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The **CHANGING WEALTH** *of* **NATIONS**

TECHNICAL REPORT

Global estimates of carbon stocks in the vegetation
and soils of terrestrial ecosystems



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ACRONYMS AND ABBREVIATIONS

AI	Artificial intelligence
ARIES	Artificial Intelligence for Environment and Sustainability
BC3	Basque Centre for Climate Change
CWON	Changing Wealth of Nations
ESA	European Space Agency
ESA-CCI	European Space Agency Climate Change Initiative
FAO	Food and Agriculture Organization of the United Nations
FIRMS	Fire Information for Resource Management System
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
REDD+	Reducing Emissions from Deforestation and forest Degradation program
SEEA	System of Environmental-Economic Accounting
SEEA EA	System of Environmental-Economic Accounting Ecosystem Accounting
UNFCCC	United Nations Framework Convention on Climate Change
UNSD	United Nations Statistics Division

1 Introduction

This section provides a general introduction to present the work done to produce global maps representing modeled vegetation carbon stocks for the period 2001–2020, available at <https://data.integratedmodelling.org/dataset/global-vegetation-carbon-soil-2001-2020>, as well as summary statistics and results derived from these outputs.

1.1 THE IMPORTANCE OF THE ECOSYSTEMS PROVIDING THE CARBON REGULATION SERVICE

The global climate crisis is one of the most pressing challenges of our time, exacerbating existing social and environmental issues. Regulating ecosystem services, and climate regulation in particular, plays a fundamental role in mitigating the effects of climate change. In this regard, terrestrial ecosystems play a crucial role as stocks for carbon that would otherwise be released into the atmosphere, causing further warming, as well as being potential carbon sinks. Terrestrial ecosystems, particularly forests, are thus essential to addressing the global climate crisis. For these reasons, it is important to include carbon in the World Bank's Changing Wealth of Nations (CWON) wealth estimates.

Terrestrial ecosystems, which are under threat, are the main focus of this analysis, given their important contribution to global carbon regulating services. To try to understand the dynamics behind the human-induced changes in the climate balance, as well as to identify ways to mitigate such effects and adapt to their impacts, significant work has been done. Such

efforts have been undertaken at different scales, from local to global, and by different stakeholders, ranging from academic and research institutions to governments and private institutions. Some of the most important are the European Space Agency (ESA), particularly the ESA Climate Change Initiative (CCI); the United Nations Statistics Division (UNSD); the Intergovernmental Panel on Climate Change (IPCC), which focuses on studying human-induced climate change; as well as the institutions advancing the Reducing Emissions from Deforestation and forest Degradation program (REDD+).

1.2 LATEST STUDIES ON FOREST ECOSYSTEMS

Forest ecosystems play a critical role among terrestrial ecosystems, especially in the context of climate regulation, and for this reason they are the focus of many important studies. Mengist and Soromessa (2019) provide a comprehensive review of the research approaches and trends in studying forest ecosystem services, including carbon regulation. Their overview shows that studies on forest ecosystem services mainly focus on three types of services: (i) provision, such as timber production and water supply; (ii) climate regulation, such as carbon sequestration; and (iii) cultural ecosystem services, such as recreation. They also found that the methodologies applied are diverse and that results are dispersed and inconclusive at the global level. In our analysis, we provide a globally consistent methodology to quantify climate regulation services from terrestrial ecosystems.

Other relevant studies that are worth highlighting to give an idea of the ongoing efforts in this field include Taye et al. (2021)¹ and Costanza et al. (2014).² The first study (Taye et al.) uses meta-analysis to estimate the economic values of global forest ecosystem services. A regression is run, considering studies published between 1990 and 2018, to derive the economic value of a hectare of forest in a particular year. By controlling for specific characteristics that make individual applications differ from others, the authors try to capture the intrinsic value of the service, which is then used to derive values across the globe. The second study (Costanza et al.) highlights the contribution of land use to human well-being and emphasizes how ecosystem services are best considered public goods, requiring new institutions. There are numerous other studies assessing and valuing ecosystem services, but in most cases, they focus on specific locations or services, and few use methods that are replicable at the global scale.

1.3 CARBON STOCK VALUATION IN BIOPHYSICAL AND MONETARY TERMS, MAIN DRIVERS OF CHANGE, AND INTERPRETATION OF RESULTS

A growing number of scientific publications quantify the contribution of the carbon regulation service in the context of climate change. While the works described in the previous section offer an important perspective, their purposes are different from the approach taken in CWON: rather than analyzing previous studies on forests around the globe, the World Bank focuses on biophysical observations to estimate both physical and monetary values of the services reported in their work. This approach

aims to produce a comprehensive collection of measurements, in which all assets are reported individually and aggregated.

This analysis was carried out by the Basque Centre for Climate Change (BC3), which develops multidisciplinary knowledge to support decision-making on this global challenge. Within the research center, the Artificial Intelligence for Environment and Sustainability (ARIES) team developed an integrated modeling system with a platform capable of combining data and models to study the interaction of human and natural systems, with a strong focus on the environment and sustainability dimensions. More information is provided in the next section (1.4) to briefly describe how the modeling integration based on artificial intelligence (AI) and semantics is used to obtain results aligned with the World Bank's CWON approach. The global model to estimate vegetation carbon stock used in this analysis quantifies how the global landscape is changing as a result of ecological transformations that occur at biophysical (environmental), social, and economic levels. In the context of the CWON program, the World Bank collaborates with the BC3 team, who developed the ARIES for System of Environmental-Economic Accounting (SEEA)³ platform, to create global baseline biophysical and monetary accounts of the *carbon storage ecosystem service*.

It is important to emphasize that changes in these results are mainly driven by land cover changes, and potentially by land cover re-classification, which do not always match with the real, but rather the modeled, ecological information. The complexity of an observed area is greatly simplified to allow a global representation of the reality. The landscape

¹ Table 3.

² Appendix 2 (spreadsheet).

³ <https://seea.un.org/>.

is classified into discrete classes, which are of course artificial constructs. This trade-off is well known by experts in spatially explicit analyses, with no completely accurate solution, though some approximations are better than others. Other dynamic variables used in the model that can contribute to change include the occurrence of fire and the presence of pristine forests. Fire, as well as data gaps and information on fire intensity and vegetation regrowth, can also be the main reason for changes in the forest carbon stock of a country (more details are given in Appendix 3). The model is built to allow annual carbon stocks all over the world to be globally comparable, and the reader should interpret the outputs of this analysis as such. Such an approach is fundamental to be able to observe trends and produce comparable results over a long time period, and the main reason for choosing a global model as opposed to, for instance, global biomass datasets that exist for a single year or only several recent years.

