A Spatially Explicit Assessment of the Biocapacity of Brazilian Forests from 2001 to 2019

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Abstract

Through the demand for resources and ecosystem services, the accumulation of atmospheric carbon dioxide poses a striking example of how humanity exceeds the regenerative and absorptive capacity of the biosphere. The magnitude to which humans exceed this threshold is often expressed using the Ecological Footprint (EF) methodology. This approach tracks the amount of biologically productive areas on Earth for which human demands compete. Forested land is an integral component of the EF methodology since it is expected to meet multiple competing demands. This paper assesses the forest component of the National Footprint & Biocapacity Accounting (NFBA) framework – the most widely known application of the EF methodology. It investigates the forest component from a methodological and data perspective through an extensive literature review. Since the discussion of outdated input data to the forest component seems neglected in the literature, this study explores alternative datasets to estimate a key parameter of the carbon Footprint (cF), the Average Forest Carbon Sequestration (AFCS). A spatially explicit analysis involving net primary productivity (NPP) and land use datasets is conducted to generate forest metrics and timeseries data for the country of Brazil between 2001 and 2019. The results are subsequently compared to forest area and biocapacity data found in the NFBAs. The outcome of this analysis presents forest extent and productivity data in a more nuanced manner which could work towards improving the robustness of the Accounts if applied at the global scale.

Foreword

The following research is being submitted to the Faculty of Environmental and Urban Change in partial contribution to complete my Master's degree in Environmental Studies. It assesses the forest component of the Ecological Footprint (EF) methodology from both a conceptual and technical standpoint. The research required a theoretical and empirical understanding of the methodology which was enabled through my involvement with the Ecological Footprint Initiative at York University. The Ecological Footprint is an accounting framework which tracks the annual demand for, and availability of resources and ecosystem services generated by limited, biologically productive surfaces on Earth. The EF approach and the spatially explicit data used to carry out this research are categorized as "environmental management methods" and fulfill the third component of my Plan of Study. Spatial analysis was used to investigate datasets which might improve the EF methodology so that it is better employed in facilitating resource & environmental management.

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AFCS – Average Forest Carbon Sequestration

cF – Carbon Footprint

EF – Ecological Footprint

EQF – Equivalence Factor

FAO – Food and Agriculture Organization

FAO-LCCS2 – FAO Land Cover Classification System (Property 2)

GFN – Global Footprint Network

gha – Global Hectares

IYF – Intertemporal Yield Factor

IPCC – Intergovernmental Panel on Climate Change

NFBA – National Footprint and Biocapacity Accounting

NFBAs – National Footprint & Biocapacity Accounts

NEP – Net Ecosystem Productivity

NFP – Net Forest Productivity

NPP – Net Primary Productivity

REDD – Reducing Emissions from Degradation and Forest Degradation

YF – Yield Factor

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Section 1: Introduction

The pervasiveness of human pressure on the biosphere has become quite clear. Human demand for resources and ecosystem services is exceeding the planet's regenerative and absorptive capacity. The degree to which humanity exceeds such thresholds – e.g., through the accumulation of carbon dioxide in the atmosphere – can be quantified using the Ecological Footprint (EF) concept (Wackernagel & Rees, 1996). Ultimately an accounting framework, the EF addresses one key question: *How much of Earth's regenerative capacity do human activities demand compared to what is available?* EF accounting answers this question by recognizing that human demand competes for a limited amount of biologically productive space; consequently, the methodology adds up areas of the planet for which these demands compete. In a given year, human demand (Ecological Footprints) is compared to the amount of resources and ecosystem services generated by bioproductive surfaces on Earth – the biocapacity. This comparison is made between five distinct land use types which provide (or regenerate) resources and ecosystem services: crop land, grazing land, forest land, fishing grounds, and built-up land. Using yield factors (YF) and equivalence factors (EQF) to facilitate the comparison, both EF and biocapacity are expressed in global hectares (gha) – a standardized unit of world-average bioproductive area.

Ecological Footprint accounting is commonly used in the National Footprint & Biocapacity Accounts (NFBAs). The NFBAs provide annual accounts of humanity's demand for the planet's regenerative capacity and is produced for 234 countries and the world (Lin et al., 2021). Throughout the NFBA framework, forest land plays a critical role in assessing multiple Footprint components. This paper aims to shed light on the forest land component of the NFBAs from a methodological and data standpoint. It describes both explicit and implicit aspects of this component and the input data used to calculate forest Footprint and biocapacity. It also examines the existing literature on the forest component which seeks to determine the effectiveness of the EF in quantifying the demand on, and availability of forest biocapacity. The review leads to numerous conclusions about the current state of this component and suggests that a discussion on source data is neglected. Thus, this study explores alternative datasets needed to estimate a key factor of the carbon Footprint (cF), the Average Forest Carbon Sequestration (AFCS). Using the country of Brazil as a case study, global datasets of net primary productivity (NPP) and land use are examined to generate forest metrics and timeseries data that are compared to forest area and biocapacity from the NFBAs.

1.1 Forest Land in the National Footprint & Biocapacity Accounts

In the NFBA framework, forest land biocapacity represents the amount of biologically productive forest area that can provide resources and ecosystem services in a year. At the country-level, it is calculated as follows:

$$Biocapacity \;= A_N * YF * EQF \tag{1}$$

Where:

A_N is the amount of biologically productive forest area in country N in hectares

YF is the country-specific yield factor, represented as the ratio of the national forest yield to the world-average forest yield (Y_N/Y_W)

Y_N is the national yield or the average amount of wood products harvested per hectare over a year

Y_W is the world average yield or the average amount of wood products harvested harvest per average world hectare over a year

EQF is the equivalence factor, represented as the ratio of average productivity of forest land to all bioproductive areas

Conversely, the forest [products] Footprint indicates the area of world average forest land needed to meet the demand for wood products. When calculating the Footprint of forest products, timber harvests are compared to the net annual growth rate of forests and then multiplied by the EQF, as shown here:

$$EF = \frac{P}{Y_W} * EQF \tag{2}$$

Where:

P is the production (or harvest) of wood products within a jurisdiction in tonnes

Eq. (1) and (2) demonstrate how forest biocapacity and the Footprint of forest products are defined in the NFBAs. Collectively, they represent the forest component, and their calculations are based on multiple global datasets. Data on the amount of forest land within a nation are drawn from two sources: CORINE Land Cover data (European Environment Agency (EEA), 2021) and FAO ResourceSTAT Statistical Database (FAO, 2021b). Global and country specific forest yields (i.e., net annual increments) are estimated using a combination of sources, including the FAO Temperate and Boreal Forest Resource Assessment (UNECE and FAO, 2000), Mancini et al. (2016), and Global Footprint Network calculations based on an Intergovernmental Panel on Climate Change (IPCC) accounting methodology (Intergovernmental Panel on Climate Change (IPCC), 2006). The EQF of forest land is derived using suitability indexes from the Global Agro-Ecological Zones (GAEZ) model (FAO and International Institute for Applied Systems Analysis, 2000) in combination with land cover data from FAO ResourceSTAT. Lastly, the forest Footprint is calculated according to two types of primary product: wood used for fuel; and timber and pulp used as raw material to produce derived wood products. Country-level data on the production, import and export of these products are sourced from FAO ForeSTAT (FAO, 2021a).

