet Union; WAf = Western Africa; WEu = Western Europe.

3.4 National contributions to global carbon stocks

We further analysed the contribution of each country to total CS in each subcontinent in the best-guess estimate *(Figure 6A)*. India and China contributed more than 80%

of total BCS in Southern Asia and Eastern Asia respectively. United States and Canada contributed equally to CS in Northern America. Mexico (54.2%) and Brazil (54%) contributed the highest in Central America and Southern America respectively. Country contributions were more evenly distributed in Western Europe and Southern Africa, where other countries contributed half and about a third to the total respectively.

Among countries, we found that Brazil (65.7 PgC, or more than 14% of the total) and the Soviet Union (57.4 PgC, or 12.6% of the total) contained the highest BCS *(Figure 6B)*. Forests in these countries contributed 59.4 and 37.4 PgC, or 87% and 64.9% of the country totals. Other countries with a high proportion of total BCS included Belgian Congo, United States, Canada and Indonesia.

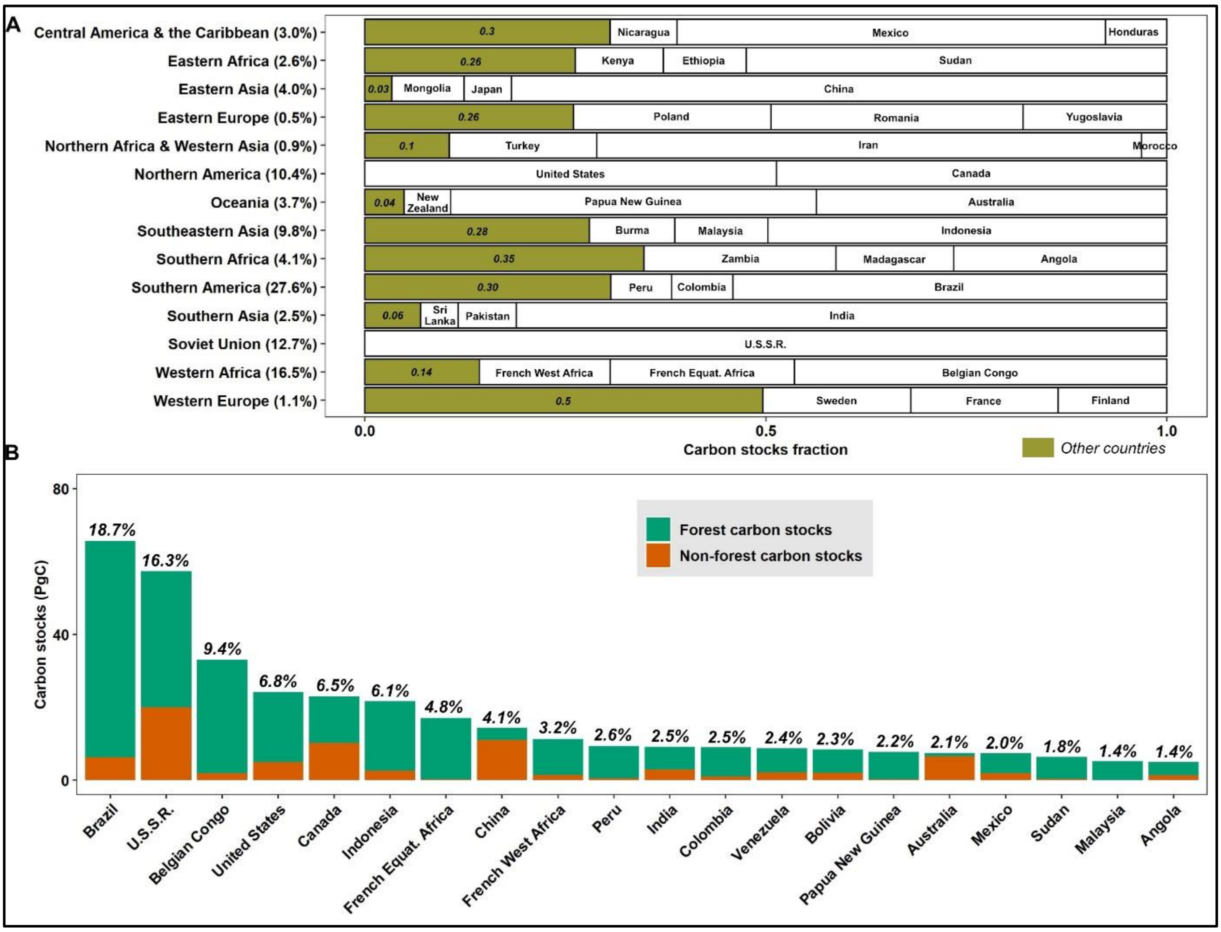

Figure 6: (A) Country contributions to total carbon stocks for each subcontinent for the best-guess case. Top 3 countries in each subcontinent are highlighted, and all

others are summarised under 'Other countries'. Percentages in brackets on the y-axis represent the contribution of each subcontinent to total carbon stocks. (B) Top 20 countries with the highest biomass carbon stocks for the best-guess estimate. Percentages on top of each bar represent the contribution of each country to total carbon stocks. For information on current administrative boundaries of larger administrative units in the mid-20th century, see SI Table 2.

3.5 Trajectories over the late 20th century

Compared to the best-guess estimate for the year 1950, 2 out of 3 estimates (Erb et al., 2018; Xu et al., 2021) for the year 2000 suggest a decrease in global BCS over the 2nd half of the 20th century *(Figure 7, SI Table 8)*. The Pan-based estimate from Erb et al. reports a total of 472.6 PgC, 4.8% higher than the best-guess estimate. Both BCS estimates for the year 2010 and 2019 (Spawn et al., 2020; Xu et al., 2021) report a decrease of 52.9-82.7 PgC (11.7-18.3%) compared to the best-guess estimate. When compared to the median estimate of 518.3 PgC for 1950, all estimates for the year 2000 suggest a decline in global BCS of 45.7-151.8 PgC (8.8-29.2%). Xu et al. report net increases in BCS for the years 2010 and 2019, as compared to 2000.

Changes in BCS across subcontinents were not uniform. Some subcontinents witnessed an increase in CS between 1950 and 2000. Compared to the best-guess estimate, BCS in Western and Eastern Europe grew by 3.81-4.77 PgC (72.1-92.2%) and 0.87-1.32 PgC (38.6%-58.6%) respectively. In both these regions, BCS have stabilised over 2000-2019. BCS in Northern America only showed marginal changes when compared to the year 2000, witnessed an increase till the year 2010 and then marginally declined in 2019. In Eastern Asia, our results are inconclusive, with the difference to Xu et al. dataset indicating an increase, while the difference to both the Erb et al. datasets indicating a decrease in BCS. In the Xu et al. dataset, BCS have continued to increase over 2000-2019. BCS in the Soviet Union witnessed a decline of 1.3-17.8% over the late 20th century, but have remained stable over 2000-2019. Some tropical subcontinents witnessed a decline in BCS. In frontier deforestation regions like Central America, Southeastern Asia, Southern Asia and Western Africa, BCS declined by more than 38.7%, 15%, 27.7% and 10.4% respectively when the best-guess estimate was compared with corresponding estimates for the year 2000. These four regions have witnessed marginal changes over 2010-2019

In other tropical subcontinents, BCS changes were highly dependent on the dataset used for comparison. In Eastern Africa, where Kenya has undergone a late-20th century forest transition (Rudel et al., 2020) and parts of Ethiopia also show signs of greening (Belay et al., 2015), we find signs of a net increase in BCS by 9.7% when compared to the Erb et al. FAO-based dataset and 27.8% when compared to the Erb et al. Pan-based dataset. In the Xu et al. dataset, BCS is increasing over 2000-2019 in this subcontinent, but remains below our best-guess estimate for 1950. However, datasets on land areas and carbon densities are least robust and uncertainties in BCS are highest in tropical subcontinents, limiting efforts to completely interpret these changes.

These limitations are demonstrated most starkly in Southern America. In this subcontinent, absolute values of BCS for the year 2000 differs substantially across datasets. A comparison of the best-guess estimate with the Erb et al. FAO-based dataset suggests negligible net CS changes, while comparisons with the Xu et al. dataset and Erb et al. Pan-based dataset suggest an increase of 30 PgC and a decrease of 30 PgC respectively. These differences are driven by Brazil, Argentina, Peru and Surinam, where a combination of the under-reporting of forest areas in 1950, underestimation of forest CS densities in inaccessible and extra forests *(SI*

Table 5 for Brazil) as well as the relatively high CS densities used in the Erb et al. dataset contribute to this observation.