Considering this primary purpose, caveats to the use of the data are clearly stated in section 2.1.2. Users should be aware that the main goal of the results is to observe *trends in global changes of carbon stock over time*. Indeed, the results are intended to support climate policy makers to verify trends observed in related reports, contribute to filling gaps in time series, or raise awareness of potential hotspots of carbon fluxes—all with a view to informing actions to combat the adverse effects of climate change. Annual changes in vegetation carbon stocks throughout the time series reflect the effect of updated information on land cover classes or other dynamic model inputs. They should not be interpreted as a proxy for complete and accurate figures of net carbon fluxes and other non-CO₂ emissions from lands. The results include a dataset and tabular time series that can be downloaded and used for the above-noted purposes.

This report starts with a general overview of the model used to estimate global climate regulation services, then covers specific methods, data, and models used in ARIES. The report then discusses the limitations and caveats to be considered when interpreting and using the results. It concludes with a discussion of the improvements planned to enhance future outputs and align results from different analyses.

The monetary valuation based on the biophysical results is also discussed in section 4. The main ecosystem service priced in monetary terms is *carbon retention*, which consists of carbon storage expressed as an annual flow. The total physical carbon stock from all the different pools (above- and belowground biomass and soil organic carbon) is first priced to estimate the avoided damages and subsequently multiplied by a rate of return to obtain an annuity.

1.4 THE ARIES APPROACH TO INTEROPERABILITY: ONGOING PRODUCTION OF RESULTS USING STATE-OF-THE-ART SCIENTIFIC KNOWLEDGE

The results produced in this work are an important output, but as scientific knowledge evolves and better models and data become available, the results will be adjusted accordingly. Some improvements are already planned and future results will include, at the minimum, the incorporation of IPCC 2019 guidelines, and further information on the uncertainty associated with these outputs. These planned revisions are further described in section 4.

The process to produce results based on improved information is made easier by the inherent interoperable nature of ARIES, a modeling platform that enables the integration of science-based

knowledge. Interoperability⁴ is the ability of humans and computer systems or software to exchange and make use of information, and is at the core of the strategy that the ARIES team is working to promote, and that other institutions, like the World Bank and UNSD, also want to bring forward.

Whenever new and reliable data and methodologies (or specific model components) are added in the system, ARIES can automatically prioritize the use of these new inputs if they help to improve the results. Thus, new data and models are prioritized when they better suit a specific context or more precisely answer a question posed by a user.

ARIES is powered by its cutting-edge integrated modeling technology, in development since 2007. Its artificial intelligence is based on *machine reasoning*,⁵ which guides the AI system to the most appropriate data and models to answer each question, providing clear and fully documented answers to critical questions in the context of the ecological crisis. These answers inherently contain a wide range of information, spread across multiple areas of knowledge (such as ecology, hydrology, and sociology), which are compiled by integrating the information through the power of AI. This allows ARIES to provide the answer based on the most up-to-date knowledge across different areas of expertise. In this context, interoperability means

that experts can model the particular phenomena that they know best, while the AI combines that particular piece of knowledge with the rest of the information contributed by others in order to answer larger questions. Since all the information used in ARIES has been added by experts specializing in specific domains and with different expertise, its AI can answer a particular question by distilling the complexity of the query into a workflow that is executed in order to provide the final user with a clear and fully documented answer, regardless of the complexity of the needed analysis.

ARIES works at different scales and automatically adjusts its results to the spatio-temporal context under analysis. While using local data and models is not the purpose of this analysis, as global comparability is emphasized here in order to support a global analysis, ARIES can digest different data, at different spatio-temporal scales. Its underlying AI automatically accesses, assembles, and runs data and models needed to adjust the output to a particular spatio-temporal context, or automatically uses a better model for that particular context, if it exists in the system. For this work, a unique global model and global data are used, but context-specific (regional, national, or subnational) modifications are possible and encouraged in ARIES.

⁴ https://seea.un.org/sites/seea.un.org/files/seea_interoperability_strategy.pdf

⁵ Machine reasoning is a type of artificial intelligence that draws conclusions from ideas and concepts using logic and rules introduced to the system by humans.

2 Overview of the Carbon Stock Estimates

The terrestrial carbon storage model, as currently coded in ARIES, computes terrestrial carbon stock as the sum of vegetation stocks, composed of aboveground biomass and belowground biomass, and soil organic carbon stocks. None of these components are limited to forests, but the model does not take into account woody debris.⁶ The first two stocks (aboveground biomass and belowground biomass) are modeled simultaneously using the vegetation carbon model for the years 2001 to 2020. To estimate vegetation stocks, it is assumed that each terrestrial land cover class, with a few exceptions,⁷ contributes to storing carbon to varying extents. The classes with the highest contribution to carbon stock are forests and wetlands, particularly mangroves, but each class contributes proportionally to the total carbon stock of an area. The estimates provide annual snapshots of the stock for every year considered in the time series. In contrast, the information provided on soil organic carbon stocks is based on a static dataset produced in 2020 that maps global soil organic carbon.

Separately, the World Bank is estimating mangrove carbon storage using higher resolution data from Global Mangrove Watch for a subset of years (1996, 2007, 2010, 2015, 2018, and 2020). The results of this work have been produced by Silvestrum Climate Associates. Appendix 2 of this report includes technical aspects considered for the potential

integration of the mangrove carbon storage data, with some recommendations on how to produce a harmonized but comprehensive and consistent result. Specifically, attention is given to the best way to reconcile the vegetation carbon stock results with the maps and outputs produced for mangroves (outside ARIES). Preliminary discussions were held among the groups to explore how these outputs could be included in ARIES in the future, which would then automatically harmonize these results.

2.1 VEGETATION CARBON BIOMASS

For vegetation, the carbon accounted for is both the carbon stock in aboveground biomass, with a particular focus on forest ecosystems, and in belowground biomass. The model quantifies the total carbon stored in vegetation in each year. The information is produced using IPCC 2006 default factors⁸ and by incorporating yearly updated land cover data and other inputs described below.

Using a multi-layer lookup table, the model merges spatially explicit data on land cover classes and other features with carbon stocks derived from the IPCC guidelines to map the carbon in vegetation globally. This approach replicates the method developed by Gibbs and Ruesch (2008).⁹ The current inputs used in the model are as follows (further details on the data sources are included in the next section):

⁶ Fallen dead trees and the remains of large branches on the ground.

⁷ For example, the ESA-CCI includes classes for water bodies, and glaciers, which do not store carbon, and bare soil/rocks, which only store limited amounts of carbon: [Legend of the global CCI-LC maps based on LCCS](#).