The forest component – particularly the biocapacity of forests – plays an extended role in evaluating the carbon component of the EF or the carbon Footprint (cF). The cF represents the area of bioproductive forest land required to sequester anthropogenic carbon emissions at a national or global scale. This definition builds on the assumption that forests are likely conducting most of the sequestration for terrestrial ecosystems on Earth (Goldfinger et al., 2014). The cF is calculated as follows (see Mancini et al., 2016):

$$cF = \frac{P_C * (S_{OCEAN})}{Y_W} * EQF \qquad with\; Y_S = \frac{AFCS}{0.27} \tag{3}$$

Where:

P_C is the annual anthropogenic emissions of carbon dioxide of a nation, or the world in Mt CO_2

S_{OCEAN} is the fraction of CO_2 emissions sequestered by oceans in a given year

Y_S is the annual rate of CO_2 sequestration per hectare of world average forest land

AFCS is the average forest carbon sequestration rate, expressed in tC ha^{-1} yr^{-1}

0.27 tC $(t\ CO_2)^{-1}$ illustrates the portion of C within the CO_2 molecule (used to convert tons of carbon into
tons of carbon dioxide)

AFCS demonstrates the long-term capacity of a hectare of world average forest land to uptake atmospheric carbon dioxide through photosynthesis. It is expressed in tons of carbon per world-average hectare of forest per year (tC *w*ha^{-1} yr^{-1}) and can be calculated as:

$$AFCS = \frac{NFP}{A_F} \tag{4}$$

Where:

NFP (Net Forest Production) is the total biomass productivity of a forest in a year (tC yr^{-1}) and depending on the system boundaries under examination, NFP can be defined as Gross Primary

Productivity (GPP), Net Primary Productivity (NPP), Net Ecosystem Productivity (NEP) or Net Biome Productivity (NBP).

A_F represents the total forested area of a nation or the world in hectares.

Eq. (3) and (4) define the cF in EF methodology by accounting for the demands placed on the long-term capacity of forests to sequester carbon dioxide emissions. Thus, forest land is an integral part of the Ecological Footprint as it is the only category whose biocapacity fulfills multiple competing demands. Forest biocapacity – which is represented as globally average areas of forest in EF methodology – is expected to meet humanity's demand for wood products and simultaneously assimilate anthropogenic CO_2 emissions. Land use change may be limiting the availability of these areas; consequently, a better understanding of the demands on forest biocapacity seems increasingly necessary. How effective is the EF methodology in quantifying the demand on, and availability of forest biocapacity? This question is explored through a literature review which seeks to understand the current state of the forest component in the NFBAs. The review will also investigate the existing methodological and data limitations associated with this component and how those might be improved.

1.2 Literature Review of the Forest Component

A discussion of the forest component of the Ecological Footprint (EF) methodology occurs throughout a substantial body of literature. This work provides insight into the forest component by examining of the data and methodology behind its composition. Recent publications describe the methodology and data sources used to estimate the forest [products] Footprint and biocapacity at national and global scale. Many academic papers discuss methodological criticisms and include responses to these critiques. Others provide quantitative assessments of the forest component through empirical analyses and updates to methodological parameters.

Literature providing the most recent descriptions of the forest component methodology include Borucke et al., (2013) and Lin et al., (2021). These articles also present the source data used to estimate the forest Footprint and biocapacity within the NFBAs. Much of the other literature includes methodological criticisms of the forest component and subsequent responses to these critiques. They allude to several underlying assumptions within EF methodology which seem inherently misleading. Several other studies examine the methodological role of forests in assimilating humanity's CO_2 emissions through criticisms of the lack of forest area accounting, forest productivity, carbon sequestration rates, ecosystem services and ecological characteristics & value. The following paragraphs discuss such critiques by highlighting the shortcomings of forest component from a methodological and data perspective.

Published research on the EF criticizes the forest component for several underlying assumptions which seem inherent to the approach. Giampietro and Saltelli (2014a) and Galli et al. (2016) suggest the methodology favours the replacement of natural ecosystems (e.g., forests) with human-managed systems (e.g., cropland). According to Giampietro and Saltelli's interpretation, the biocapacity of a local system is larger when there is greater human intervention. A larger biocapacity is considered beneficial in ecological terms, but the change only suggests an increase in global biocapacity. Lenzen et al. (2007) illustrate two examples where this type of increase would occur. First, Sweden's Footprint accounts would see an increase in national biocapacity if ancient woodlands were replaced by monoculture forests. This conversion improves the comparison between Footprint and biocapacity because monocultures have higher yields; however, the change is a recognizable threat to biodiversity in Swedish forests. Second, replacing tropical forests with monocultures misleadingly increases biocapacity since the latter is categorized as primary crop land and has a higher equivalence factor (EQF) than the former. The conversion from forests to monocultures is favourable because a larger EQF would increase biocapacity; however, the stability and long-term regenerative capacity of ecosystems are compromised (Lenzen et al., 2007). Identical claims and arguments about EQFs within the EF protocol are made in Tabi and Csutora (2012). This study also claims the use of yield factors (YF) in EF methodology favours fast-growing invasive species which are capable of outcompeting slow growing native species. YFs compare a country's national yield to the world-average yield of roundwood, which essentially implies that tree species with a short growing period are preferred in the logging industry. Moreover, Tabi and Csutora suggest that the proliferation of non-native species has a favourable effect on biocapacity as the logging of these species has shown to increase biocapacity more than native species. Blomqvist et al. (2013a) and Blomqvist et al. (2013b) make similar assumptions about higher biocapacity and suggest planting fast-growing Eucalyptus trees to reduce ecological overshoot. This type of afforestation would be reported as forest area with high biocapacity in the Accounts; however, a substantial amount of land – i.e., roughly half the area of the United States – would be necessary to eliminate global overshoot. Thus, criticisms of the EF protocol and results allude to assumptions that are perceived to be misleading and counterproductive to policymaking.

Giampietro and Saltelli discuss other inherent assumptions, such as those involving a "virtual" forest area which EF accounting is based upon. They criticize the protocol quantifying forest biocapacity for the carbon Footprint (cF) which is calculated using the AFCS rate. Using this parameter is highly problematic because it assumes that: i) a virtual global forest will continue to grow forever on a hectare of land committed to long-term carbon uptake and ii) a change in the stock of forest biomass is the only available solution for locking away CO_2 emissions. The cF calculation assumes forests will continue to fix the same amount of carbon per hectare per year forever (i.e., the given area of forest should perpetually absorb the flow of CO_2). This assumption does not reflect real world dynamics (Blomqvist et al., 2013a) since an area of forest capable of stocking carbon cannot be used again. The flow is coming from a transitional process and can be absorbed by a growing forest providing a given sink capacity 'per hectare per year' only once (Giampietro & Saltelli, 2014b). Consequently, the sequestration rate used in the cF calculation is valid only for a specific year and will decrease over time, eventually reaching zero. AFCS represents the average sequestration capacity of actual growing forests and its use in the cF refers to a special situation the planet momentarily experiences. This situation is destined to change in the future which according to Giampietro and Saltelli, makes EF an impractical accounting methodology.

Despite these remarks, Giampietro and Saltelli allude to circumstances which allow forests to continue to assimilate CO_2 emissions in EF accounting. As the flow of emissions is still expected from society in the coming years, the annual stock of forest used to absorb the flow should increase in time or the assumption of perpetual carbon fixation must be accepted. If the methodology is based on the quantity of hectares which appear to be in a transitional period on Earth, it should refer to empirical measurements of forest area (actual hectares) in each year. They argue that it is the area of forests in this special situation which sequester significant quantities of carbon. When using this assessment to offset a steady-state flow of carbon, the estimate should not be given in global hectares but in the quantity of actual growing forests that are continuously generated in time (Galli et al., 2016; Giampietro and Saltelli, 2014b). Moreover, Giampietro and Saltelli believe the sequestration rate per area used in the cF calculation should no longer be measured in global hectares because it represents the measured sequestration capacity of actual growing forests.

The claims made thus far stem from researchers' interpretation of the EF methodology and indicate the weaknesses of the forest component. Criticisms of underlying assumptions do not end with scholars like Giampietro and Saltelli – van den Bergh and Grazi point to another assumption of the forest component when interpreting the cF. They claim the cF assumes an arbitrary "sustainable energy scenario" where CO_2 emissions are translated into a hypothetical area of forest land through carbon sequestration (van den Bergh and Grazi 2010, 2014a, 2014b, 2015). Their assumption challenges the methodology of the forest component and is supported by criticisms of carbon sequestration in previously published literature.