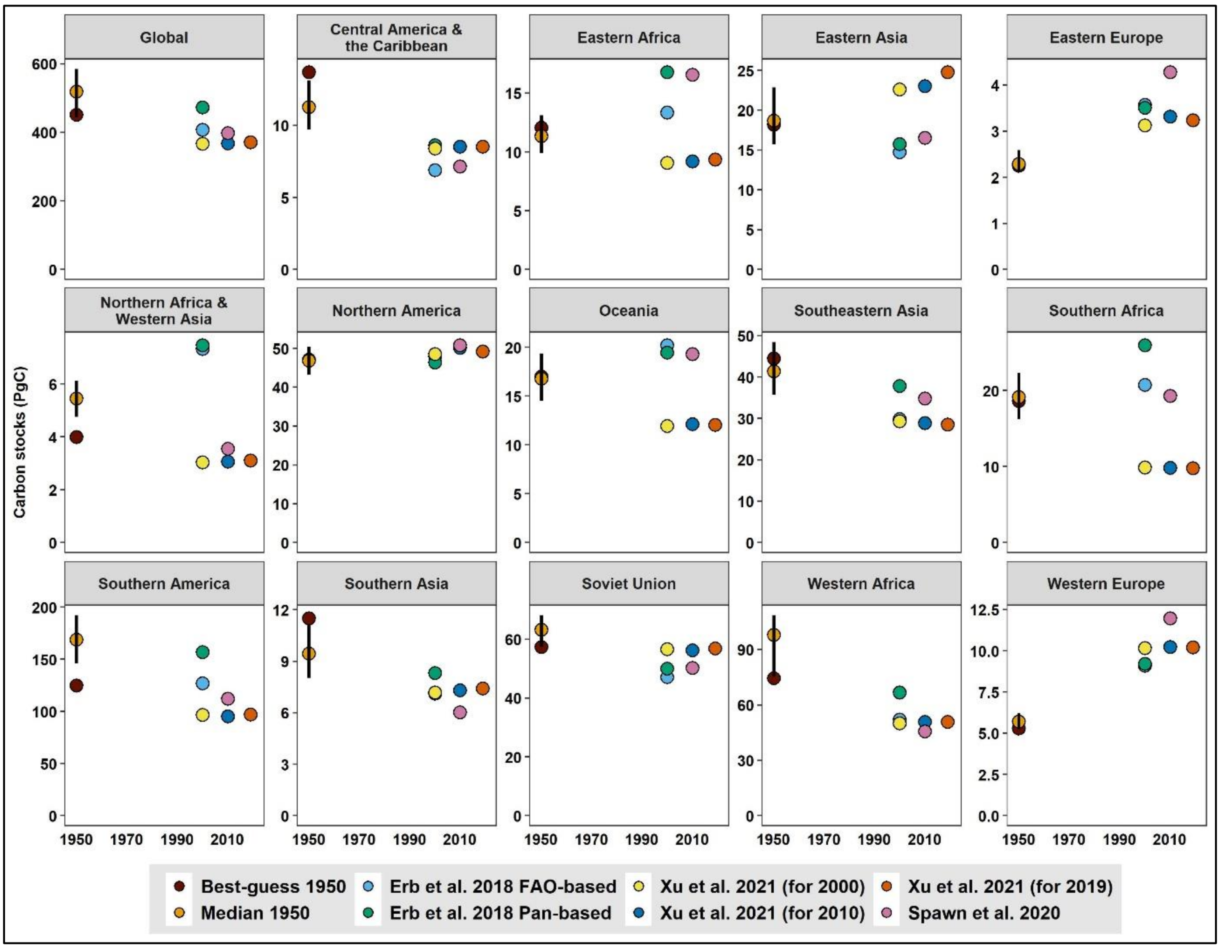

Figure 7: Change in biomass carbon stocks globally (top left) and at the subcontinent level over 1950-2019. We use carbon stocks estimates for 2000-2019 from Erb et al. 2018, Spawn et al. 2020 and Xu et al. 2021 to compare against estimates developed in this study. The whiskers represent the lower and upper quantiles. Note the different scales on the y-axis for each facet.

4. Discussion

4.1 Carbon stocks in the mid-20th century

Compared to the BCS in potential vegetation of 900-950 PgC (Olson et al., 1983; Erb et al., 2018) and pre-industrial estimates of 610-620 PgC (Houghton, 2003), we report BCS in the range of 443.9-584.6 PgC, with the median of all performed modulations being 518.3 PgC. Our best-guess estimate of 450.7 PgC for the year 1950 is comparable to the median estimate of 450 PgC for the year 2000 reported by Erb et al. 2018, which encompasses the FAO-based estimate of 406.6 PgC and the Pan et al.-based estimate of 472.6 PgC (Erb et al., 2018), but uncertainties remain high. Our best-guess estimate is significantly higher than two other contemporary estimates for the years 2000-2019 (Spawn et al., 2020; Xu et al., 2021) (*Table 3 and SI Table 7*). Compared to the median estimate for 1950, all estimates for the 21st century report a significant decrease in BCS globally.

Our analysis highlights the tension between a probable range of total BCS and a plausible best-guess estimate. While the inner quantiles of the modulations derived from aggregating 1728 cases per subcontinent encompasses a reasonable range of 30% and thus represent plausible cases of total BCS in 1950, it is driven by remarkable variations in BCS of other vegetated lands *(Figure 4, SI Figures 5 and 6)* and the cumulative nature of the uncertainty analysis. This highlights the need for more research to understand the carbon state of, and fluxes in, these diverse tree-bearing lands which cover tropical and subtropical dry forests and savannas, where BCS are often underestimated (Pötzschner et al., 2022), as well as tundra and taiga in the northern latitudes, which store significant proportions of their biomass in below-ground carbon pools (Thurner et al., 2014; Campioli et al., 2015), to help narrow the large uncertainty ranges in global carbon budgets over the last six decades (Le Quéré et al., 2013; Friedlingstein et al., 2019).

On the other hand, the best-guess estimate represents a modulation which is based on carbon densities derived from direct observations to the extent possible. The allocation rationales utilised for the best-guess estimate combine well-considered assumptions on the reporting capabilities of the FAO in the mid-20th century (FAO, 2018) with the likely carbon state of ecosystems (Erb et al., 2018), thereby providing a plausible estimate based on inventory statistics. The best-guess estimate is also remarkably close to the figure of 449 PgC reported by Elhacham et al. 2020 for the year 1950. Elhacham at al. 2020 link recent global BCS estimates (Erb et al., 2018) with information on carbon fluxes derived from DGVM-based averages, which account for both land use and environmental changes, over the 20th century (Elhacham et al., 2020). Our analysis goes a step further and allows the comparison of consistent stock-based estimates across two timepoints, providing a complement to such hybrid stock-flux based approaches.

4.2 Carbon fluxes over the 2nd half of the 20th century

Our estimates of carbon emissions from land change over 1950-2000 are in line with other established estimates of net emissions from book-keeping models as well as vegetation modelling-based approaches *(Table 4).* Currently, annual carbon emissions derived from flux-based approaches amount to 0.9-1.5 PgC/year. These approaches, which include both book-keeping and process-based models, account for several land cover change and land management processes impacting both biomass and soils. Process-based approaches additionally account for environmental effects (Houghton et al., 2012; Friedlingstein et al., 2020).

In comparison, our inventory-based stock-change approach developed by annualising the difference between our best-guess estimate and the BCS estimates for the year 2000 indicates a similar range (-0.43-1.68 PgC/year) of net emissions but includes an opposite sign *(SI Table 9)*. The range of net emissions estimates widens (-0.57 to 4.36 PgC/year) when the median and inner quantiles of all modulations is included.

In effect, the similar range of net land change emissions indicates that our best-guess estimate closely relates to reported flux-based estimates, even though our analysis does not include soil carbon fluxes. The influence of soil carbon fluxes on land change emissions, although regionally pronounced, has been found to be modest when considered at the global scale (Ito et al., 2020; Pongratz et al., 2021).

The observation that all flux-based approaches indicate net emissions over this timperiod suggests that BCS were higher in 1950 and have declined since then. This corroborates recent evidence that the Pan-based estimate for the year 2000, which is the only one above our best-guess estimate, may indeed overestimate BCS, possibly due to spatial biases in the geographical distribution of forest carbon flows (Spawn et al., 2020; Xu et al., 2021).

These emissions estimates also suggest that, over the 2nd half of the 20th century, environmental changes like CO_2 fertilization effects which have led to greening (Zhu et al., 2016; Chen et al., 2019) have only partly counteracted land use changes which decrease BCS (Yu et al., 2019; Harris et al., 2021; Le Noë et al., 2021a). These land use changes not only include extensive deforestation in the tropics (Skole and Tucker, 1993; DeFries et al., 2002; Williams, 2006) but also land management-induced BCS reductions in forest ecosystems globally (Erb et al., 2018).

Table 4: Comparison of annual net carbon fluxes from biomass carbon stock changes over the 2nd half of the 20th century. Carbon fluxes for this study are developed by comparing the best-guess estimate developed in this study with the global estimates from Erb et al. 2018, Spawn et al. 2020 and Xu et al. 2021. All other described estimates sourced from other studies also report soil carbon fluxes, which remains outside the scope of our study. Estimates for 1920-1999 are taken from a contemporary review of studies describing land change emissions (Houghton et al., 2012). In the 'Processes captured' column, 'ALCCLM' = Anthropogenic land cover and land management changes; SC = shifting cultivation in the tropics; EC = environmental change. Negative net emissions imply a net carbon sink.

Net land change emissions (PgC/year)	**Accounting period**	**Processes captured**	**Source**
-0.43-1.68	1950-1999	ALCCLM (+ SC) + EC	**This study, best-guess**
-0.57-4.36			**This study, inner quantiles**
1.3-1.5	1960-1999	ALCCLM (+ SC), range of bookkeeping approaches	Friedlingstein et al. 2020, Table 5
1.4	1960-1999	ALCCLM (+ SC) + EC, average of DGVM-based approaches	Friedlingstein et al. 2020, Table 5
0.92	1920-1999	ALCCLM + EC	Arora and Boer 2010
1.21		ALCCLM (+ SC)	Houghton et al. 2010
1.31		ALCCLM + EC	Piao et al. 2009
0.9-0.99		ALCCLM + EC	Pongratz et al. 2009
1.03-1.34		ALCCLM	Reick et al. 2010
1.28-1.44		ALCCLM (+ SC)	Shevliakova et al. 2009
1.39		ALCCLM	Strassmann et al. 2008
1.31		ALCCLM	Stocker et al. 2011
1.16		ALCCLM + EC	Van Minnen et al. 2009
1.32		ALCCLM	Zaehle et al. 2011

4.3 Identifying an emerging global land transition

Our analysis provides grounds for the extension of land use transition research to account for the evolution of global and subcontinental BCS. While our estimates indicate a decline in BCS over 1950-2000 globally, some subcontinents indeed report an increase in BCS *(SI Table 8)*. This suggests that the trajectory of BCS changes remains a function of geographic setting and previous land use histories of subcontinents.