⁸ Guidance that officially governs the current submission of GHG inventories. A refinement of this document was published in 2019 (IPCC 2019 refinement to the 2006 IPCC Guidance), although this has not yet been adopted by the UNFCCC reporting framework.

⁹ New IPCC Tier-1 Global Biomass Carbon Map for the Year 2000 (dataset): <https://www.osti.gov/biblio/1463800>.

1. Data about land cover classes to estimate changes in the extent of the vegetation.
2. Ecological region (Food and Agriculture Organization (FAO) ecofloristic zone) to distinguish different regional ecological characteristics that influence carbon storage.
3. Presence of primary forest to identify areas of greatest carbon storage.
4. Occurrence of fire to take into account loss of carbon stored in vegetation in burned areas.

The code used in ARIES to estimate these values is publicly available in this [repository](#). An example of the first lines of the lookup table is shown in Table 2.1. The complete table, which summarizes the inputs to implement the original methodology by Gibbs and Ruesch (2008), can be explored at this [link](#). As mentioned above and shown in the code, all the terrestrial land cover classes are included, except for bare soil/rock, water bodies, and glaciers,

which have no vegetation that stores carbon.

The first items in the lookup table (Table 2.1) show how inputs are combined to obtain the carbon stock in each grid cell. For each land cover class, located in a specific ecofloristic zone, within a particular continent, the model assigns a specific value for the vegetation carbon stock in that area. In the case of a forest, the carbon content also depends on how pristine, old, and/or intact the forest is. A so-called primary forest stores a greater quantity of carbon. The model also identifies burned areas and assigns a significantly lower to zero vegetation carbon stock for that year in the burned area. To provide an example, a broad-leaved forest, located in the African tropical rainforest and in an area where there was no record of fire in that year, is estimated to store, for each hectare, 200 tonnes of vegetation carbon, contained in its aboveground and belowground biomass. Table 6.4 provides more information on the default values set in the IPCC guidelines, which is discussed in more detail in section 6.

TABLE 2.1: EXTRACT FROM THE ARIES LOOKUP TABLE

LAND COVER CLASS	FAO ECOFLORISTIC ZONE	CONTINENTAL REGION	PRIMARY FOREST	BURNED LAND	CARBON STOCK (t/ha)
Broadleaf forest	Tropical rainforest	Africa	Either	False	200
Broadleaf forest	Tropical rainforest	North and South America	Either	False	193
Broadleaf forest	Tropical rainforest	Continental Asia	Either	False	180
Broadleaf forest	Tropical rainforest	Asia	Either	False	180
Broadleaf forest	Tropical rainforest	Insular Asia	Either	False	225
Broadleaf forest	Tropical rainforest	Australia	Either	False	199.5

2.1.1 Data Used to Estimate the Vegetation Biomass Carbon Storage of Terrestrial Ecosystems

The inputs used in the model and briefly listed in the previous sections include:

1. **ESA-CCI land cover data used to retrieve a complete time series of land cover classes from 1992 to 2020.** Land cover classes are used to assign IPCC values of carbon stock. It should be noted that some classes, such as water bodies and glaciers, are excluded from the computation in this first set of results, while others, like lichen and moss-covered areas or bare areas, only contribute modestly to carbon stock.

2. **Ecofloristic zones and continental regions.**

The zones are assumed to be static and are used to select default IPCC values and to produce results at different spatial scales.

3. **Spatially explicit layers on intact/primary forests.** The layers provide information on the presence of intact forests, which are used as a proxy for primary forests. The information is available for the years 2000, 2013, 2016, and 2020. The location of intact and non-intact forests allows for a proxy of the degree of forest degradation and other anthropogenic effects that affect the carbon stock in the vegetation in non-intact areas.

4. **Occurrence of fires (annually available from 2000 to 2020).** The information is needed to incorporate the effect of wildfires on the carbon budget of the ecosystem in the model. An approach is also suggested to smooth out post-burned effects (see section 2.1.4 for further detail).

The data initially considered for this work are the ESA-CCI land cover maps¹⁰ from 1995 to 2020; MODIS burned land maps¹¹ for 2000 to 2020; Intact Forest Landscapes maps¹² for 2000, 2013, 2016, and 2020; and FAO ecofloristic and continental regions.¹³ The original goal was to estimate a time series starting in 1995 to align results with the comprehensive wealth estimates in other CWON products, but limited data availability restricted the analysis to a shorter time series from 2001 to 2020.

The integration of several alternative datasets was considered but eventually discarded because of limited geographical coverage or shorter temporal coverage. For example, the Joint Research Centre's tropical moist forest dataset was considered as an alternative for the Intact Forest Landscapes data to capture deforestation and degradation, but it was ultimately dismissed due to its limited geographic coverage. Similarly, several alternatives to the MODIS burned land datasets were considered, as they might provide over- or under-estimates in some instances, due to the coarse resolution (1km²) of the input data from the Fire Information for Resource Management System (FIRMS).¹⁴ However, the alternatives were either not accurate enough¹⁵

¹⁰ <https://doi.org/10.24381/cds.006f2c9a>

¹¹ <https://modis-fire.umd.edu/ba.html>, product MCD64A1.

¹² Intact forest landscapes data are available at <https://intactforests.org/data/ifi.html>.

¹³ New IPCC Tier-1 Global Biomass Carbon Map for the Year 2000: https://cdiac.ess-dive.lbl.gov/epubs/ndp/global_carbon/carbon_documentation.html
FAO's ecofloristic region dataset: <https://databasin.org/datasets/dc4f6efd1fa84ea99df61ae9c5b3b763/>

¹⁴ The FIRMS data detect thermal anomalies in either MODIS AQUA or TERRA data, at <https://www.earthdata.nasa.gov/learn/find-data/near-real-time/firms>

¹⁵ The MODIS/Terra Vegetation Continuous Fields Yearly L3 Global 250m SIN Grid, LAADS DAAC.

(<https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD44B#overview>), is a possible alternative, but has several limitations. First, inter-annual comparisons of vegetation continuous fields must be interpreted cautiously, considering the high potential of inter-annual fluctuations in the percentage of tree cover due to various forms of forest disturbance and regrowth. Second, the data are only validated to stage 1, so the accuracy was estimated through an assessment of the training data's accuracy and from limited in situ field validation datasets (Data maturity levels, Science Mission Directorate, <https://science.nasa.gov/earth-science/earth-science-data/data-maturity-levels>)

or had a too limited time series¹⁶ for the purpose of building a consistent, global, and relatively long time series for fire occurrence.