The application of carbon sequestration and its role in assimilating anthropogenic CO_2 emissions within EF accounting is initially criticized in Herendeen (2000) and Haberl et al. (2001). Herendeen (2000) suggest that using carbon sequestration to offset emissions can simultaneously under and overestimate the carbon Footprint when it is dependent on the net carbon uptake of an immature, successional forest. Net carbon uptake can be overestimated because as forest succession is completed, uptake approaches zero. This scenario leads to an underestimation of the cF. However, net carbon uptake can be underestimated since higher levels of CO_2 might stimulate forest growth – leading to an overestimation of the cF. Haberl et al. (2001) is also skeptical of its application because of ecological factors such as forest age. They argue that carbon uptake land cannot be repeatedly used every year since ecosystem productivity is dependent on forest age. Only “young” forests sequester considerable amounts of carbon and do so at a rate well below NPP. Alternatively, mature forests only fix significant quantities of carbon for some decades, after which they approach a climax state, and their net carbon balance gets close to zero. Giampietro and Saltelli make similar comments about carbon sequestration, arguing that a hectare of forest cannot grow (and sequester CO_2) forever. These scholars also consider age a determining factor for the capacity of forests to sequester CO_2 emissions. They openly criticize the methodology for ignoring that a given hectare of forest can uptake emissions only during growth (Galli et al., 2016; Giampietro and Saltelli 2014a). Many articles ultimately suggest the need for additional hectares of [young] forest land to uptake emissions since carbon fixation decreases in maturing forests (Galli et al., 2016; Giampietro & Saltlelli 2014a, 2014b; Haberl et al., 2001).

Blomqvist et al. (2013a) also criticize carbon sequestration when discussing global uptake rates in existing forests. As demonstrated in the article, overshoot depends on a single determinant within the Accounts – the estimated global average sequestration rate of forests. These researchers caution the use of carbon sequestration rates because of their large natural variability over space and time and the uncertainties present in their measurement. Moreover, they believe the additional amount of forest with world-average sequestration capacity that would be required to completely offset carbon emissions is highly uncertain. If minor adjustments are made to the assumed carbon sequestration rate, the size of humanity’s EF would be considerably affected. For example, global ecological overshoot disappears if a carbon sequestration rate of 2.6 t C per ha per year or higher is applied (Blomqvist et al., 2013a). Overshoot could also be eliminated by dedicating large tracts of land to Eucalyptus plantations – a species capable of sequestering carbon at rates up to 12 t C per ha per year. Consequently, the authors criticize EF accounting for using a single value for this parameter without specifying its uncertainty. They recommend including estimates of uncertainty (e.g., confidence intervals) to avoid giving an impression of precision, which can be misleading.

The preceding concerns found in the literature reveal the limitations of EF methodology. Researchers like Haberl, Blomqvist and their respective co-authors not only criticize EF for its treatment of carbon sequestration but provide their recommendations for improving the methodology. Their claims illustrate the fragility of the forest component – particularly the drawbacks of assimilating CO_2 emissions using forested land. This is elaborated in several papers which criticize the EF methodology for disregarding alternative mechanisms for CO_2 assimilation. Van den Bergh and Verbuggen (1999) suggest that carbon uptake by forests is one of many options available to offset emissions; however, it is a land-intensive option. Many others consider carbon sequestration through forestation as an arbitrary choice for offsetting CO_2 emissions (Blomqvist et al., 2013; van den Bergh & Grazi 2014a, 2014b, 2015). The consensus being that there is simply not enough land available on Earth to support a quantity of forest area that can capture all of humanity's emissions, in fact only 31% of the planet's surface is appropriately characterized and given status as a forest (Giampietro & Saltelli, 2014b). Van den Bergh and Grazi (2015) criticize the EF approach for using only forests to offset CO_2 emissions regardless of the source of these emissions (e.g., deforestation, transport, etc.). They insist carbon sequestration can be accomplished without needing to designate large expanses of land to forestry. Blomqvist et al. (2013) agree and suggest that forests need not be the only mechanism to offset atmospheric carbon accumulation – solar panels or wind farms could be used. Lastly, van den Bergh and Grazi believe the arbitrary nature of EF methodology is not substantiated by referring to similar approaches (e.g., the UN Reducing Emissions from Deforestation and Forest Degradation or REDD) or by using readily available sequestration values from FAO. This part of the literature criticized the forest component for overlooking alternative methods of CO_2 assimilation and exclusively relying on the sequestration capacity of forests to offset humanity's emissions. Researchers also demonstrate the arbitrary and limited role of forests within EF methodology. Along with this commentary, there are others who evaluate the methodological role of forests by pointing to specific concerns.

Additional criticisms of the forest component are illustrated through discussions on forest productivity, area, ecosystem services, and the ecological value and characteristics of forests. Haberl et al. (2001) criticize the methodology for basing its calculations on global average forest productivity that is assumed to be constant. They argue that forest yields are known to vary spatially and temporally, and changes in forest area are likely to influence productivity. Therefore, deforestation is expected to cause a decrease in average forest productivity since highly productive forests are usually cleared for agriculture or built infrastructure. Blomqvist et al. (2013) claim the EF approach fails to demonstrate changes in forest area. Others claim EF denies the multifunctionality of forest ecosystems, which cannot service other functions (e.g., water catchment value) to avoid double-counting (McManus & Haughton, 2006; van den Bergh & Grazi 2014b). Tabi and Csutora (2012) consider EF an inappropriate sustainability indicator for forest management since the methodology mostly provides a static snapshot of resource consumption and ignores the dynamics of natural processes. The scholars claim EF overlooks the productivity differences and ecological value of various tree species and forest types. They criticize equivalence factors for not considering the ecological value of a forested area – i.e., EF calculations do not include protected forests in the assessment because they are not used for roundwood production. Yield factors are a methodological concern to Tabi and Csutora since they do not indicate yields from different forest types. Therefore, EF methodology should distinguish between forest types because from an ecological perspective, they do not have equivalent yields (Tabi & Cstuora, 2012). Tabi and Csutora believe EF calculations should reflect the carrying capacity – which is influenced by different forest management practices – and the ecological value of different forests to obtain more accurate estimates of biocapacity. Their method of estimation demonstrated an increase in forest biocapacity through the introduction of 'naturalness' and modified YFs. They recommend incorporating the naturalness of different forest types into the calculations to capture their ecological value. Additionally, sophisticated estimates of forest biocapacity would be possible through research on other factors which influence the ecological quality of forests (e.g., soil quality). These critiques and the criticisms presented by other authors illustrate how EF methodology might ineffectively measure the demand for and supply of forest biocapacity. Although a large portion of the literature focuses on the ineffectiveness and the limited scope of the forest component, there are publications which openly refute many of these critiques.

The literature includes detailed responses to critiques on the forest component methodology which are discussed and refuted by proponents of EF accounting. First, the claims made by Giampietro and Saltelli are openly refuted in Goldfinger et al. (2014). The authors demonstrate that the modification of natural ecosystems does not necessarily increase biocapacity (Galli et al., 2016). They argue that Giampietro and Saltelli incorrectly compare areas of tropical forests and crop monocultures using equivalence factors and ignore the role of yield factors in EF accounting. A hectare of tropical forest most likely has a higher bio-productivity than world average forest (i.e., a yield factor greater than one), where most of the nutrients are stored in the biomass rather than the soil. When a hectare of forest is converted to cropland, crop productivity will likely drop below the world average for cropland and have a yield factor of less than one. Therefore, a higher equivalence factor for cropland could be counteracted with a lower yield factor, which would result in an overall decrease in biocapacity per hectare when converting from forest to cropland. Goldfinger et al. (2014) also argue that the cF does not indicate the use of “virtual” forests which grow forever. The carbon component of EF is estimated using the average rate per hectare at which global forests can sequester carbon; thus, it demonstrates the actual amount of forest area required to sequester a given annual flow of carbon emissions. The cF can exceed the forest biocapacity available for sequestration, but this does not mean that it is based on virtual forest. This scenario indicates overshoot and suggests that there is an insufficient amount of forest available to sequester all of humanity’s carbon emissions.