As forests in the Global North, for example in France (Le Noë et al., 2020), Austria (Gingrich et al., 2007) and the United States (Magerl et al., 2019), recover due to resource substitution, externalization and state-driven actions after years of net deforestation (Mather, 2005; Meyfroidt and Lambin, 2011; Gingrich et al., 2019; Rudel et al., 2020), we find evidence of BCS recoveries in these regions as well. We observe such ‘carbon stock transitions’ for Western and Eastern Europe as well as Northern America. Carbon gains in these subcontinents can only partly counteract observed BCS reductions globally, since these subcontinents have significantly lower carbon densities than tropical subcontinents *(Figure 5)*. Moreover, a comparison of annual carbon fluxes in these subcontinents across 3 timeperiods indicate an accelerating rate of carbon gains *(SI Table 9)*, suggesting the thickening of forests in the constituent countries driven by environmental change (Gingrich et al., 2007; Magerl et al., 2019; Le Noë et al., 2020). However, further gains may be limited due to limitations of land availability (Kalt et al., 2021) and the saturation of environmental effects (Le Noë et al., 2021a).

In the tropics, some countries have reported net forest area gains over the late 20th century, for example India (Singh et al., 2017) and Vietnam (Meyfroidt and Lambin, 2008). However, from our results, we do not find definitive evidence of a carbon stock transition at the subcontinental level in the tropics, except for some evidence in the case of Eastern Africa *(SI Table 8)*, although uncertainties remain high. Forest area increases which have led to the forest transition in some tropical countries are not mirrored by BCS gains, owing to the differential impacts of land use on tree cover and BCS changes (Bhan et al., 2021). In reality, the overwhelming signal in the tropics remains the net loss of BCS. These subcontinents have high carbon densities

(Figure 5) which drive the BCS reductions observed globally. The rate of carbon loss in these subcontinents remains variable across 7 decades *(SI Table 9)*, with some indications of accelerating carbon losses over the last 2 decades also consistent with recent evidence (Feng, 2022). In these subcontinents, the overwhelming challenge that exists is to significantly reduce, or even halt, deforestation (Griscom et al., 2017; Roe et al., 2021) while undertaking realistic restoration interventions (Zeng et al., 2020).

To further contextualise these changes, future re-investigations of regional inventories can help demonstrate the relative role of forest area changes and biomass thickening in determining these changes (Thom et al., 2018; Gingrich et al., 2019; Kauppi et al., 2020), while combining BCS assessments with the analysis of socio-metabolic indicators (Gingrich et al., 2022) can reveal the divergent pathways of such land transitions across the world.

Conclusion

By integrating land use datasets with information on carbon densities from forest inventories, we reconstruct estimates of BCS for the year 1950. We report a best-guess estimate of 450.7 PgC, while the median of all modulations is 518.3 PgC. We find that forests were the primary storehouse of BCS and tropical subcontinents stored the most BCS. Our estimates of annual carbon fluxes over the 2nd half of the 20th century are largely similar to other modelling-based efforts, and indicate that additional carbon sinks due to environmental change only partly offset land use change impacts on BCS. Comparisons to contemporary estimates of BCS reveal an aggregate global reduction in BCS, albeit with pronounced subcontinental characteristics of change which differentiates between tropical and northern subcontinents. The carbon stock transition following a forest transition helps contextualise such a geographical distribution of BCS changes.

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Declaration of interest statement

No potential conflict of interest was reported by the authors.

Data availability statement

All data underlying the analysis are available at: *10.5281/zenodo.6372858.*

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Supplementary Information

A mid-20th century estimate of global vegetation carbon stocks based on inventory statistics

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The sections below include:

SI Text 1-4

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SI Text

SI Text 1: Land use/land cover reconstruction for non-forest categories

We used the land use/land cover reconstruction performed in a recent HANPP assessment (Kastner et al., 2021) to estimate areas under non-forest land categories. Here, we describe the method used for reconstruction in brief. For a detailed description, please refer to their publication.

The main data source for their assessment is the recent version of the HYDE database (Klein Goldewijk et al., 2017), combined with other land use/land cover maps (Ramankutty and Foley, 1999; European Space Agency, 2017; Erb et al., 2018). The assessment followed a prioritization approach, based on the extent and reliability of available land use/land cover information.

Infrastructure land consisted of the built-up layer in HYDE (Klein Goldewijk et al., 2017) and an additional estimate of small scale infrastructure areas not covered in HYDE. For this, 5% of cropland area in each cell containing cropland was considered as infrastructure land.

For cropland, the assessment combined three different datasets and modulated the datasets to ensure that cropland area is more evenly spread out across a country.

All land classified as bare soil and land classified to carry permanent ice and snow cover, according to the ESA Land cover map for the year 2000, was considered as non-productive land.

Grazing land was considered as the sum of pastures and rangelands from the HYDE database and distinguished based on their potential vegetation cover (Klein Goldewijk et al., 2017). Grazing land on potentially forested land was considered as pasture, and that on potentially non-forested land was considered as rangeland.

SI Text 2: Further information for land categories

Reconstructing global biomass carbon stocks (BCS) requires a consistent treatment of land use patterns and management practices, as well as their resulting effects on vegetation biomass (Hurtt et al., 2011). By triangulating statistical information derived from forest inventories with other spatially-aggregated information on land use, we establish a robust method of reconstructing global BCS over the mid-20th century. Our approach harnesses the complementarity of multiple land use/land cover datasets and plausible carbon densities across established land categories. We undertake a robust uncertainty analysis using a scenario-based approach considering the option space of plausible carbon densities in each land category. This allows for an assessment of the overall uncertainty as well as for identifying land categories with the highest uncertainties. In addition, we utilise cases with and without an explicit consideration of shifting cultivation fallows to modestly account for the differential nature of land use in the tropics. These subcategories help allocate carbon densities closer to their expected natural state around the year 1950, and to aim for as high a spatially-aggregated resolution as possible with the existing datasets. As such, our approach is designed to facilitate fuller and more consistent treatments of determining areas and carbon densities of land categories for which historical information remains extremely scarce to this day.

As a starting point of our country-level assessment, we chose administrative units with the following criteria:

- A minimum land area of 1 million ha, OR
- Administrative units with a land area smaller than 1 million ha but ultimately a part of bigger administrative units as an outcome of mid to late 20th century changes.

    - For example, the inclusion of Saar in Germany; the inclusion of Portuguese India and French India into India.

Further information for some land categories is described below.

Forest

We use country-level forest area estimates from the FAO World Forest Resources Assessment (FAO, 1957), the 2nd such global assessment undertaken by the FAO (FAO, 2018). Use of the mid-20th century FAO forest area estimates has some known limitations: (1) the quality of the reported data remains variable, (2) the definitions and reported categories have been subject to change across reporting cycles (Bhan et al., in prep.), especially for tropical countries (Grainger, 2008), (3) it remains of comparatively lower quality than corresponding agricultural statistics (Kastner et al., 2021) and (4) validation through remote sensing and independent ground-truthing approaches is absent.

This Assessment reports growing stock estimates for a fraction of countries and describes forest volumes for forests under active management derived from inventories. These inventories, in general, are based on the repeated measurement of permanent sample plots spread across forest zones in a country and represents an unbiased sample of the population of trees in a country. Growing stocks estimates suffer from different sampling strategies employed across countries. This contributes to the uncertainty in these estimates.

In total, we obtain forest carbon densities for 100 countries out of a total of 140 countries included in our study *(SI Figure 2)*. Among these 100 countries, we find that information from national inventories is predominantly situated in temperate and boreal biomes, where country-level reporting capabilities are higher than those in the tropics. Inventories from temperate and boreal biomes also cover a high proportion of the total forests in those countries (*SI Figure 3*).

We use forest carbon densities derived from the FAO assessments, independent country-level studies on forest BCS and continental averages for accessible forests. These forests are assumed to be under active management, based on the definition of ‘forest’ and ‘accessible forest’ provided in the assessment. In contrast, we assume that inaccessible forest and extra forests are in an intact state and have carbon densities close to their hypothetical potentials. The potential state refers to hypothetical state of vegetation under current environmental conditions but without land use (Haberl et al., 2007). The minimum carbon density threshold for forests was 30tC/ha at a 5-minute pixel resolution.

Currently available spatial estimates of potential vegetation are based on environmental conditions existing around the year 2000. Currently, there is a lack of consensus on the changes in plant growth stimulated by environmental changes over the 2nd half of the 20th century. The relative impacts of CO_2 fertilization and increased turnover on vegetation biomass is still debated within the broader ecological community. While early ecosystem modellers argued that against dramatic effects of CO_2 fertilization on biomass, there now exists abundant evidence of CO_2 fertilization effects as well (Harris et al., 2021; Le Noë et al., 2021) which may be counter-acted by shifts in vegetation turnover (Carvalhais et al., 2014; Yu et al., 2019). As a conservative measure, we assumed that environmental conditions for plant growth for the year 2000 are similar to the ones in 1950.

Cropland

We distinguished annual and permanent croplands by developing a metric of ‘Permanent Crop Fraction’ per country, based on FAO definitions in agricultural lands. We calculated the *‘Permanent Crop Fraction*’ as the ratio between ‘Land under permanent crops’ and ‘Cropland’ for each year and considered the average for the years 1961-1965 as the value for the year 1950, assuming that the intervening period would not have led to dramatic changes in the distribution between annual and permanent croplands, even if total cropland areas may have changed.

‘Land under permanent crops’ is defined as *‘Land cultivated with long-term crops which do not have to be replanted for several years (such as cocoa and coffee), land under trees and shrubs producing flowers (such as roses and jasmine), and nurseries (except those for forest trees, which should be classified under Forestry)*’.

‘Cropland’ is defined as *‘Land used for cultivation of crops. The total of areas under ‘Arable land’ and ‘Permanent crops’’*.

For countries which attained independence in the intervening period and split up in its constituent units (for example, French West Africa and French Equatorial Africa), the Permanent Crop Fraction was considered the average of its constituent administrative units weighted by their total land area in 1961.