Previous literature reviews, namely Humber et al. (2019) and Pessôa (2020), have also indicated that compatible data products do not exist. Should new data become available, the possibility of incorporating them into ARIES and extending the current estimate to cover the period 1995–2000 can be considered.¹⁷ The full list of data inputs is shown in Table 2.2.

2.1.2 Key Elements for a Correct Interpretation of Model Results

2.1.2.1 General considerations

At least three considerations should guide correct interpretation and use of the results produced using this modeling approach.

First, when viewing model results, any change identified across the time series to vegetation carbon stocks in a given area is mainly driven by a change in the land class information. If the underlying land cover class changes, so does the carbon stock value associated with that area, in accordance with the IPCC methodology. Net carbon fluxes from lands, and other emissions of non-CO₂ gases, are recognized as highly complex to accurately model, and are excluded from the approach.

TABLE 2.2: DATA INPUTS

NAME	DESCRIPTION	TEMPORAL COVERAGE	TEMPORAL RESOLUTION	SPATIAL COVERAGE	SPATIAL RESOLUTION
ESA-CCI	Land cover	1992–2020	Annual	Global	300m
MODIS	Burned land	2000–2020*	Monthly*	Global	500m
FAO	Ecofloristic regions	Static	Single observation	Global	Shapefile
Intact Forest Landscapes	Primary forest	2000–2020	2000, 2013, 2016, 2020	Global	300m

* The dataset only covers the last two months of 2000. More information is provided in the next sections to explain the consequences of the results and the decision to exclude this year from the final results.

¹⁶ For example, the timeseries of the ALOS PALSAR FNF (forest/non-forest) products (<https://asf.alaska.edu/data-sets/sar-data-sets/alos-palsar/alos-palsar-about/>) is limited to the years 2007 to 2018 (Global PALSAR-2/PALSAR Forest/Non-Forest Map. Earth Engine Data Catalog. Google Developers. at https://developers.google.com/earth-engine/datasets/catalog/JAXA_ALOS_PALSAR_YEARLY_FNF).

¹⁷ Benchmarking is a standard practice in generating economic statistics (Hillmer and Trabelsi 1987) but can involve complex and formal analyses, which are beyond the scope of this project.

Second, working at a global scale hampers the accuracy of the results, mainly because of the lack of available information covering the full time frame and spatial resolution necessary to successfully represent natural and anthropogenic effects in the carbon cycle.

Third, some factors need to be considered when using the global outcomes of the model at lower spatial or shorter time scales. Regional or forest-stand models can account for important drivers needed to quantify vegetation carbon stocks and their changes—for instance, management practices, climate conditions, species composition, and market demand. For example, direct oxidation to the atmosphere can be assumed when a deforestation event occurs. However, it is not feasible to accurately capture the effects of vegetation growth, natural disturbances, aging of trees, climate conditions, species compositions, and management practices

because the necessary data are simply not available and consistent at a global level. Such information is not available for top-down approaches that aim to produce global results. This limitation should be considered if comparing global results to those of local models that can account for more detailed ecological and management processes. When analyzing results produced using different data sources, users should be aware that the use of different land classification systems or land cover datasets introduces well-known divergences in results of two such modeling efforts.

Ultimately, model results represent snapshots of worldwide terrestrial carbon stocks in vegetation that are assigned on the basis of yearly spatially explicit information on land cover classes, FAO ecofloristic zones and location in the continental regions, and presence of primary forests and fire activity.

2.1.2.2 Spatial and temporal coverage

In terms of spatial coverage, there are some areas in which the model could not be run due to lack of inputs. These areas are mainly very small islands and administrative areas, particularly archipelagos and overseas territories, which are not covered by the FAO ecofloristic layer. They include:

- Clipperton Island (France)
- Palmyra Atoll (United States)
- Midway Island (United States)
- Kingman Reef (United States)
- Jarvis Island (United States)
- Johnston Atoll (United States)
- Howland Island (United States)
- Baker Island (United States)
- Heard Island and McDonald Islands (Australia)
- Bouvet Island (Norway)
- Ashmore and Cartier Islands (Australia)
- Wake Island (United States)
- Tokelau (New Zealand).

Other regions, such as the Antarctic, were intentionally excluded due to the insignificant or complete absence of vegetation. However, the model is capable of producing consistent results for these excluded areas and incorporating them in the global outcome, provided that necessary information becomes available.¹⁸

In terms of temporal coverage, the results are produced for the period 2001–2020. This decision is mainly based on the forward-looking applicability of the results and because the lack of pre-2001 data for some inputs hampers the consistency of the results produced before 2001. In particular, the year 2000 was excluded after a careful review, because burned area data do not cover some areas of the world and are only available for the last two months of the year, meaning that fire activity would be strongly underestimated. For the same reason, years prior to 2000 are excluded, due to the lack of the input data on the occurrence of fire and presence of primary forest. Conducting the analysis without complete and consistent input data would lead to incomparable outputs between the areas around the globe where data gaps influence the results.

2.1.2.3 Moving from spatial to country aggregate values

The results are produced yearly at the global level. The raw model outputs from ARIES are tiled raster data, which are merged together into a single map to give annual global results. Country-level results are obtained by aggregating grid cells within the country boundaries and summarizing results in the tables by country, by land cover class,¹⁹ and by year.

In future, as new iterations of the model are endorsed by expert groups (for example, should the forest ecosystems modeling be vetted by the SEEA Ecosystem Accounting (EA) Forest Working Group), the results could be summarized by ecosystem type. This is a complex endeavor; for example, it is an open

18 An advantage of the model is that new data made interoperable with ARIES can be readily incorporated in future analyses, offering the opportunity to generate results focusing on different temporal or spatial scales using ecosystem or region-specific data. However, the implications and interpretations of future analyses go beyond the scope of this work and are not discussed here.

19 According to the ESA-CCI land cover classification.

question in the environmental and natural capital accounting communities how forests are defined by different countries. To represent the final results, the ESA-CCI land cover classes have been grouped into six aggregated classes, each representing a generalized group of ecosystems. These classes are described in the results section.

2.1.3 Measuring the Accuracy of Results

As mentioned above, a number of limitations hinder the ability to develop uncertainty estimates for these results. One approach could propagate uncertainties associated with all the input data, but such uncertainty information is not available. Moreover, this approach could provide misleading information if user-supplied land classification systems are inconsistent with the model inputs. The same caveats apply to other data used to feed the model.