Secondly, there are responses within the literature that directly refute critiques which suggest the arbitrariness of the cF calculation. Proponents of EF insist the approach is not based on any energy or pre-determined scenarios – a claim that has been postulated by van den Bergh and Grazi (Lin et al., 2015). The accounting methodology exclusively tracks competing demands on limited biologically productive areas. For example, there is a competing demand on biologically productive forests to assimilate anthropogenic CO_2; therefore, EF accounting tracks how much biocapacity is needed to sequester humanity's emissions. Advocates of EF also argue that the protocol for estimating the cF is not an arbitrary approach since it has been adopted by major international bodies and follows a strategy commonly used in carbon trading and similar protocols (i.e., REDD). The cF is based on the AFCS rate and calculated using empirical measurements of average forest productivity, not on hypothetical values. Until recently, empirical data on sequestration was obtained from FAO and implemented in the calculation in any given year. These values are in accordance with IPCC data sets and follow the UN FAO classification of forests. An updated AFCS value has been incorporated in the 2016 edition of the NFBAs to improve the accuracy of the cF calculation (see Lin et al., 2018; Mancini et al., 2016).

Lastly, Blomqvist and co-authors' skepticism of carbon sequestration rates is directly refuted in Rees and Wackernagel (2013). These authors acknowledge the significant variability in carbon sequestration rates; nevertheless, the rates have been implemented in the cF calculation since they are sourced from a thorough literature review of reports from FAO and IPCC (Rees & Wackernagel, 2013). They also point out the flaw in estimating the cF using a carbon sequestration rate of 2.6 t per ha per year. If this was the uptake rate, there would be no carbon emissions accumulating in the atmosphere. The cF is based on best estimates of *de facto* sequestration rates and not on a scenario where the world's forests consist of managed high-yield forest plantations.

Overall, the responses from proponents help counteract criticisms which challenge the validity of EF accounting. Although these have not been the only responses to methodological criticisms of the forest component. The literature also includes research which undertake empirical analysis and enhance the methodology of the forest component. Tabi and Csutora (2012) compared forest biocapacity results from the conventional EF assessment to those generated by the authors' method of estimation. The scholars' assessment incorporated modified yield and 'naturalness' factors to distinguish between three main forest types (natural, cultural and energy forests) in Hungary. Introducing the new factors illustrated a 15% increase in the biocapacity of Hungarian forests. Mancini et al. (2016) updated a key parameter for the cF calculation – the AFCS rate – by revising and improving its calculation with recent data from the IPCC and FAO. The study estimated a AFCS value range of 0.73 ± 0.37 t C ha^{-1} yr^{-1} which replaced the previously used AFCS value of 0.97 ± t C ha^{-1} yr^{-1}. Mancini et al. (2018) compared the Footprint assessment of forest land[1] to a monetary valuation of ecosystem services from forests for approximately 200 countries. The comparative analysis showed no statistical correlation between the economic value of forest ecosystems and the forest Footprint. Conversely, a strong correlation was found between forest biocapacity and economic value. Furthermore, Solarin (2020) investigated the statistical and time series properties of the forest products Footprint for 89 countries from 1961-2016. Results demonstrated overwhelming evidence for non-stationarity in the forest products Footprint – i.e., this component would not return to its original mean after experiencing a natural or economic shock. Ulucak and Lin (2017) and Yilanci et al. (2019) investigated the time series properties of the forest products footprint, alongside other components of the EF. Ulucak and Lin (2017) demonstrated that the

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[1] The forest Footprint investigated in Mancini et al. (2018) constituted both forest and carbon Footprint components of EF.

forest products footprint followed a nonstationary process in the U.S. and Yilanci et al. (2019) showed this component following a stationary process in OECD countries. Jóhannesson et al. (2020) examined the impact of the uncertainty of AFCS (Mancini et al., 2016) on cF results for Iceland. Sensitivity testing was conducted by incorporating the AFCS standard error, upper and lower limits into the cF calculation. The results from this empirical analysis suggested that input data used for the cF is lacking accuracy. The combined impact of data resulted in a 42% decrease and 147% increase in Iceland's cF. Lowering the AFCS rate by the standard error illustrated a 96% increase in cF.

1.3 Outcomes of the Literature Review

This body of literature provides an understanding of the forest component from a largely methodological standpoint. It assessed the state of this component by identifying limitations of the EF, ways to enhance the methodology and tangible improvements through empirical analysis. Ultimately, perceived limitations presented weaknesses in the EF to determine the availability of forest biocapacity and the demands placed upon it. Along with criticisms that question the legitimacy of the approach, published research included responses from EF practitioners regarding this commentary. The literature's primary focus was on the methodological limitations and the applicability of forested land in the EF approach. Non-practitioners view the methodology to be misleading and counterproductive because for the sake of greater biocapacity, an interpretation of its underlying assumptions could jeopardize the robustness of forest ecosystems. This conclusion seems reasonable to prevent EF from being misconstrued when used as a tool for policymaking. Conversely, the approach seems to neglect the complexity of forests in terms of their ecological value, productivity, and regenerative capacity. The resulting takeaway is justifiable from an environmental science viewpoint because it identifies the natural dynamics of forest ecosystems which are not necessarily considered in the EF accounting framework.

Moreover, this existing literature consisted of methodological critiques which transpired more than a decade ago. Many criticisms have been subsequently refuted by proponents of EF. Others have been addressed through empirical analysis which intended to improve the methodology in a specific way. For example, an EF research agenda was set out in Kitzes et al. (2009) which proposed the improvement of key constants with standard error estimates; consequently, the AFCS parameter was refined in Mancini et al. (2016). However, earlier criticisms (e.g., by Haberl and co-authors) have not been resolved. This is because the EF answers a particular research question using an accounting approach that simplifies complex phenomena into aggregate results and indicators. Earlier criticisms reveal the complexity of carbon sequestration, a phenomenon quantified to answer the question: *How much of the biosphere's regenerative capacity do human activities demand from forests?* The critiques in the literature do not work towards enhancing EF methodology; therefore, they were recognized but not necessarily resolved.

The literature also fails to investigate another aspect of the EF which is important to the forest component. It does not discuss the input data needed to calculate the forest Footprint and biocapacity within the NFBAs. Currently, data for the forest component are obtained from statistical databases and reports produced by FAO. The source data required to estimate the world-average forest yield and carbon uptake factor (i.e., AFCS) are retrieved from two editions of the Global Forest Resource Assessment (UN FAO, 2000, 2010). These reports provide important data needed to determine global and national-level estimates of forest and carbon Footprints; however, they were published more than a decade ago. As the EF aims to implement the most recent data within the national accounting framework, alternative datasets should be explored and considered. This paper investigates alternative data sources for the estimation of a key factor of the carbon Footprint (cF), the Average Forest Carbon Sequestration (AFCS). The country of Brazil is used as a case study to examine global datasets of net primary productivity (NPP) and land use which are analyzed to produce key metrics and timeseries data that align with the forest component. The analysis will generate data on the extent and productivity of Brazilian forests between 2001 and 2019 and is to be compared to estimates of forest area and biocapacity data from the NFBAs.

Section 2: Materials and Quantitative Methods

A spatially explicit analysis was conducted to generate key metrics aligned with Brazil's Forest component in the NBFAs from 2001 to 2019. Forest extent and productivity data was acquired using global land use data in combination with data on annual NPP. Results from this analysis are compared to Brazilian forest area and biocapacity data.

2.1 NFBA Data

Data on forest area and biocapacity were obtained from the 2021 Edition of the NFBAs. This edition was produced by York University in partnership with Global Footprint Network (GFN) and includes global and country-level assessments of footprint and biocapacity from 1961 to 2017.