Other vegetated land

Consistent land area and carbon density information of these ecosystems remains scarce to this day, and remains contingent on questions around definitions (Chazdon et al., 2016) as well as the kind and intensity of use (Erb et al., 2007, 2018). Attempts to understand and categorize land area changes in these ecosystems have been a key feature of mid to late-20th century FAO assessments, especially in the tropics (Persson, 1974; Lanly, 1982). This includes the introduction of categories like ‘Open forests’ or more recently, ‘Other wooded lands’, primarily based on tree cover densities and predominant land use.

In our study, we subtracted all known land uses (*Section 2.1-2.6 in the main text*) from the total terrestrial land area per country. There is scarce information on the nature of woody vegetation, in terms of tree-bearing capacities, and the extent of human use on these lands. However, since all known land uses were subtracted, we assumed that these lands are predominantly tree-bearing and exist around the tree density thresholds used to define ‘Other wooded lands’ and ‘Open forests’ in subsequent FAO assessments (Persson, 1974; Lanly, 1982; FAO, 2001). Thereby, it is very likely that a significant portion of this land is now considered as a ‘forest’ under current FAO definitions (Chazdon et al., 2016; FAO, 2018).

Shifting cultivation

Difficulties in accounting for lands under shifting cultivation in tropical countries extend back to the mid-20th century. Evidence suggests that shifting cultivation remains a form of forest use in particular, and land use in general, not well accounted for, with data on its historical extent extremely scarce (Fearnside, 2000; Hurtt et al., 2006; Heinimann et al., 2017).

Evidence on the changing extent of shifting cultivation and shifts in average fallow periods over the 2nd half of the 20th century remains variable (Fearnside, 2000; Heinimann et al., 2017). One FAO assessment from the 1980s predicts an increase in forest fallows of about 5 Mha/year through the late 20th century, from a value of about 410 Mha in the 1980s, because of increasing population pressures (Lanly, 1985). Backcasting these estimates over 1950-1980 and assuming the same fallow expansion rates indicate that shifting cultivation fallows of 253 Mha around the year 1950 may be credible. On the other hand, other studies report dramatic reductions in the practice of shifting cultivation across the tropics (Fearnside, 2000; Heinimann et al., 2017). Based on this evidence, we considered the estimate for the year 2000 as a modest under-estimate for the year 1950 and included it in our analysis.

We considered that shifting cultivation long and short fallows should be considered as occurring in naturally tree-bearing areas. Due to the rotational nature of the practice, we assumed that forests cleared for shifting cultivation were already fallow forests in the shifting cultivation cycle (Houghton and Hackler, 1999), ie. no new primary forests were cleared for it around the mid-20th century. For countries which were a part of bigger administrative units in 1950 (for example, French West Africa and French Equatorial Africa), we took an average of biomass densities, weighted by the area under shifting cultivation per country.

We divided the total land under shifting cultivation per country into *(average fallow length + 1)* sections. According to the fallow period logic of Fearnside et al., six sections were allocated under short fallows, and the rest under long fallows. Average fallow length was considered as 15, 13 and 10 years for countries in Asia, Africa and Latin America respectively in the mid-20th century (Fearnside, 2000).

SI Text 3: Uncertainty analysis

Sources of uncertainty vary widely in our assessment. These uncertainties and are both conceptual and data-based in nature. For example, a common mismatch among successive FRAs is in the definition of a ‘forest’, which leads to large uncertainties and a lack of consistency among successive assessments. This uncertainty has reduced since the 1990s with the introduction of a harmonized and consistent ‘forest’ definition. For pre-1990 assessments, these issues persist. There are also differences in minimum tree diameter at breast height (DBH) thresholds for inclusion in growing stock estimates, leading to data uncertainties, combined with the fact that many countries do not report growing stocks estimates around the year 1950. We have used regional averages or growing stocks estimates sourced from later FAO assessments (for the year 1958 and 1963) to make up for the absence of some of these data points.

The attention to undertake a formal uncertainty analysis and the methods for dealing with uncertainties also differ widely among data sources. There exist no single applicable quantitative methods for integrating these variable sources, methods and conceptualizations (Pan et al., 2011).

Largely, countries of the temperate and boreal zones have established forest inventories. The data availability for these countries is good. From a growing stocks perspective, these countries have lower uncertainties because they are based on unbiased statistical sample surveys. Uncertainties from the use of standardized factors to convert growing stocks into biomass carbon stocks densities remains rather low, currently around 3% (Eggleston et al., 2006).

For the tropical zones, very few countries have established forest inventories. If they are available and reported, it exists for a small fraction of commercially exploited forests. In such cases, many countries rely on subjective expert assessment, with high uncertainties expected (Persson, 1974; Grainger, 2008). The separation of accessible and inaccessible forests also remains ambiguous with respect to accounting for small-scale logging, and accounting for secondary forests in shifting cultivation cycles remains, to this day, extremely challenging (Heinimann et al., 2017).

SI Text 4: Limitations of our analysis

We discuss below some important limitations and constraints associated with our analysis that should be kept in mind when using or reporting these results.

In all interpretations and descriptions, we assume that climate (and region) is a fixed conditioning variable or explanatory variable. We ignore the possibility of large-scale environmental and climatic changes which would alter the bioclimatic classification of countries across the 2nd half of the 21st century.

We have performed a global analysis in this study. Our primary aim is to look for subcontinental and country-level averages and trends to demonstrate large-scale patterns. We aim for averages for large regions to be realistic, with trends and differences between regions reflecting real differences.

As the nature of land accounting has undergone dramatic changes over the last few decades, abundant caution needs to be exercised before comparing land areas and BCS for particular land categories across time because every subsequent assessment over the 20th century not only reflects changes in areas but also improvements in measuring capacities (Chazdon et al., 2016).

In such a spatially-aggregated assessment relying on triangulating historical data, we have limited information on the configuration of land use classes in the landscape. A country can have all land use classes spatially-segregated, all land use classes mixed with each other or most likely, any combination of these two extremes. We cannot, and do not, make judgements on distribution of carbon stocks in sub-national units.

Readers knowledgeable about specific geographical areas may identify over or under-estimations of land areas and BCS in our results. These biases can occur from, for example, our underestimation of forest areas in several tropical countries with a history of deforestation over the late 20th century (Lanly, 1982; Grainger, 2008). Much of the disagreements in existing long-term land use assessments arise from multi-functional landscapes or areas of low cropping density, where sparse agriculture can often tend to be confused with natural vegetation. For example, in tropical regions, where subsistence agriculture mixed with natural vegetation is a common practice, mixed-use landscapes may have higher carbon stocks in biomass than previously known.

Land use assessments based on the country reporting structures of the FAO that we use in this study are often biased towards intensive, productive, and managed agricultural systems, while other extensive land use classes are often distributed among several different land categories, subject to country context and reporting capacities. Due to our closed-budget subtractive approach based on identifying productive lands, these mixed-use landscapes are reflected in the category of Other Vegetated Land. This land category exists in a range of tree-bearing states across a country, where small-scale agriculture, grazing and forestry activities are expected to coincide. Reliable and typical carbon stock densities for such a land category is sparse, and remains a critical research gap to this day (Erb et al., 2007, 2017, 2018). We also use a conservative estimate of the extent of smallholder shifting cultivation as a land management practice in the mid-20th century. The classification of this practice in FAO estimates remains to this day, extremely variable, with extensive differences between countries (Houghton et al., 2012). In our study, we assume that shifting cultivation occurs in forests and other vegetated lands. We allocate carbon densities derived from recent assessments to these land categories. Knowledge on the extent and impacts of this practice on carbon stocking capacities remains under-explored. Our attempt in this study is to provide a conservative estimate of this land management practice.

SI Tables 1-9

SI Table 1: World regions considered for this study and constituent countries for each region.

Subcontinent	Notation	Constituent countries
Central America & the Caribbean	**CAmC**	Bahamas, Costa Rica, Cuba, Dominican Republic, Guatemala, Haiti, Jamaica, Mexico, Honduras, British Honduras, El Salvador, Nicaragua, Panama
Eastern Africa	**EAf**	Anglo-Egyptian Sudan, Eritrea, Ethiopia, French Somaliland, Kenya, Nyasaland, Ruanda-Urundi, Uganda, Somalia, Tanganyika
Eastern Asia	**EAs**	Hong Kong, Korea (North), Korea (South), Mongol. Peopl. Rep., Taiwan, Japan, China
Eastern Europe	**EEu**	Albania, Bulgaria, Czechoslovakia, Hungary, Poland, Rumania, Yugoslavia
Northern Africa & Western Asia	**NAWA**	Algeria, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Muscat & Oman, Qatar, Saudi Arabia, Spanish Sahara, Syria, Trucial Oman, Tunisia, Turkey, French Morocco, Yemen
Northern America	**NAm**	Canada, United States
Oceania	**Oc**	Australia, Br. Solomon Islands, Fiji, New Caledonia, New Guinea (Austr.), New Hebrides, New Zealand
Southeastern Asia	**SEAs**	Philippines, Portuguese Timor, Cambodia, Malaya, Brunei, Burma, Thailand, Viet Nam, Indonesia, Laos
Southern Africa	**SAf**	Basutoland, Bechuanaland, Mozambique, Northern Rhodesia, South West Africa,

		Southern Rhodesia, Swaziland, Union of South Africa, Angola, Madagascar
Southern America	**SAm**	Argentina, Chile, Falkland Islands, Uruguay, Bolivia, Peru, Surinam, Venezuela, Brazil, British Guiana, Ecuador, Paraguay, French Guiana, Colombia
Southern Asia	**SAs**	Afghanistan, Nepal, Bhutan, Ceylon, Pakistan, India
Soviet Union	**SU**	U.S.S.R.
Western Africa	**WAf**	Gambia, Sierra Leone, Belgian Congo, Spanish Guinea, French Cameroons, French Togoland, Portuguese Guinea, French Equat. Africa, French West Africa, Gold Coast, Liberia, Nigeria
Western Europe	**WEu**	Andorra, Austria, Belgium, Denmark, Finland, France, Greece, Iceland, Ireland, Liechtenstein, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Germany, Italy, United Kingdom, Svalbard