For transparency and whenever possible, information on the uncertainty of the input data was incorporated. For example, various studies note accuracy dimensions for the ESA-CCI data at 70 percent²⁰ and 82 percent.²¹

2.2 ESTIMATING SOIL ORGANIC CARBON STORAGE STOCKS

In this analysis, the latest available spatially explicit information on soil organic carbon was used. Earlier global soil carbon datasets were generated in the past, covering previous years,²² but they were produced using different methodologies, and they are not comparable or cannot be used as a time series. The incomparability of these products is due to the increasingly sophisticated machine learning methods used to estimate global soil sample databases, as well as the larger and more accurate number of Earth observation and other environmental datasets used as covariates, combined to map the spatial distribution of soil properties around the globe. For this reason, this analysis uses the most recent dataset, covering the year 2020, which is incorporated into the final results as a separate output from vegetation carbon stock, to increase the completeness of the outputs. The dataset used for this purpose is a product from [ISRIC—World Soil Information](#),²³ which includes soil carbon information at different depths, up to 200cm. The generated results account for the soil organic carbon at 30cm of depth.

Since these outputs are the best global estimates of soil organic carbon stock, they are added to the final results without any manipulation and their values are shown in addition to the vegetation carbon stock. Results are disaggregated by country, and by land cover class, but the results should be carefully interpreted, considering that the ESA-CCI layer was not an input to the model.

²⁰ https://www.esa-landcover-cci.org/?q=webfm_send/84; pp. 31–33. chapter 4.2.2 Validation results.

²¹ Annual dynamics of global land cover and its long-term changes from 1982 to 2015: Classification accuracy of the ESA-CCI European Space Agency Climate Change Initiative:

https://www.researchgate.net/figure/Classification-accuracy-of-the-ESA-CCI-European-Space-Agency-Climate-Change-Initiative_tbl3_341894401

²² [ISRIC, SOTER, and SOTWIS among others](#)

²³ <https://www.isric.org/explore/soilgrids>

3 Monetary Valuation of Carbon Retention in ARIES for SEEA

In the ecosystem services literature, the dominant approach to the monetary valuation of carbon is to apply monetary values to carbon sequestration. This is, however, problematic from an accounting perspective when ecosystems are net emitters of carbon, as this would lead to a negative service flow and hence negative production. Moreover, a strict focus on sequestration may lead to counterintuitive outcomes: for instance, old-growth ecosystems that may be near equilibrium (and hence provide relatively low or even zero sequestration) would receive low asset values, undermining the case for their conservation.

To address these issues, an alternative framing was developed for the SEEA EA revision process, focusing instead on carbon storage as the main ecosystem service. As the ecosystem service (in monetary units) would need to be expressed as an annual flow, this proposal was described as “carbon retention” to set it apart from carbon storage. Essentially, carbon retention in physical units consists of a stock of carbon in the various carbon pools (for example, aboveground biomass + belowground biomass + soil organic carbon). In monetary units, this physical stock is first multiplied by a suitable carbon price to estimate the avoided damages and subsequently turned into an annual service flow by multiplying this number by a rate of return to obtain an annuity.

While the proposal received broad support, it was also criticized for failing to account for the fact that different ecosystems vary in their risk of release, and that a focus on carbon storage would be out of touch with policy contexts that focus on (increasing)

sequestration. Eventually, a compromise was found for SEEA EA, which considers global climate regulation as a single service consisting of a sequestration and a retention component: “In principle, carbon retention and carbon sequestration components should be measured for all ecosystem assets. In practice, it is likely that different ecosystem assets will provide different contexts for measurement. In stable ecosystems, carbon retention will be the primary component while in those ecosystems where there is clear expansion in the stock of carbon, then carbon sequestration may be the focus of measurement” (NCAVES and MAIA 2022).

Arguably, for the majority of developing countries carbon retention will be the primary component, which is why this was implemented as the default in ARIES for SEEA. For the monetary valuation, one needs two key inputs: an appropriate price for each tonne of carbon retained and a discount rate.

As described in Edens et al. (2019), there are various ways to determine the price of carbon:

- An estimate based on the value of damages avoided
- The marginal costs of abatement of carbon
- Observed market prices.

As the carbon retention framing is based on the idea of avoided damages, the valuation report (NCAVES and MAIA 2022) recommends applying a social cost of carbon: “Different Tiers may be distinguished depending on the sophistication of the model used

for deriving the [social cost of carbon]. A Tier 3 approach may consist of using a national model (such as Brucknall et al. 2021). A Tier 1 approach may consist in choosing a value from the scientific literature.” The ARIES for SEEA model, as a Tier 1 approach, has opted for the latter.

While multiple studies on the social cost of carbon exist, ARIES for SEEA has opted to use a value of \$33.70 per tCO₂ based on Nordhaus (2017). The social cost of carbon measures the net present value of future damage costs calculated for a long time horizon. As ecosystem services are (annual) flows, we need to turn the avoided damage costs into an annual service flow. The ARIES for SEEA model does this based on the approach from Turpie, Forsythe, et al. (2021) by annualizing the social cost of carbon as follows:

$$ASCC = (\delta \times SCC) \times [1 - (1 + \delta)^{-t}]^{-1}$$

in which:

ASCC stands for annualized social carbon cost, δ is the discount rate, SCC stands for social carbon cost, and t is the number of years.

The default ARIES for SEEA model (inspired by Turpie, Letley, et al. 2021) applies a 3.66 percent discount rate based on Kotchen et al. (2019) and a 100-year time horizon. The price is adjusted 3 percent upward/downward for years later/earlier than 2015 (as suggested by Nordhaus 2017). For this project, the monetary value of carbon storage is expressed in constant 2020 US dollars, and discounted at a 4 percent rate over time to be consistent with CWON practices for other resource valuations.

This approach has been implemented to produce homogenous results on a global scale. This allows for direct comparison of monetary valuations across the globe, reflecting the differences in biophysical terms across years and countries. If the valuation moves to a country-specific economic valuation, considering regional markets, local economic conditions, and other social aspects, results can diverge greatly.

4 Recommendation for Future Developments and Improvements

Several developments could be considered for producing the next generation of carbon storage results for CWON. ARIES by design supports re-running of updated models that reflect improvements, incorporating updated knowledge into the platform as it becomes available.

The model currently uses default factors and approaches based on the 2006 IPCC guidelines (IPCC 2006), which is the reference officially adopted for reporting and reviewing under the international reporting framework of greenhouse gas (GHG) inventories and related information that is framed by the United Nations Framework Convention on Climate Change (UNFCCC).

However, during the 49th session of the IPCC, held in May 2019, an update of these guidelines was adopted (IPCC 2019) to incorporate more recent science-based knowledge. These guidelines, hereafter named the IPCC 2019 refinement, are expected to soon replace the 2006 IPCC guidelines as the official source of data that will govern the international reporting framework of GHG information.