2.2 Spatial Data

A shapefile of Brazil was obtained from the Stanford Digital Repository. This data layer delineates the administrative boundary of Brazil and is part of the Global Administrative Areas 2015 (v2.8) dataset (Hijmans & University of California, Berkeley, 2015). Sources of annual land use and NPP data originate from the Land Processes Distributed Active Archive Center (LP DAAC) within the NASA Earth Observing System Data and Information System (EOSDIS). Both datasets are derived from the Moderate Resolution Imaging Spectroradiometer (MODIS), a sensor onboard the Terra and Aqua satellites. The source of land use data for this analysis was the MODIS Land Cover Type Product (MCD12Q1) (Friedl & Sulla-Menashe, 2019). MCD12Q1 is a raster dataset providing 13 global maps of land cover at yearly intervals and 500-meter spatial resolution. Global land cover types are derived from six classifications schemes, which supply a suite of datasets within the product (Sulla-Menashe & Friedl, 2018) for 2001 to 2019. This spatially explicit analysis uses Land Cover Property 2 or LCCS2, a land use layer based on the Land Cover Classification System from the Food and Agriculture Organization (FAO). Refer to Table A-1 in Appendix A for the land use classification legend and class descriptions for LCCS2. The source of NPP data was the MOD17A3HGF Version 6 product (Running & Zhao, 2019). MOD17A3HGF is a raster dataset which provides measures of annual NPP at 500-meter spatial resolution from 2000 to 2020. This data product is derived from the sum of all 8-day Net Photosynthesis (PSN) products (MOD17A2H) for a given year (Running et al., 2015).

2.3 Data Processing Methodology

The workflow used to process spatial data for this analysis is summarized in Figure 1[2]. It was automated using multiple Python programming scripts which were executed in the ArcMap v10.6 Python window. Comma Separated Value (CSV) files are produced for each year and include the sum of pixels of a specific land use type (e.g., dense forests) and the average NPP value of those pixels. These files were brought into a MySQL database environment and collated into one file indicating the average NPP and the sum of pixels for all years within the study period.

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[2] The boundary layer or shapefile of Brazil was reprojected into the native projection of the NPP data layers before executing the process shown in Figure 1.

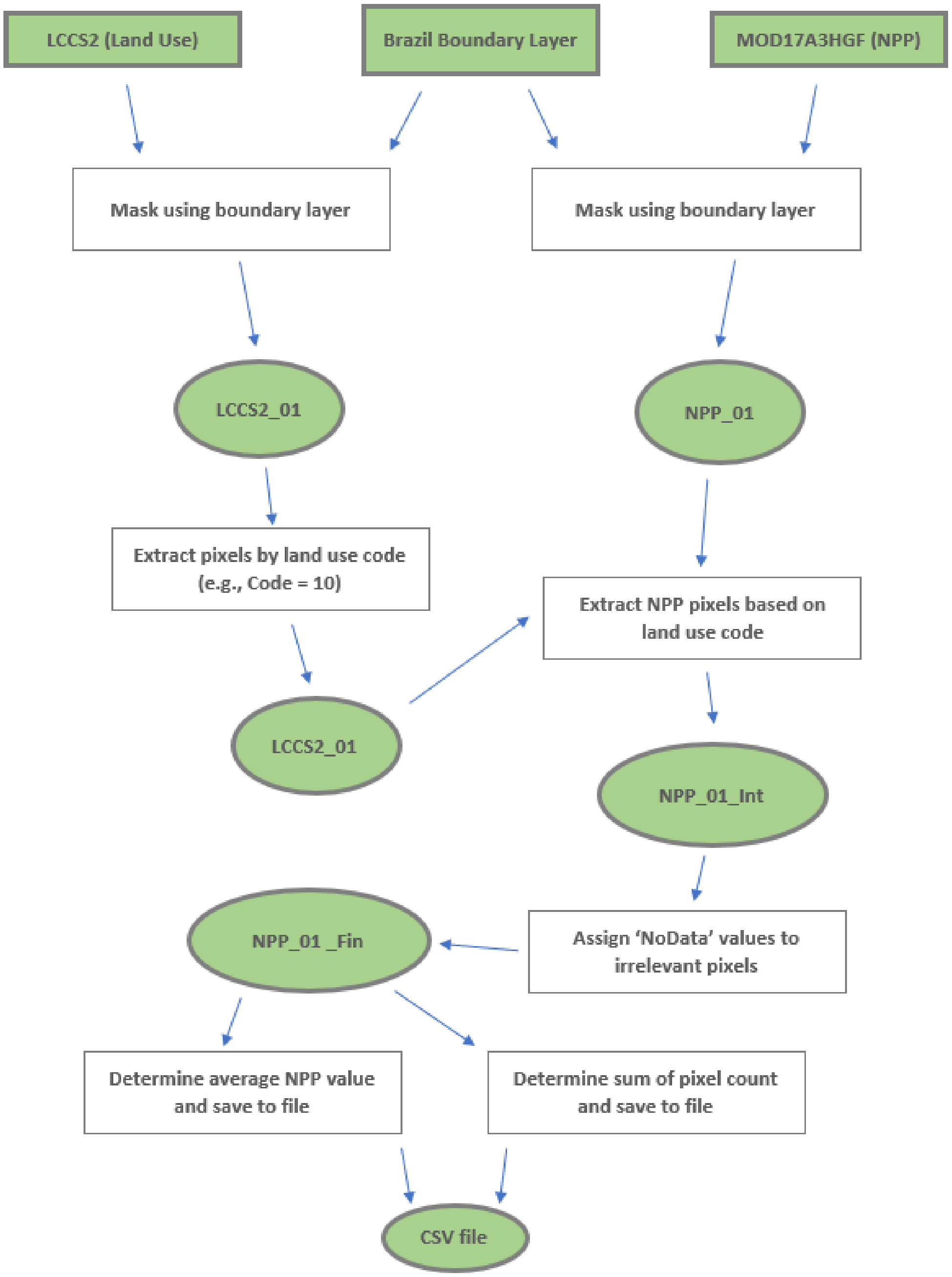
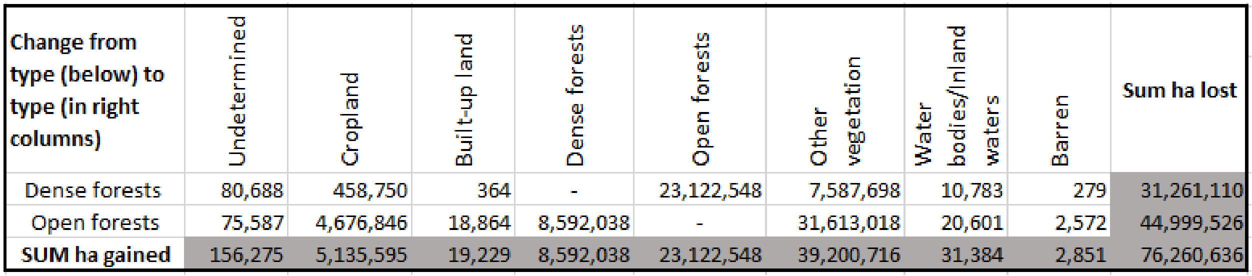


Figure 1. The workflow used to process Brazil's forest extent and productivity data from 2001 to 2019. The first year in the study period is used as an example. Green rectangles indicate input data, green ovals represent output data and white rectangles represent the processes performed. Each process was executed as a stand-alone Python script and applied to every year in the study period.

Changes in the forested landscape of Brazil (Table 1) was investigated by combining the 2001 and 2019 land use data layers. A combined data layer was generated to evaluate these changes by determining the number of pixels which changed from one land use type to another (e.g., from dense to open forests).

Table 1. Forest area changes in hectares (ha) across Brazil from 2001-2019. This approach was sourced from Miller et al. (2021).



Change from type (below) to type (in right columns)	Undetermined	Cropland	Built-up land	Dense forests	Open forests	Other vegetation	Water bodies/Inland waters	Barren	Sum ha lost
Dense forests	80,688	458,750	364	-	23,122,548	7,587,698	10,783	279	31,261,110
Open forests	75,587	4,676,846	18,864	8,592,038	-	31,613,018	20,601	2,572	44,999,526
SUM ha gained	156,275	5,135,595	19,229	8,592,038	23,122,548	39,200,716	31,384	2,851	76,260,636

Section 3: Results and Discussion

3.1 Forest Productivity

The data generated from this analysis was used to construct a time series of carbon uptake by Brazilian forests (Figure 2) from 2001 to 2019. Figure 2 illustrates variations in the annual amount of carbon sequestered for ‘dense’ and ‘open’ forests as characterized in the land use dataset. Relatively consistent trends are observed where the annual uptake of dense forests is roughly two times the magnitude of open forests. Dense forests demonstrate a slight decline in carbon uptake whereas uptake in open forests incrementally increases until 2014, and subsequently levels off (see Table B-2 in Appendix B). The average amount of carbon sequestered in Brazil is approximately 66,000 Gt C per year within the study period.