SI Table 2: Country name and administrative boundary changes for some major countries considered in this assessment between 1950 and 2000

Country in 1950	***Country in 2000***
Anglo-Egyptian Sudan	Sudan
Basutoland	Lesotho
Bechuanaland	Botswana
Ceylon	Sri Lanka
Czechoslovakia	Czech Republic, Slovakia
French Cameroons	Cameroon
French Equatorial Africa	Central African Republic, Chad, Congo, Gabon
French Somaliland	Djibouti

French Togoland	Togo
French West Africa	Benin, Guinea, Cote d'Ivoire, Mali, Mauritania, Niger, Senegal, Burkina Faso
Mongol. Peopl. Rep.	Mongolia
New Hebrides	Vanuatu
Nyasaland	Malawi
Pakistan	Pakistan, Bangladesh
Portuguese Timor	Timor-Leste
Ruanda-Urundi	Rwanda, Burundi
Northern Rhodesia	Zambia
Southern Rhodesia	Zimbabwe
Tanganyika	Tanzania
U.S.S.R.	Azerbaijan, Armenia, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
Yugoslavia	Bosnia and Herzegovina, Croatia, Montenegro, Slovenia, Macedonia, Serbia and Montenegro

SI Table 3: Forest carbon stock densities sourced from country-specific studies (n = 17)

Country	**Forest carbon stock densities from country-specific studies (tC/ha)**	**Year of estimate**	**Source**	**Forest carbon stock densities from contemporaneous FAO assessments (tC/ha)**
Austria	33.0	1950	Gingrich 2007	39.2
China	49.5	1950	Fang 2001	41.3
United States	40.0	1950	Magerl 2019	35.3
France	49.0	1950	Le Nöe 2019	31.2

Japan	35.3	1950	Fang 2005	35.1
U.S.S.R.	44.0	1961	Shvidenko 2005	55.7
South Korea	4.8	1950	Choi 2002	3.7
India	66.3	1950	Richards and Flint 1994	24.2
Indonesia	131.0	1950	Richards and Flint 1994	172.3
Laos	85.7	1950	Richards and Flint 1994	121.2
Viet Nam	71.0	1950	Richards and Flint 1994	96.1
Ceylon	72.5	1950	Richards and Flint 1994	74.3
Malaysia	134.2	1950	Richards and Flint 1994	105.9
Philippines	120.9	1950	Richards and Flint 1994	110.2
Cambodia	108.3	1950	Richards and Flint 1994	50.3
Burma	45.0	1950	Richards and Flint 1994	13.6
Thailand	56.8	1950	Richards and Flint 1994	250.3

SI Table 4: Countries where an additional sub-category of 'Extra forest' was considered. Names of countries are as represented in the FAO World Forest Resources Assessment 1953.

Country	Extra forest (Mha)	Country	Extra forest (Mha)
Angola	1.99	Madagascar	14.17
Bahamas	0.43	Malaysia	10.6
Belgian Congo	86.06	Mexico	33.05

Bolivia	8.95	Mozambique	6.93
Brazil	31.95	New Guinea (Austr.)	7.29
British Guiana	0.18	Nyasaland	0.14
Cambodia	5.31	Peru	7.57
Cuba	4.98	Ruanda-Urundi	0.01
Ecuador	3.93	Sierra Leone	3.52
Honduras	3.19	Spanish Guinea	0.72
Jamaica	0.27	Surinam	2.14
Kenya	0.56	Uganda	0.15
Laos	6.29	Venezuela	48.71

SI Table 5: Countries where growing stock-derived forest carbon stock densities are greater than average potential forest carbon densities (n = 15). Potential forest carbon densities are derived from the FAO 2000 run described in Erb et al. 2018. Forest carbon densities are derived from growing stock information in the Global Forest Resource Assessments 1953, 1958 and 1963. For these 15 countries, we use forest carbon densities estimated in column (E) to calculate carbon stocks in 'Inaccessible Forest' and 'Extra forest'.

Country	**Potential forest carbon density (tC/ha)**	**Forest carbon density (tC/ha)**	**Forests for which growing stocks are provided in the Assessment (Mha) (A)**	**(A) as a proportion of total forest in 1950 (D)**	**Carbon stock density of forests for which growing stocks not given (tC/ha) (E)**
Belgian Congo	158.6	523.8	5.3	0.02	150.1
Brazil	145.4	258.7	331.82	0.64	72.4

Guyana	159.6	189.3	0.26	0.01	159.3
Chile	85.7	119.9	6.59	0.4	80.3
Cameroon	141.3	167.9	3.0	0.13	139.4
French Guiana	207.7	261.1	0.05	0.005	207.4
French West Africa	106.2	164.3	10.5	0.09	101.5
Ghana	133.0	167.9	2.91	0.19	128.1
Iran	65.3	153.6	1	0.05	63.5
Madagascar	123.0	165.3	2.1	0.10	121.4
Ruanda-Urundi	95.0	101.2	0.04	0.22	95.0
Sierra Leone	153.3	180.5	0.27	0.07	152.2
Syria	43.3	44.6	0.24	0.54	43.1
Uruguay	90.8	106.0	0.48	1	90.3
Panama	165.6	364.8	1.18	0.22	126.5

SI Table 6: The option space for all considered cases per land category used for uncertainty analysis and sensitivity analysis. In total, 1728 cases were considered per country and summarized at the subcontinental level. Cases in bold were considered for the best-guess case.

Land Category	**Case**	**Source**
Accessible forest	**Growing stock-derived from FAO assessments (n = 83); independent studies (n = 17); subcontinental averages (n = 40)**	See Section 2.2
	Growing stock-derived from FAO assessments (n = 100); subcontinental averages (n = 40)	See Section 2.2
	± 25/40/50% of (Growing stock-derived from FAO assessments (n = 83); independent studies (n =	See Section 2.9

	17); subcontinental averages (n = 40))	
Inaccessible forest	**FAO-based run of potential forest carbon densities**	See Section 2.2, Erb et al. 2018
	Growing stock-derived from FAO assessments (n = 83); independent studies (n = 17); subcontinental averages (n = 40)	See Section 2.2
	Carbon densities of wild, unused forests in 2000	Erb et al. 2018
Extra forest	**FAO-based run of potential forest carbon stock densities**	See Section 2.2, Erb et al. 2018
	Growing stock-derived from FAO assessments (n = 83); independent studies (n = 17); subcontinental averages (n = 40)	See Section 2.2
	Carbon densities of wild, unused forests in 2000	Erb et al. 2018
Shifting cultivation fallows	Not considered	See Section 2.8
	Shifting cultivation long and short fallow carbon densities	See Section 2.8, Silva et al. 2011
Other vegetated land	**50% of (Growing stock-derived from FAO assessments (n = 83); independent studies (n = 17); subcontinental averages (n = 40))**	See Section 2.7
	75% of (Growing stock-derived from FAO assessments (n = 83); independent studies (n = 17); subcontinental averages (n = 40))	See Section 2.2 and 2.9, Erb et al. 2018, FAO 2010
	50% of (FAO-based run of potential forest carbon densities)	See Section 2.2, Erb et al. 2018
	Carbon density of natural otherland, maybe grazed, tree cover > 10% in 2000	Erb et al. 2018
	Carbon density of natural otherland, maybe grazed, tree cover 5-10% in 2000	Erb et al. 2018
	50% of carbon densities of wild, unused forests in 2000	Erb et al. 2018
Rangeland	**2 x NPP**	See Section 2.4
	Carbon densities of grasslands	Xia et al. 2014

	Carbon density of natural otherland, maybe grazed, tree cover < 10% in 2000	Erb et al. 2018
	Carbon density of wild otherland, maybe grazed, tree cover < 5% in 2000	Erb et al. 2018
Cropland + pasture + infrastructure	**Cropland and pasture with NPP; infrastructure areas with the FAO-based run of 1/6th of potential carbon stocks**	See Section 2.3-2.5
Total cases (per subcontinent)		1728

SI Table 7: Global biomass stocks over the late 20th century and early 21st century from available studies. Cases in bold represent estimates from this study.

Biomass carbon stocks (PgC)	Year of estimate	Source
900	Potential	Olson et al. 1983
950	Potential	Erb et al. 2018
610-620	Pre-industrial	Houghton et al. 1999
450.7	**1950**	**Best-guess, this study**
518.3	**1950**	**Median of considered scenarios, this study**
443.9-584.6	**1950**	**Inner quartiles of considered scenarios, this study**
449	1950	Elhacham et al. 2020
560	1970-1980	Olson and Watts 1982
450 (inner quartiles 380-536)	2000	Erb et al. 2018
466-654	2000	Prentice et al. 2001
393	2005	Pan et al. 2013
417	2005	Holtsmark 2012

SI Table 8: Change in biomass carbon stocks globally and at the subcontinent level over 1950-2019.