To align the current model with this more recent development and to meet future users' demands, the ARIES team is collaborating with land use, land-use change, and forestry experts to update the model to reflect the 2019 IPCC refinement.

Incorporating data from the 2019 IPCC refinement into the model offers the possibility of selecting more disaggregated input data. Without losing sight of the unavoidable uncertainty associated with default factors, the new data are expected to produce more accurate results for representing

land-based conditions. In addition, using the 2019 IPCC refinement introduces several cross-cutting improvements. For instance, it allows a measurement of the uncertainty associated with certain IPCC parameters.

It should be noted that the integration of the 2019 IPCC refinement into the model will not replace the 2006 IPCC guidelines. Instead, users will have the option to choose between these two approaches depending on which is the most suitable for their purposes.

In addition, work is ongoing to produce in-house results for vegetation carbon stock estimates using the 2006 IPCC guidelines. The model intrinsically uses these guidelines, because the data produced by Gibbs and Ruesch (2008) are based on the 2006 IPCC guidelines. However, it was decided that using available expertise on land use, land-use change, and forestry to produce results by implementing the 2006 IPCC guidelines from scratch would lead to improved results. Specifically, it is expected that these refinements will:

- Avoid the uncertainty of incorporating inputs pre-processed by third parties that are prone to misinterpretation due to difficulties in tracking the entire data production process.
- Allow for verification by comparing final outcomes and the model results, and, when relevant, assist with identifying artifacts and areas for further refinement.
- Offer the possibility of providing users with transparent information on each step of the data production process.

TABLE 4.1: CARBON STRATIFICATION

CARBON STOCK (GIBBS & RUESCH 2008)	CARBON FRACTION	ROOT TO SHOOT RATIO	IPCC ABOVEGROUND BIOMASS	CARBON COMPUTED	EMISSION (+)
200	0.47	0.37	310	199.61	-731.9
193	0.47	0.37	300	193.17	-708.29
180	0.47	0.37	280	180.29	-661.071
225	0.47	0.37	350	225.37	-826.338
200	Ave	Ave	Ave	199.50	-731.5

Finally, for the sake of transparency, and without modifying the results based on using Gibbs and Ruesch (2008) inputs, disaggregated information about the calculation steps followed by the authors to derive carbon stock values will be included. Table 4.1 shows a practical example of the implementation of this development for carbon stratification.

As mentioned above, efforts are being made to include, to the extent possible, complete information of the uncertainty associated with the model inputs. This represents an important improvement that is recognized by the UNFCCC as a good practice for reporting data. However, due to the lack of data for some sources of uncertainty, and partial information for others, any attempt to propagate this uncertainty in order to measure the uncertainty of model results is deemed meaningless.

Lastly, approaches are being discussed to improve how the model treats the post-fire carbon dynamics. Although for stands that have reached maturity, it can be assumed that the carbon stock is in a steady balance over time, all the changes, either naturally or human-induced, produce dynamic effects that need to be considered. With the intention of selecting

the most reliable approach to model the effects of natural disturbances including fires, which play an important role in the carbon cycle, discussions are ongoing with experts from the SEEA EA Forest Working Group, as well as experts who developed the International Union for Conservation of Nature (IUCN) Global Ecosystem Typology.

As mentioned previously, UNSD and the World Bank also plan to reassess the monetary valuation approach.

A separate analysis of the carbon stock contribution of mangroves is also available, but it is currently not comparable with the results produced due to the different spatial resolution (level of detail of the spatial information used) and temporal scales (time period and the frequency of the observations) of this study (for more information, refer to Appendix 2). Depending on the demand for the inclusion of specific models to estimate these results, and on the availability of data, mangroves are also expected to be computed as a separate model in the future, while preserving consistency with the results obtained in this analysis.

5 Discussion of Results

The produced maps of vegetation carbon stocks are broken down by the 36 ESA-CCI land cover classes and aggregated at the country level to provide information on carbon stocks for given years and their changes over time. This section presents a summary of results for the country-level data. The figures below serve as examples of the results that can be obtained with this dataset and as inspiration for further, more in-depth analysis. All the code run to obtain the results from the vegetation carbon stock maps, the main outputs of this analysis, is also made available in this [public repository](#). Using this code, users can replicate the outcome or obtain other statistics of interest.

Since not all changes are caused by a change in the land cover data, Appendix 3 provides examples and the interpretation of changes resulting from different causes. Appendix 4 provides an overview of all the large changes observed over the time series, and for each case, describes the main drivers for that result. Whenever the change of vegetation carbon stock for a country was mainly driven by the lack of input data, this was excluded from the graph, and the next country ranking for the largest change (increase or decrease of vegetation carbon stock) was instead shown in the figure.

The last section presents the results for the soil organic carbon in 2020.

5.1 VEGETATION CARBON STOCK RESULTS AGGREGATED BY COUNTRY

Several graphs show country-level results:

- Figure 5.1A depicts the status of vegetation carbon stock, by year, at the country level
- Figure 5.1B shows the relative change of vegetation carbon stocks.