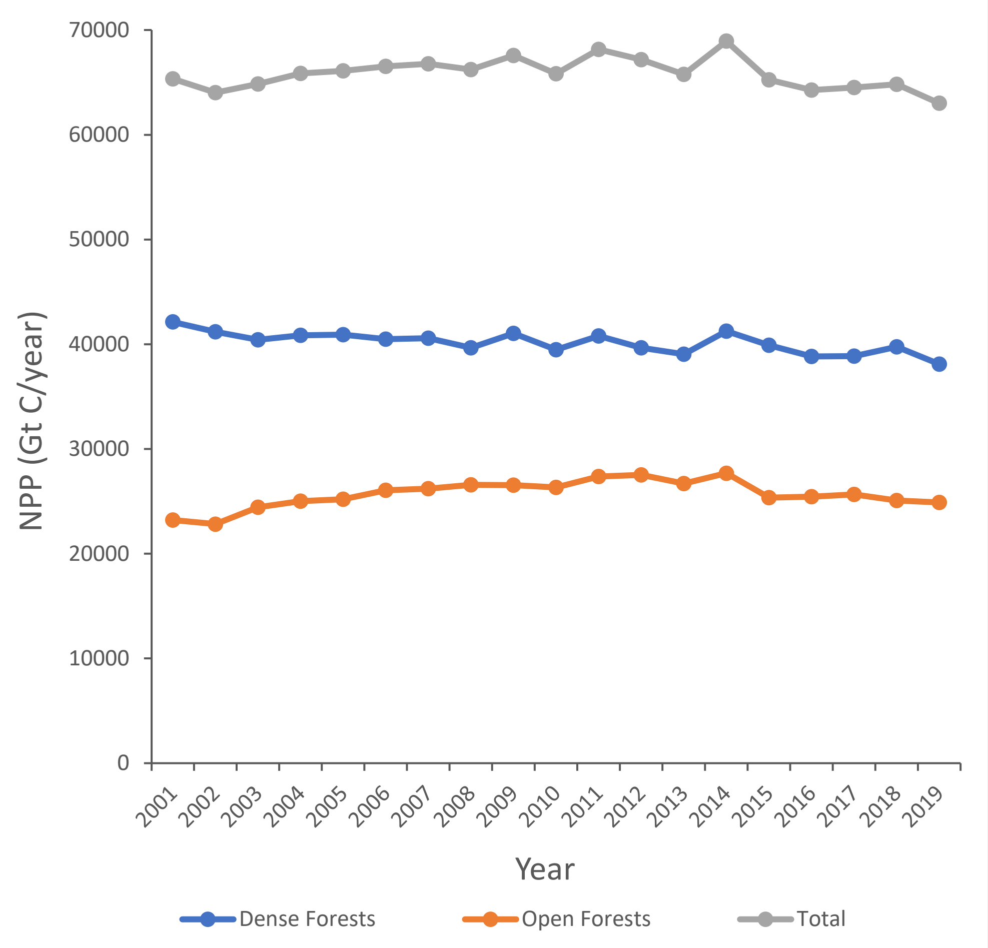


Figure 2. Time series data depicting the amount of carbon sequestered by forests in Brazil between 2001 and 2019.

3.2 Forest Extent

The spatial analysis also generated data on the quantity forests within Brazil's boundaries. A change in the composition of total forest extent is observed during the study period. Open forests saw a 5-7% increase in area along with a decline in dense forests between 2002 and 2017 (Figure 3).

3.3 Changes in Brazilian Forest Extent between 2001-2019

Furthermore, changes in Brazil's forested landscape were examined using an approach illustrated in Miller et al. (2021). Table 1 presents the changes in area from forest types to other land uses within Brazil. The country lost a combined total of 76 million hectares of forests as identified by the land use dataset. The largest increases in area are observed for two land use categories: open forests and other vegetation. More than 39 million hectares were gained by 'other vegetation', which includes the 'natural herbaceous' and 'shrubland' land use categories from the original dataset. Approximately 23 million hectares of dense forests were converted to open forests between 2001 and 2019. Figure 4 visualizes the data shown in Table 1 with bars on the left indicating the reductions in dense and open forest areas and the right demonstrating gains in all other land use categories. Each bar is colour-coded to illustrate the origin of change – where the gain was from or what the land was converted to.

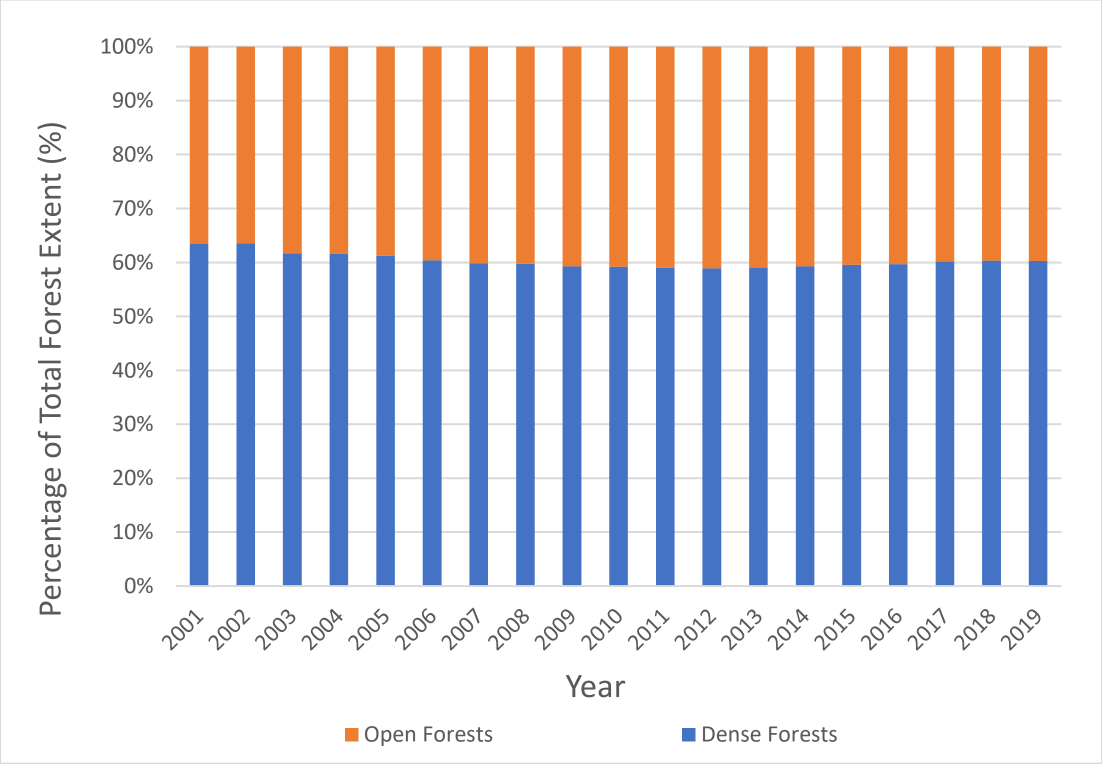


Figure 3. The composition of forest area in Brazil between 2001 and 2019. Based on the classifications defined in the LCCS2 dataset.