	1950	2000	2010	2019

	Best-guess estimate (PgC) (% of total)	**Median of all modulations (PgC) (inner quantiles)**	**Erb et al. 2018, FAO-based (% of total)**	**Erb et al. 2018, Pan-based (% of total)**	**Xu et al. 2021 (% of total)**	**Xu et al. 2021 (% of total)**	**Spawn et al. (2020) (% of total)**	**Xu et al. 2021 (% of total)**
Global	450.77 (100%)	518.3 (443.9-584.6)	406.6 (100%)	472.6 (100%)	366.5 (100%)	368 (100%)	397.8 (100%)	371 (100%)
Central America & the Caribbean	13.69 (3.0%)	11.28 (9.71-13.14)	6.9 (1.6%)	8.6 (1.8%)	8.39 (2.2%)	8.52 (2.3%)	7.1 (1.8%)	8.51 (2.2%)
Eastern Africa	12.05 (2.6%)	11.35 (9.90-13.14)	13.35 (3.2%)	16.7 (3.5%)	9.07 (2.4%)	9.19 (2.4%)	16.5 (4.1%)	9.35 (2.5%)
Eastern Asia	18.17 (4.0%)	18.68 (15.70-22.89)	14.73 (3.6%)	15.7 (3.3%)	22.6 (6.1%)	23.0 (6.2%)	16.5 (4.1%)	24.76 (6.6%)
Eastern Europe	2.25 (0.5%)	2.29 (2.12-2.59)	3.57 (0.8%)	3.5 (0.7%)	3.12 (0.8%)	3.31 (0.9%)	4.3 (1.1%)	3.23 (0.8%)
Northern Africa & Western Asia	3.99 (0.9%)	5.45 (4.75-6.13)	7.33 (1.8%)	7.4 (1.5%)	3.04 (0.8%)	3.06 (0.8%)	3.5 (0.9%)	3.1 (0.8%)
Northern America	47.12 (10.4%)	46.76 (43.22-50.37)	47.88 (11.7%)	46.3 (9.8%)	48.5 (13.2%)	50.1 (13.6%)	50.7 (12.7%)	49.12 (13.2%)
Oceania	16.99 (3.7%)	16.78 (14.53-19.38)	20.19 (4.9%)	19.4 (4.1%)	11.92 (3.2%)	12.1 (3.2%)	19.3 (4.8%)	12.03 (3.2%)
Southeastern Asia	44.49 (9.8%)	41.34 (35.76-48.43)	29.79 (7.3%)	37.8 (8.0%)	29.26 (7.9%)	28.88 (7.8%)	34.8 (8.7%)	28.52 (7.6%)
Southern Africa	18.6 (4.1%)	19.14 (16.26-22.35)	20.73 (5.1%)	25.9 (5.5%)	9.88 (2.6%)	9.81 (2.6%)	19.3 (4.8%)	9.78 (2.6%)
Southern America	124.71 (27.6%)	168.83 (145.95-192.16)	126.85 (31.1%)	156.9 (33.2%)	96.76 (26.4%)	95.2 (25.8%)	111.9 (28.1%)	97.1 (26.1%)
Southern Asia	11.49 (2.5%)	9.44 (8.04-11.14)	7.12 (1.7%)	8.3 (1.7%)	7.19 (1.9%)	7.29 (1.9%)	6.0 (1.5%)	7.42 (2.0%)
Soviet Union	57.38 (12.7%)	63.24 (57.37-68.15)	47.16 (11.5%)	49.9 (10.5%)	56.62 (15.4%)	56.24 (15.2%)	50.2 (12.6%)	56.88 (15.3%)

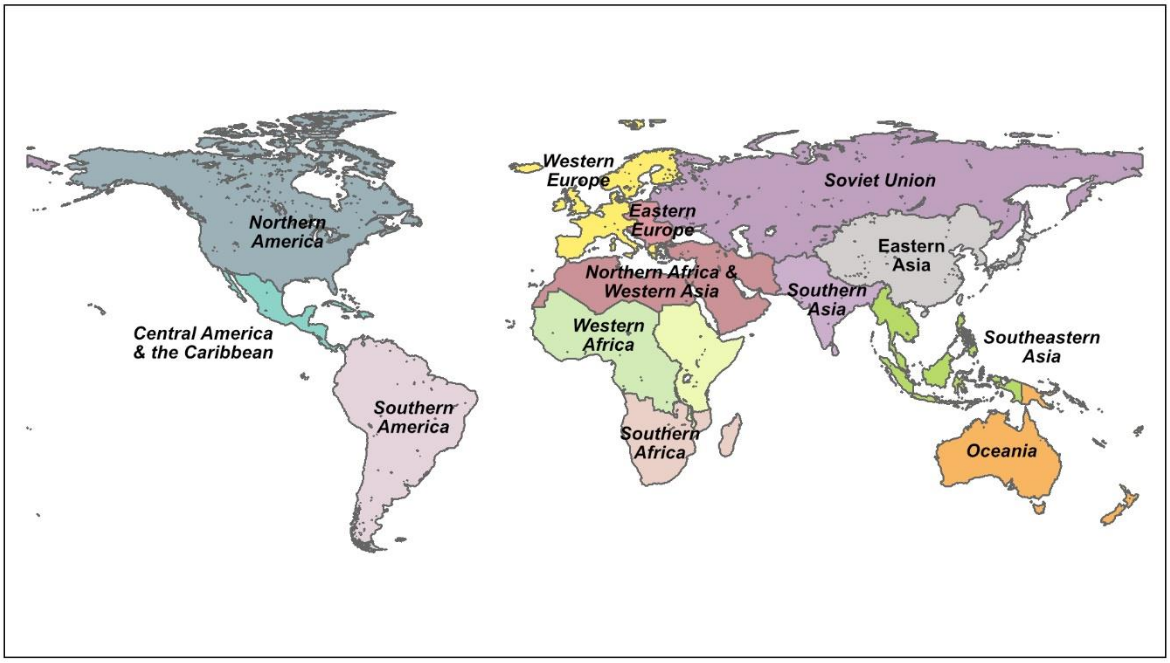
Western Africa	74.47 (16.5%)	97.93 (75.29-108.60)	51.94 (12.7%)	66.7 (14.1%)	49.99 (13.6%)	50.77 (13.8%)	45.5 (11.4%)	50.83 (13.7%)
Western Europe	5.28 (1.1%)	5.71 (5.25-6.23)	9.09 (2.2%)	9.2 (1.9%)	10.15 (2.7%)	10.22 (2.7%)	11.9 (3.0%)	10.21 (2.7%)

SI Table 9: Range of annual change rates (minimum, maximum) of biomass carbon stocks (PgC/year) across three timeperiods (1950-2000, 2000-2010 and 2010-2019). Change rates are calculated by comparing the best-guess estimate and the median estimate for the year 1950 with the corresponding estimates described in Erb et al. 2018, Spawn et al. 2020 and Xu et al. 2021 for the years 2000, 2010 and 2019. Negative sign indicates loss of biomass carbon stocks.

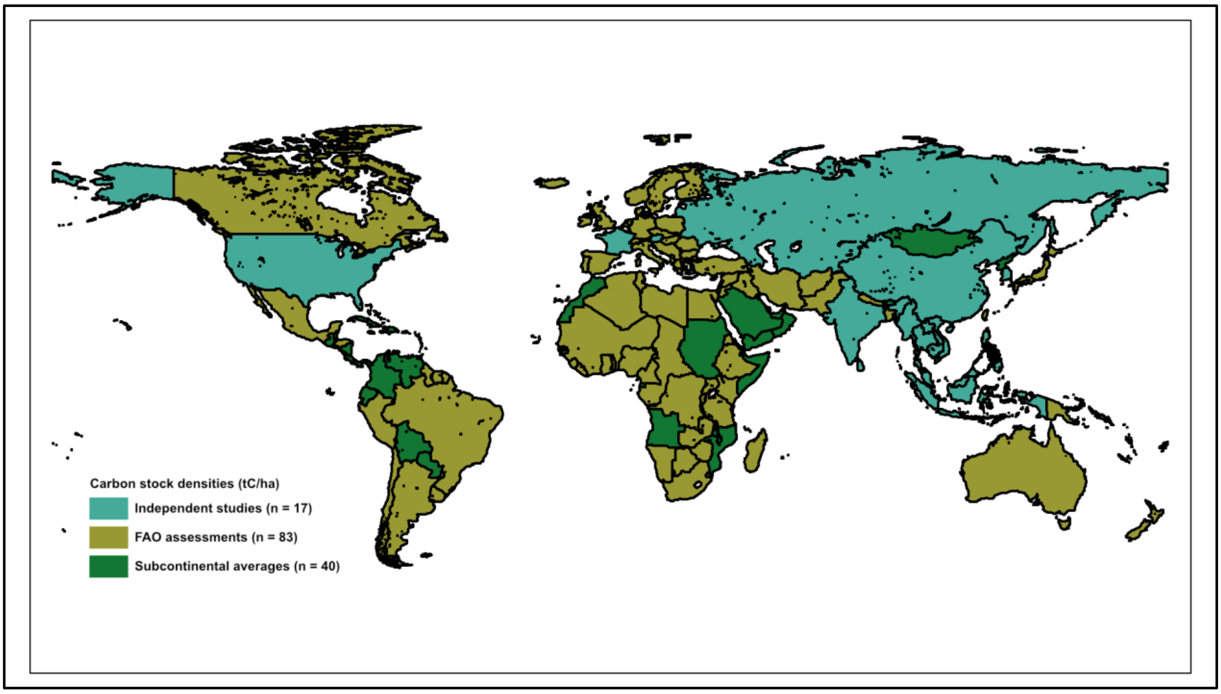
	1950-2000 (PgC/year)		**2000-2010 (PgC/year)**	**2010-2019 (PgC/year)**
	With best-guess estimate	**With both best-guess and median estimate**		
Global	-1.68, 0.43	-3.0, 0.43	-10.46, 3.13	-2.97, 0.33
Central America & the Caribbean	-0.13, -0.10	-0.13, -0.05	-0.14, 0.16	-0.001, 0.15
Eastern Africa	-0.04, 0.09	-0.04, 0.1	-0.75, 0.66	-0.80, 0.01
Eastern Asia	-0.06, 0.08	-0.08, 0.08	-0.61, 0.82	0.19, 0.91
Eastern Europe	0.01, 0.02	0.01, 0.02	-0.02, 0.11	-0.01, 0.11
Northern Africa & Western Asia	-0.01, 0.06	-0.04, 0.06	-0.43, 0.05	-0.05, 0.003
Northern America	-0.01, 0.02	-0.01, 0.03	0.16, 0.44	-0.18, -0.11
Oceania	-0.1, 0.06	-0.01, 0.06	-0.81, 0.73	-0.81, -0.007
Southeastern Asia	-0.30, -0.13	-0.3, -0.07	-0.89, 0.55	-0.04, -0.69
Southern Africa	-0.17, 0.14	-0.18, 0.14	-1.61, 0.94	-1.05, -0.001
Southern America	-0.56, 0.64	-1.44, 0.64	-6.17, 1.5	-1.64, 0.21
Southern Asia	-0.08, -0.06	-0.08, -0.02	-0.23, 0.01	0.01, 0.15