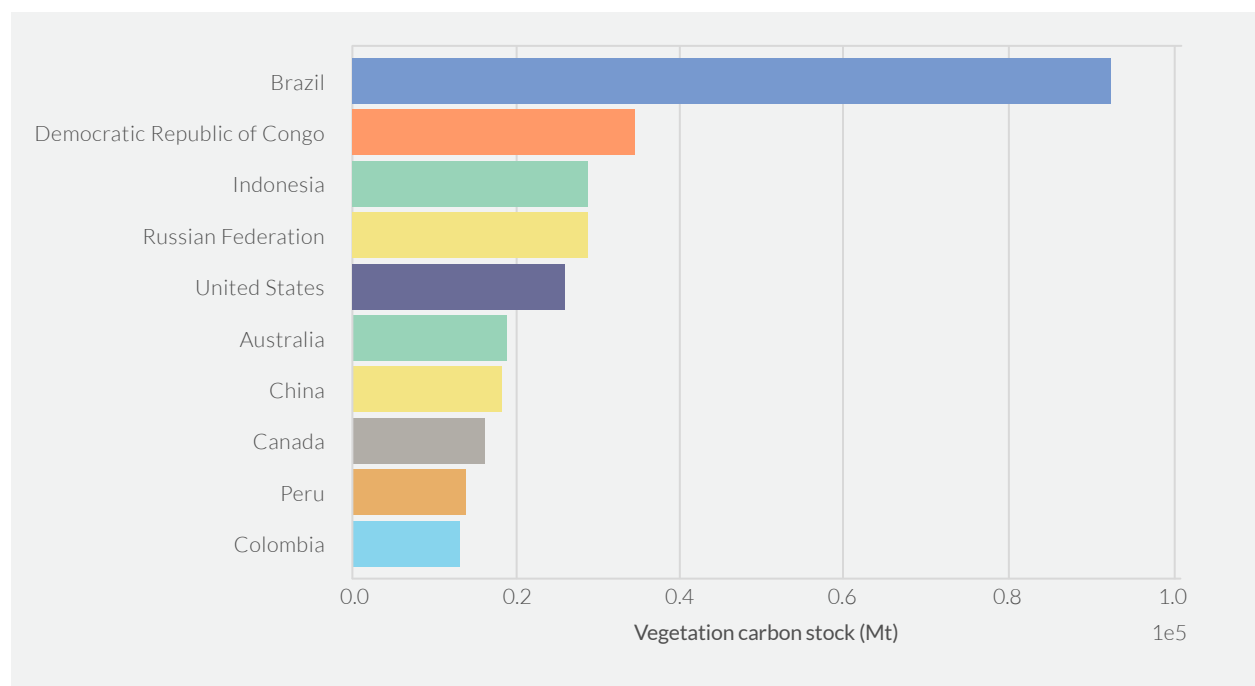
Note that the carbon stocks depicted in the map are in megatonnes, and not in tonnes per hectare, thus the absolute value of the whole country is ranked, without taking into account how large or small its area is. Intuitively, larger countries have more land area, which results in a greater capacity for carbon storage. In Figure 5.1, small countries with large carbon stock densities can thus show small carbon stocks, as seen for Ecuador and some Central African and East Asian countries. Figure 5.1B shows that most of the world's vegetation carbon stock is concentrated in large countries or tropical countries, with Brazil being both vast and tropical, accounting for almost 20 percent of the world's stock.

FIGURE 5.1A: COUNTRY-LEVEL GLOBAL MAP (MEGATONNES)

Total global vegetation carbon stock (Mt), 2020

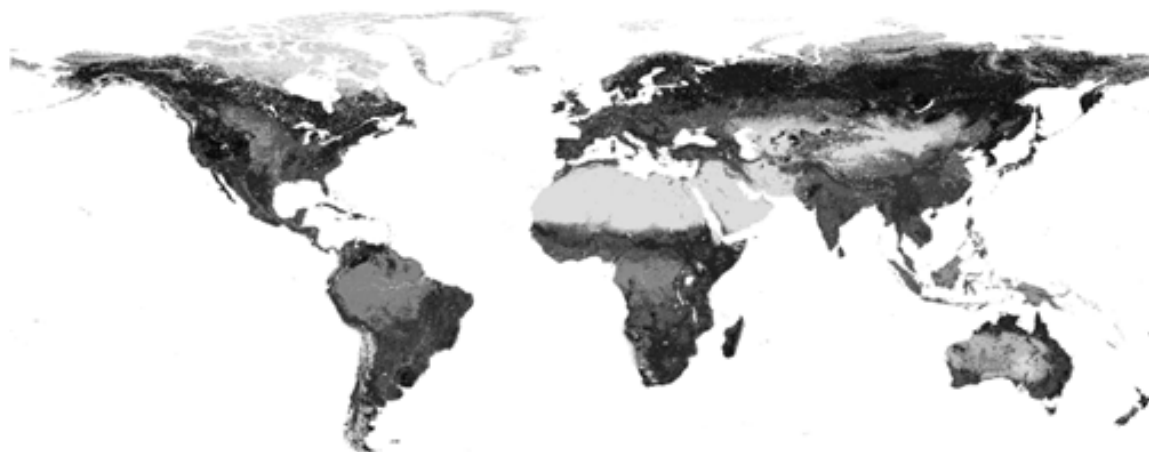
**FIGURE 5.1B:** DISTRIBUTION OF THE VEGETATION CARBON STOCK AMONG THE TOP 10 COUNTRIES

2020



It is also useful to visualize the density of the carbon regulating service provided, expressed in tonnes per hectare (as in Figure 5.2). This map can be used to identify hotspots with high carbon storage density. The map below shows the vegetation carbon density for the year 2020.

FIGURE 5.2: VEGETATION CARBON DENSITY MAP FOR 2020 (TONNES/HECTARE)



The following graphs illustrate the dynamics of vegetation carbon stock for the countries that experienced the greatest vegetation carbon stock declines and increases, in absolute terms, between 2001 and 2020. The curves of absolute change look flat because of the disparate scales of carbon stock across countries. The yearly variability is better observed in the relative change curves, as all the stocks are rescaled and their evolution from the

initial year is depicted. Four out of the five countries with the largest decrease in vegetation carbon stock are among the 10 countries with the largest stocks: Brazil, Democratic Republic of Congo, the United States, and Russia. Peru is one of the 10 countries with the largest stocks, and the only country in this group with increasing stocks. This is aligned with the global decline of vegetation carbon stock observed in the final results.

FIGURE 5.3A: TOTAL VEGETATION CARBON STOCK DECLINE BY COUNTRY (MEGATONNES)