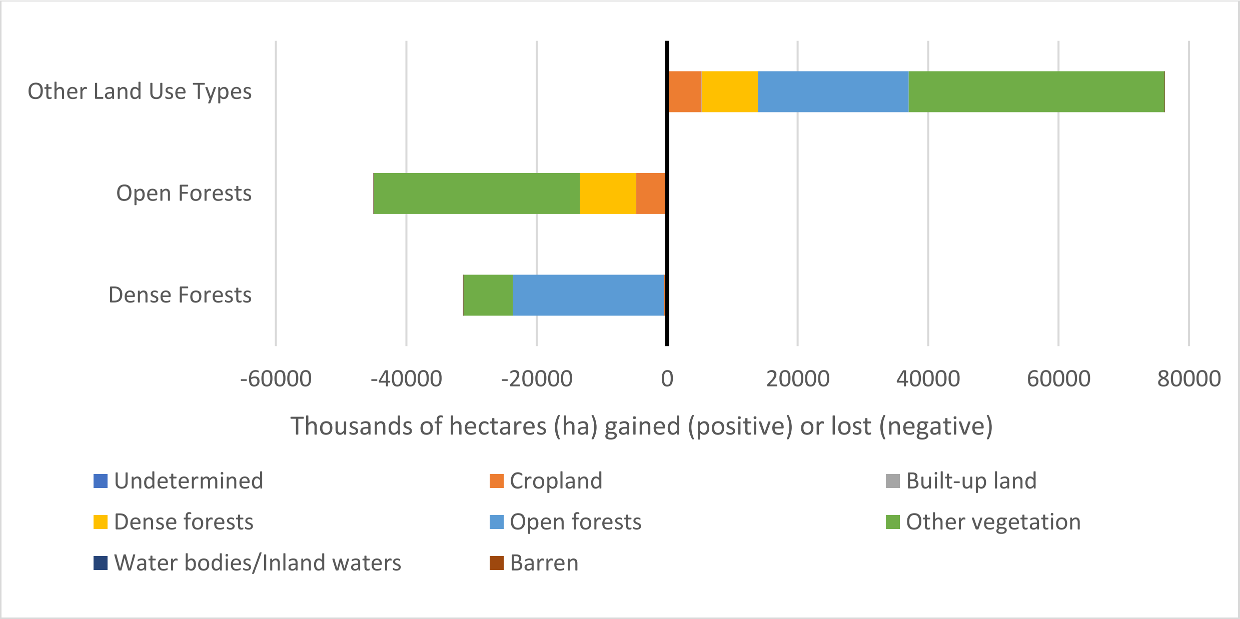


Figure 4. Visualization of changes in the forest landscape across Brazil from 2001-2019. This approach was sourced from Miller et al. (2021).

3.4 Forest Area and Biocapacity

Data from NFBA 2021 indicates a decline in both forest area and biocapacity in Brazil between 2001 and 2017 (Figure 5). The difference in recorded forest area and biocapacity was approximately 47 million national hectares and 169 million global hectares respectively (see Table C-1 in Appendix C).

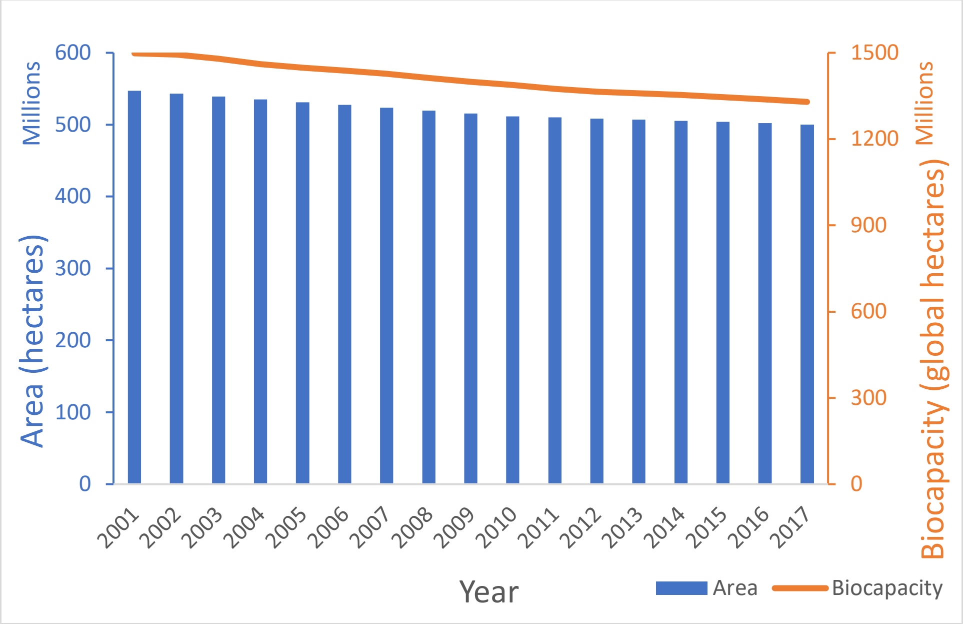


Figure 5. Time series trends of forest area and biocapacity in Brazil from 2001-2017.

3.5 Comparability of Results

Forest metrics and time series trends derived from spatially explicit data do not necessarily align with those generated from NFBA 2021. This difference in trends is seen when comparing NFBA data with metrics derived from the spatial analysis. Figure 5 illustrated a decline in forest area between 2001 and 2017 whereas the spatially explicit data demonstrated a change in the composition and an overall increase in forest extent within Brazil's boundaries (see Table B-3 in Appendix B). This increase was due to an expansion of open forests, although a contraction of dense forests between 2001 and 2019 simultaneously occurred. These trends may not be reconcilable due to differences in the categorization of forests between datasets. Forests in NFBA 2021 are defined by an individual, overarching FAO land use category called "forest land". In the LCCS2 dataset, forests are categorically defined using two (technically three) classes; consequently, changes in forest extent are illustrated in a less simplistic manner.

This examination of spatially explicit data has led to similar conclusions about Brazilian forests within overlapping timeframes. Forest extent metrics obtained from each dataset are within the same order of magnitude. Table 1 suggest that declines in forest extent and changes in land use occur from forests to other vegetative land use types between 2001 and 2019. These trends are visualized in Figure 4 and align with conclusions drawn from NFBA data. The decline in forest area – which is observed using data from each dataset – may be validated by recent spatially explicit studies pointing to deforestation in the Brazilian Amazon (Harris et al., 2021). The decline in extent also provides insight into Brazil's decreasing trend in forest biocapacity (Figure 5). This trend is likely a result of decreasing area as the forest biocapacity calculation in NFBA 2021 applies the same EQFs, YFs, and IYFs between 2001 and 2017. Thus, Brazil's forest biocapacity in NFBA 2021 may not necessarily be influenced by the values of EQFs, YFs and IYFs but rather the decline in forest area during the study period[3].

3.6 Limitations of Data and Processing Workflow

This study facilitated an understanding of Brazil's forested landscape across time using spatially explicit land use and NPP data. Despite enabling the production of relevant information, both the data and workflow were limited in their capacity to generate results. First, the NPP dataset became the focus of the spatial analysis as productivity data was provided on a per pixel (per area) basis. This dataset could not be modified – e.g., through pixel size resampling – without distorting the productivity value designated to a pixel. All other datasets were considered and implemented in this workflow based on their compatibility with the NPP dataset. LCCS2 was

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[3] Temporal variations in forest biocapacity may also be due to methodological or data updates between editions.

selected for this analysis because it had the same spatial and temporal resolution as the NPP dataset. Consequently, the spatial resolution of both datasets was coarse which meant the analysis overlooked landscape changes at smaller scales across the study period. Secondly, acquiring forest metrics through this process likely resulted in an underestimation in the extent and productivity of Brazilian forests. The workflow focuses explicitly on pixels of land use which had an affiliated productivity value within the NPP dataset. Land use pixels which were not associated with a productivity pixel are excluded from estimates of forest area and landscape changes. The collective NPP of Brazilian forests is also underestimated as the 'forest/cropland mosaics' land use category was not included in forest productivity metrics generated from the analysis.