Soviet Union	-0.20, -0.01	-0.32, -0.01	-1.11, 0.91	0.07, 1.25
Western Africa	-0.48, -0.15	-0.95, -0.15	-2.11, 0.08	0.006, 0.58
Western Europe	0.07, 0.09	0.06, 0.09	0.01, 0.28	-0.001, -0.19

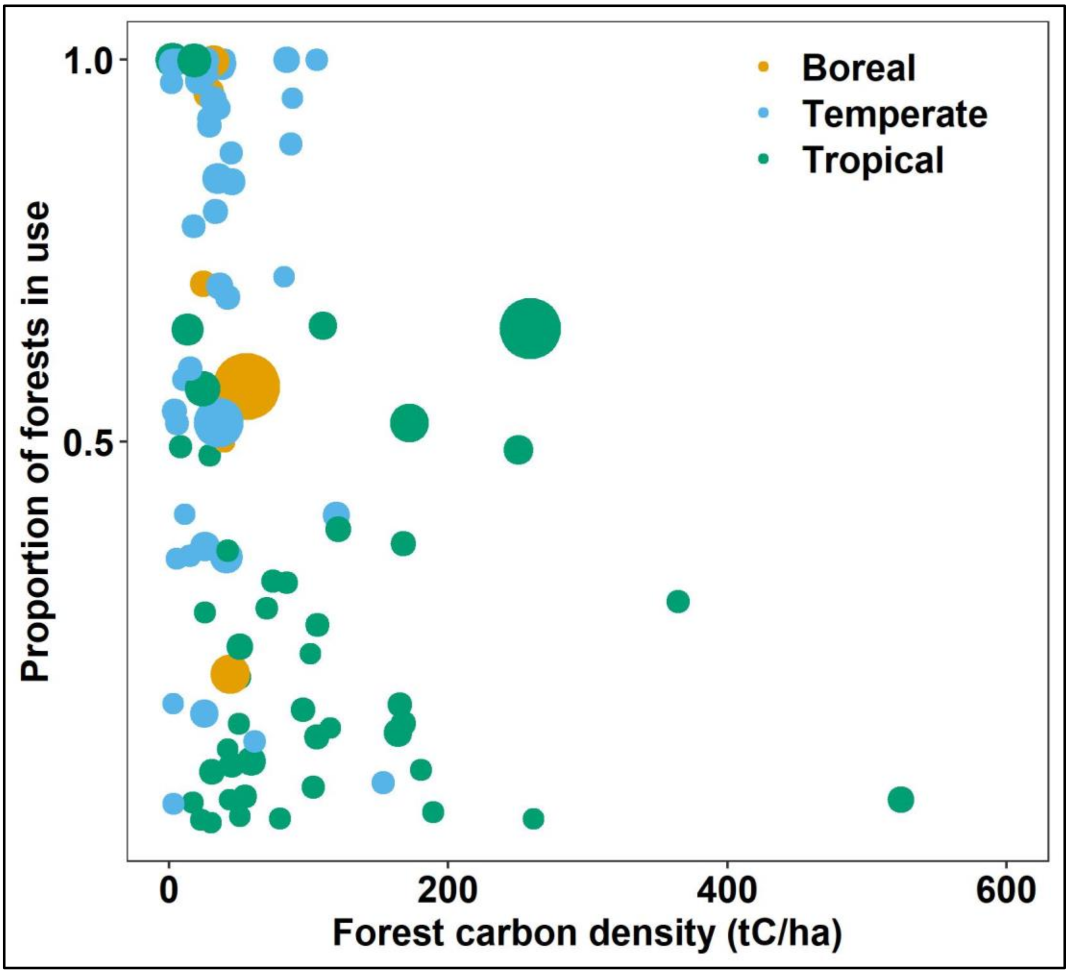
SI Figures 1-7



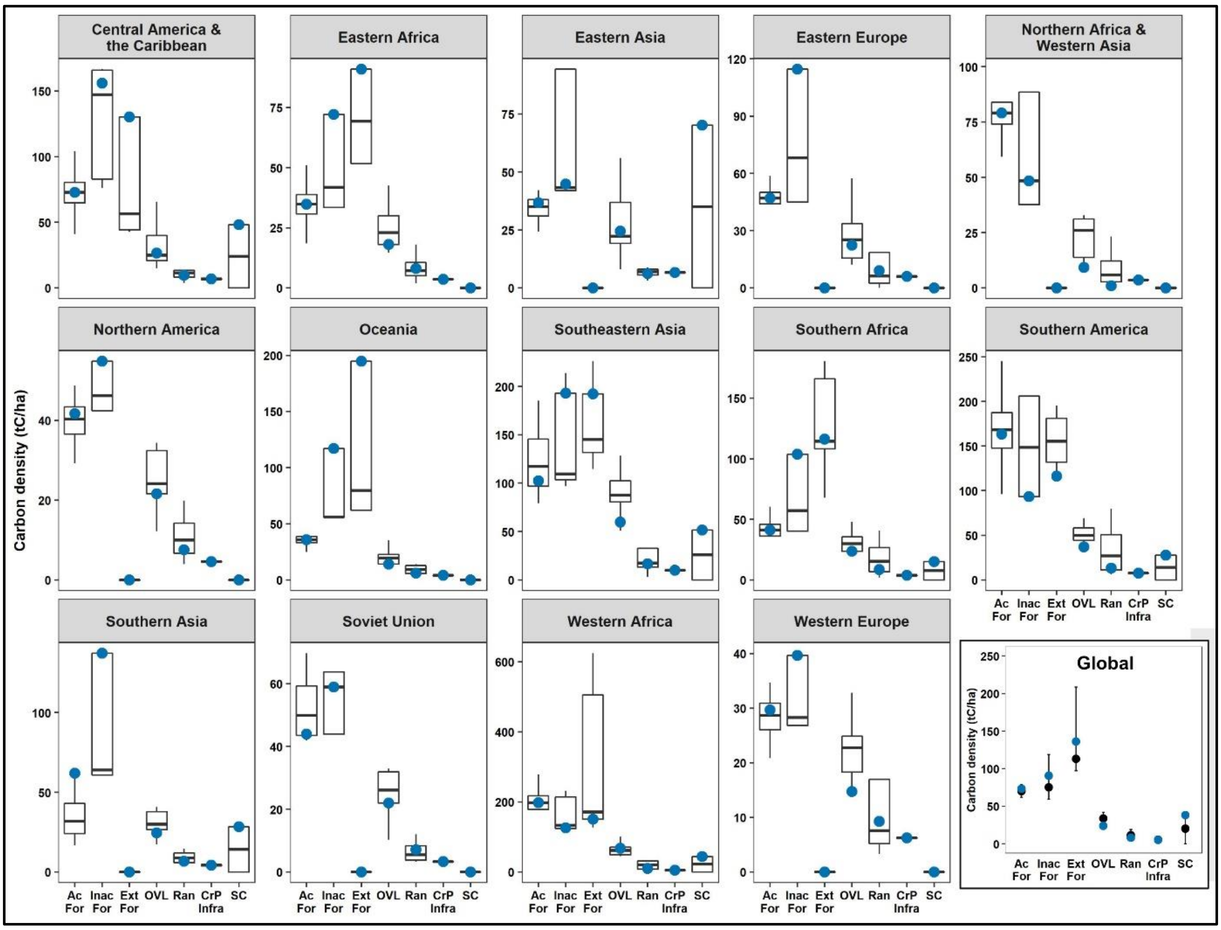
SI Figure 1: Subcontinental units used for the description of the results.



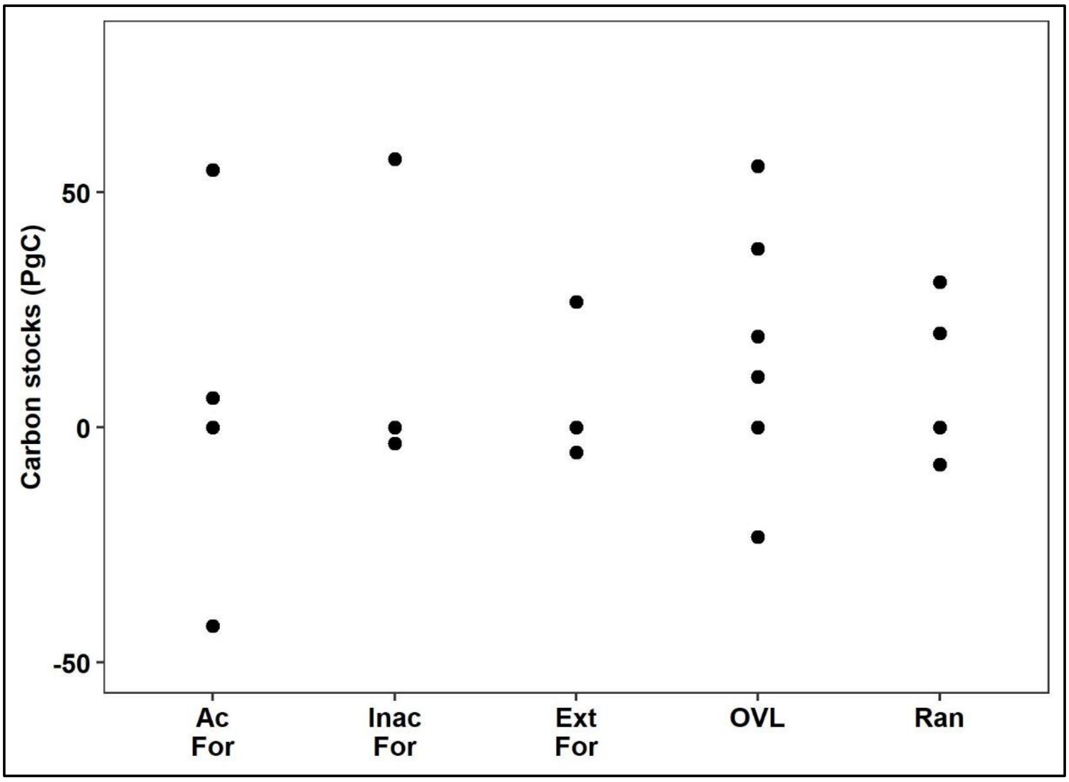
SI Figure 2: Forest carbon stocks densities used for all countries in the study.



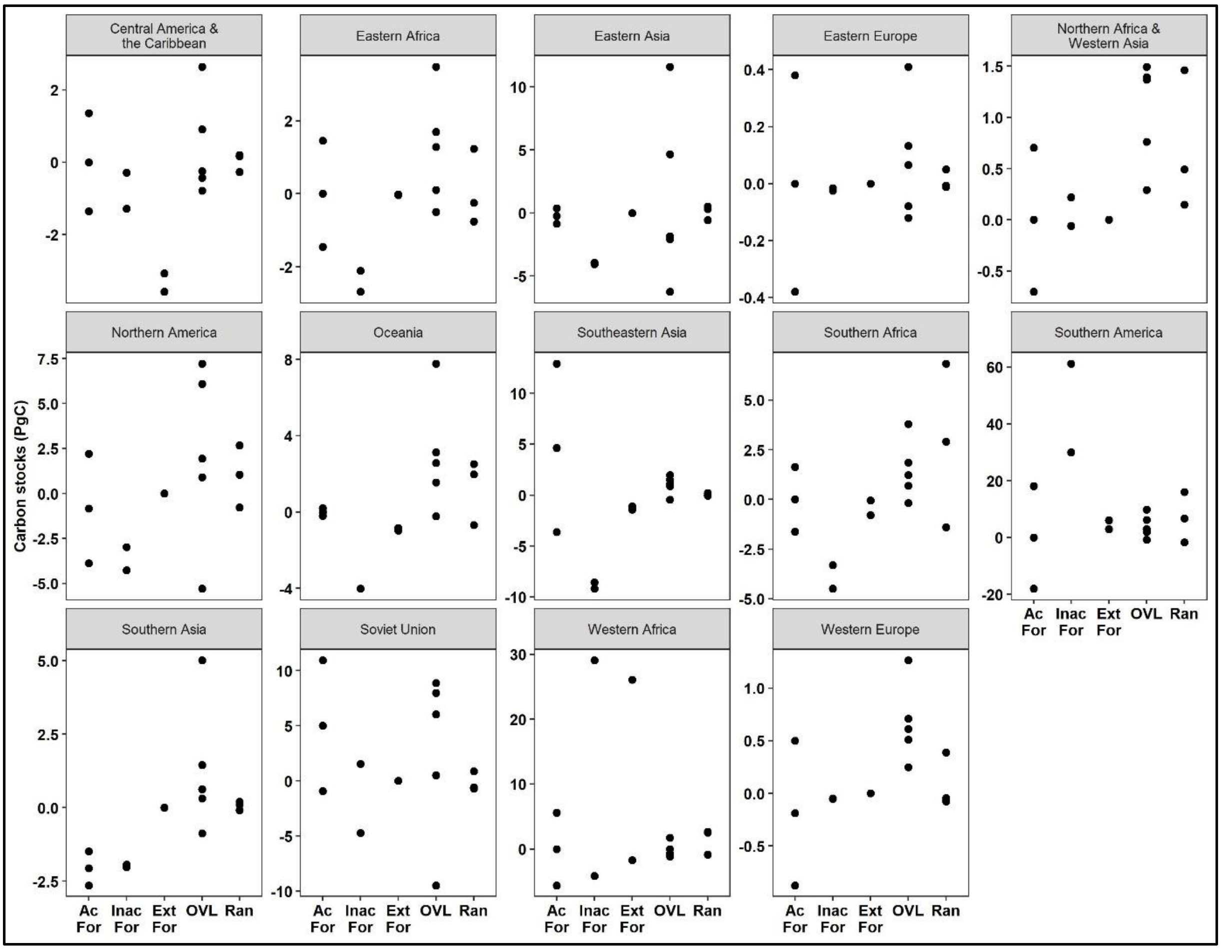
SI Figure 3: The proportion of total forests from where forest carbon densities using growing stock information have been derived (n = 100). The size of the dot is proportional to the total forests in use in that country. For information on the Forest In Use land category, see text.



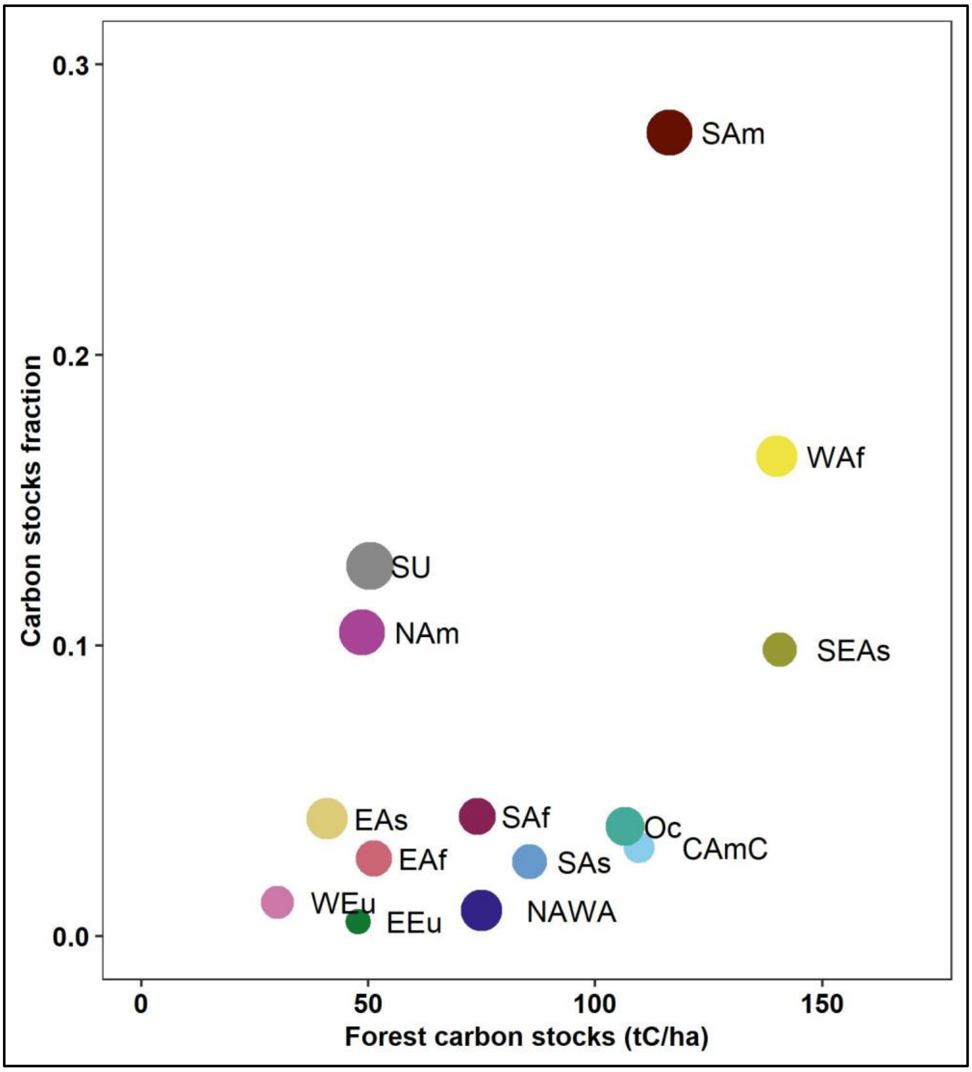
SI Figure 4: Distribution of carbon stocks among land categories across all subcontinents and globally (bottom right inset). The blue dots represent the best-guess estimate (see main text). Note the different scales on the y-axis for each facet. Here, AcFor = Accessible Forests, InacFor = Inaccessible Forests, ExtFor = Extra Forests, OVL = Other Vegetated Lands, Ran = Rangeland, CrPInfra = Crop, Pastures and Infrastructure. For information on land categories, see Materials and Methods.



SI Figure 5: The sensitivity of global biomass carbon stocks to estimates of land areas and carbon densities. Each point represents the difference of the best-guess estimate from the estimate developed from changing carbon stocks density of only the land category identified on the horizontal axis. Here, AcFor = Accessible Forest; InacFor = Inaccessible Forest; ExtFor = Extra Foreest; OVL = Other Vegetated Land; Ran = Rangeland. See SI Table 6 for the list of considered cases.



SI Figure 6: The sensitivity of biomass carbon stocks in each subcontinent to estimates of land areas and carbon densities. Each point represents the difference of the best-guess estimate from the estimate developed from changing carbon stocks density of only the land category identified on the horizontal axis. Here, AcFor = Accessible Forest; InacFor = Inaccessible Forest; ExtFor = Extra Foreest; OVL = Other Vegetated Land; Ran = Rangeland. See SI Table 6 for the list of considered cases.



SI Figure 7: The contribution of each subcontinent to total carbon stocks as a function of its average forest carbon density for the best-guess case. The size of the circle indicates the total land area of the subcontinent. Here, CAmC = Central America & the Caribbean; EAf = Eastern Africa; EAs = Eastern Asia, EEu = Eastern Europe; NAWA = Northern Africa & Western Asia, NAm = Northern America, Oc = Oceania; SEAs = Southeastern Asia; SAf = Southern Africa, SAm = Southern America; SAs = Southern Asia; SU = Soviet Union; WAf = Western Africa; WEu = Western Europe.

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