The preceding discussion highlights the limitations of the data and processing workflow to generate results from the spatially explicit analysis. This is an important discussion to have if the data products are to be considered potential sources for the NFBAs. It evaluates the applicability of the data and the approach to update the AFCS for cF assessments at the global scale. The data products could be appropriate options for this update because they provide global spatial coverage of NPP and land use. However, the temporal coverage of both data products[4] overlaps with only 30% of the current NFBA timeline which ranges from 1961 to 2017. The workflow is also applicable at the global scale if the datasets are downloaded in a projection that aligns with a country's boundary file. Although a reprojection would inherently change the data from its original format, a distortion in pixel values in the datasets after

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[4] The temporal extent of MOD17A3HGF is ranges from 2000 to present (its production is ongoing) and LCCS2 extends from 2001 to 2019.

applying such a change has not been explored. This approach was not applied to the Brazil case study because the native projection of the data products experienced minimal distortion due to geographic location of the country. Nevertheless, a variation of the workflow might be used to extract global estimates of forest area and productivity by country, but only after determining if reprojection has any effect on the value of pixels. A similar analysis was recently conducted in Park, Gan and Park (2021) which compared estimates of global forest NPP in 2015 from MODIS-derived monthly data to annual estimates of NPP determined using Global Forest Resources Assessments (FRA) data. The methods outlined in Park, Gan & Park (2021) and this case study can provide appropriate estimates of the AFCS rate within certain timeframes; however, they would likely result in different outcomes when compared to current AFCS rate. This is because the AFCS from Mancini et al. (2016) reflects NFP that is defined by NEP whereas the preceding approaches are defined by NPP. The variations in the estimated AFCS also exist because the rate is based on how forest land is defined, along with the data on forest extent which varies between approaches.

Section 4: Conclusion

This analysis was inspired by the outcomes of a literature review that appraised existing research on the forest component of the Ecological Footprint. The review was suggestive of numerous methodological criticisms but did not discuss the antiquated nature of input data, which is used to estimate the cF, the Footprint of forest products and forest biocapacity. Thus, this paper looked to alternative data sources for the AFCS calculation and its usefulness to the NFBAs. The country of Brazil was used as a case study to explore global datasets of NPP and land use and the investigation generated forest extent and productivity metrics between 2001 and 2019. Subsequently, the metrics and time series data produced from this spatially explicit analysis were compared to trends in forest area and biocapacity data from the NFBAs. The trends between datasets were consistent in demonstrating the decline in forest extent across Brazil during overlapping timeframes; however, the spatially explicit data showcased a more nuanced perspective to changes in the forested landscape of Brazil. In terms of the applicability of the data and processing workflow, both aspects are limited in their capacity to produce results at the national or global scale. The workflow implemented in this study generated results which underestimate the extent and productivity of forests within a country's boundaries. The spatial and temporal resolutions of the global datasets are important determinants of this analysis because they dictate whether the workflow is reproducible. The possibility of applying the data and workflow from this study calls for further investigation of the abovementioned aspects, especially if the goal is to strengthen key parameters through the implementation of recent datasets.

Despite the preceding calls to action, this study elicits an investigation of relevant data that researchers and proponents of EF might consider beneficial for the enhancement of the NFBAs. It presents an analysis of spatially explicit data and how a slightly different approach could improve the robustness of the Accounts. For example, the application of the data and workflow at the global scale could generate distinct estimates of AFCS between 2001 and 2019, rather than applying the same AFCS to every year within the current NFBA timeline. This approach also is indicative of trends in Brazilian forest extent that are not fully captured by the current Accounts. It ultimately has the potential to enrich the forest component of the NFBAs (particularly the cF) by specifying trends in forest extent in a more nuanced manner while simultaneously generating a time-series showcasing the uptake of carbon aligning with those areas.

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Appendix A: Land Use Data

Table A-1. FAO-land cover classification system (LCCS2) land use legend and class definitions.

Name	Value	Description
Barren	1	At least 60% of area is non-vegetated barren (sand, rock, soil) or permanent snow/ice with less than 10% vegetation
Permanent Snow and Ice	2	At least 60% of area is covered by snow and ice for at least 10 months of the year.

Water Bodies	3	At least 60% of area is covered by permanent water bodies
Urban and Built-up Lands	9	At least 30% of area is made up of impervious surfaces including building materials, asphalt, and vehicles.
Dense Forests	10	Tree cover >60% (canopy >2m).
Open Forests	20	Tree cover 10-60% (canopy >2m).
Forest/Cropland Mosaics	25	Mosaics of small-scale cultivation 40-60% with >10% natural tree cover.
Natural Herbaceous	30	Dominated by herbaceous annuals (<2m). At least 10% cover
Natural Herbaceous/Croplands Mosaics	35	Mosaics of small-scale cultivation 40-60% with natural shrub or herbaceous vegetation.
Herbaceous Croplands	36	Dominated by herbaceous annuals (<2m). At least 60% cover. Cultivated fraction >60%.
Shrublands	40	Shrub cover >60% (1-2m).
Unclassified	255	Has not received a map label because of missing inputs.

Appendix B: Spatially Derived Data

Table B-1. Average net primary productivity (NPP) of dense and open forests in Brazil from 2001-2019.

Year	**Average NPP (kg C m^{-2} yr^{-1}) of Dense Forests**	**Average NPP (kg C m^{-2} yr^{-1}) of Open Forests**
2001	11344.73	10848.95
2002	11229.35	10846.37
2003	10875.86	10579.90
2004	11045.56	10847.14
2005	11154.98	10839.25
2006	11102.03	10896.32
2007	11182.14	10760.27
2008	10943.46	10887.82

2009	11316.77	10642.76
2010	10919.22	10566.56
2011	11319.87	10936.00
2012	11069.96	11003.90
2013	10911.55	10733.46
2014	11523.33	11241.30
2015	11175.60	10447.77
2016	10929.56	10597.00
2017	10921.42	10890.54
2018	11175.90	10711.03
2019	10717.10	10621.61

Table B-2. Total net primary productivity (NPP) of forests in Brazil from 2001-2019.

Year	**Total NPP of Dense Forests (Gt C yr^{-1})**	**Total NPP of Open Forests (Gt C yr^{-1})**	**Total NPP Combined (Gt C yr^{-1})**
2001	42120.26	23210.23	65330.48
2002	41181.47	22831.16	64012.63
2003	40430.42	24425.72	64856.14
2004	40840.36	25019.63	65859.99
2005	40921.40	25186.65	66108.05
2006	40473.39	26044.58	66517.97
2007	40566.10	26218.30	66784.40
2008	39657.03	26579.99	66237.02
2009	41023.61	26545.07	67568.67
2010	39488.47	26334.16	65822.63
2011	40778.66	27379.36	68158.02
2012	39653.10	27523.69	67176.79
2013	39046.37	26711.24	65757.61
2014	41238.44	27689.47	68927.91
2015	39896.44	25356.95	65253.39
2016	38841.77	25430.76	64272.53
2017	38857.54	25662.68	64520.22
2018	39743.99	25066.96	64810.95
2019	38102.59	24900.27	63002.85
Average (2001-2019)	**40150.60**	**25690.36**	**65840.96**

Table B-3. The extent of dense and open forests in Brazil from 2001-2019

Year	Area of Dense Forests (millions of national hectares)	Area of Open Forests (millions of national hectares)	Combined Area of Forests (millions of national hectares)
2001	371.28	213.94	585.22
2002	366.73	210.50	577.23
2003	371.74	230.87	602.61
2004	369.74	230.66	600.40
2005	366.84	232.37	599.21
2006	364.56	239.02	603.58
2007	362.78	243.66	606.43
2008	362.38	244.13	606.51
2009	362.50	249.42	611.92
2010	361.64	249.22	610.86
2011	360.24	250.36	610.60
2012	358.20	250.13	608.33
2013	357.84	248.86	606.70
2014	357.87	246.32	604.19
2015	357.00	242.70	599.70
2016	355.38	239.98	595.36
2017	355.79	235.64	591.43
2018	355.62	234.03	589.65
2019	355.53	234.43	589.96

Appendix C: NFBA Data

Table C-1. Forest area and biocapacity data from the 2021 Edition of the National Footprint & Biocapacity Accounts (NFBAs).

Year	Forest Area (millions of national hectares)	Forest Biocapacity (millions of global hectares)
2001	547.14	1498.14
2002	543.19	1494.21
2003	539.24	1479.64
2004	535.29	1460.76
2005	531.33	1447.75
2006	527.38	1438.61
2007	523.43	1426.99
2008	519.48	1412.66
2009	515.53	1399.06
2010	511.58	1387.55
2011	510.04	1374.08
2012	508.50	1364.47
2013	506.96	1358.99

2014	505.42	1353.21
2015	503.88	1345.26
2016	502.08	1337.74
2017	500.09	1329.24