Top 5 countries decreasing their vegetation carbon stock (Mt), 2001–2020

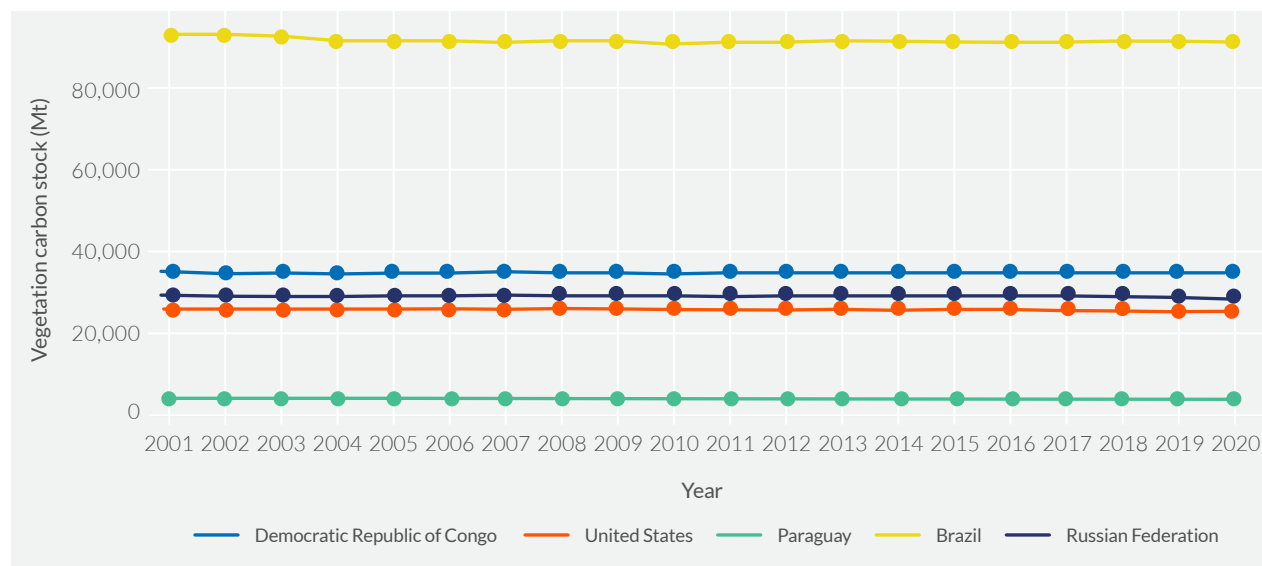
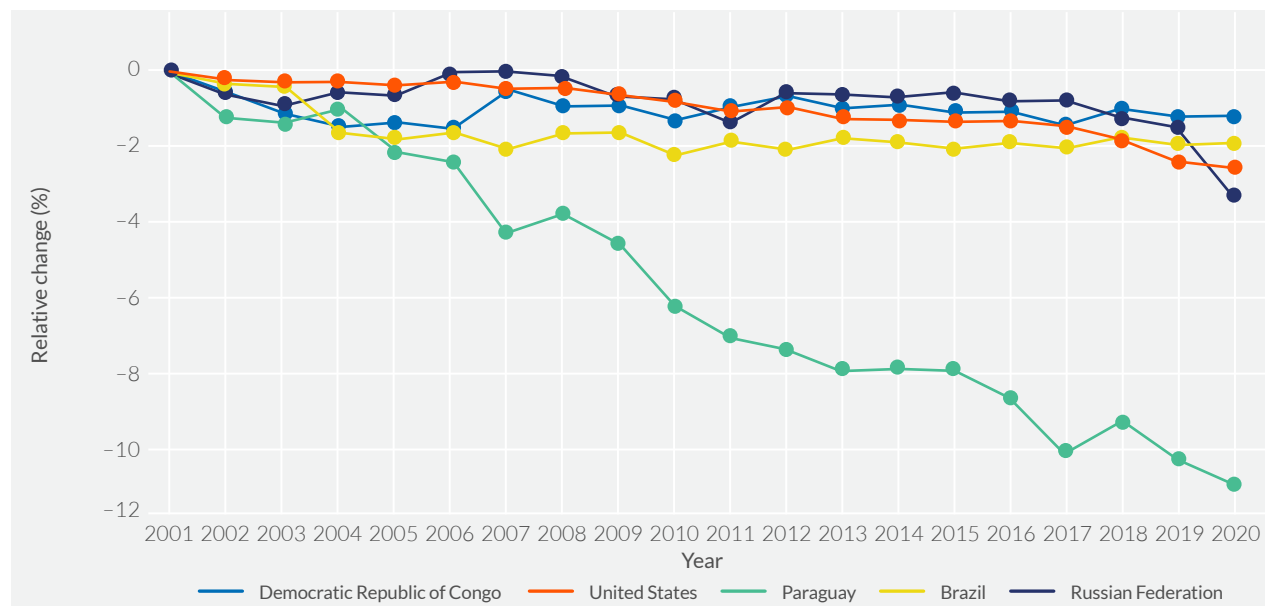


FIGURE 5.3B: TOTAL VEGETATION CARBON STOCK DECLINE BY COUNTRY (IN RELATIVE TERMS)

Top 5 countries decreasing their vegetation carbon stock (% change from 2001), 2001–2020

**FIGURE 5.3C:** TOTAL VEGETATION CARBON STOCK INCREASE BY COUNTRY (MEGATONNES)

Top 5 countries increasing their vegetation carbon stock (Mt), 2001–2020

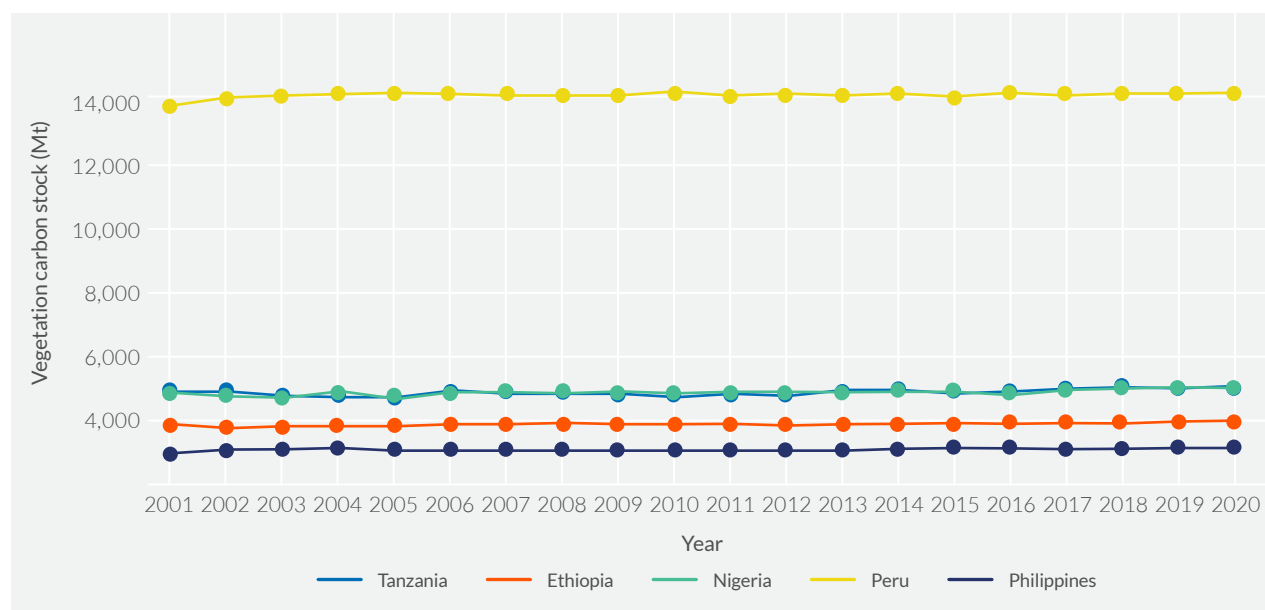
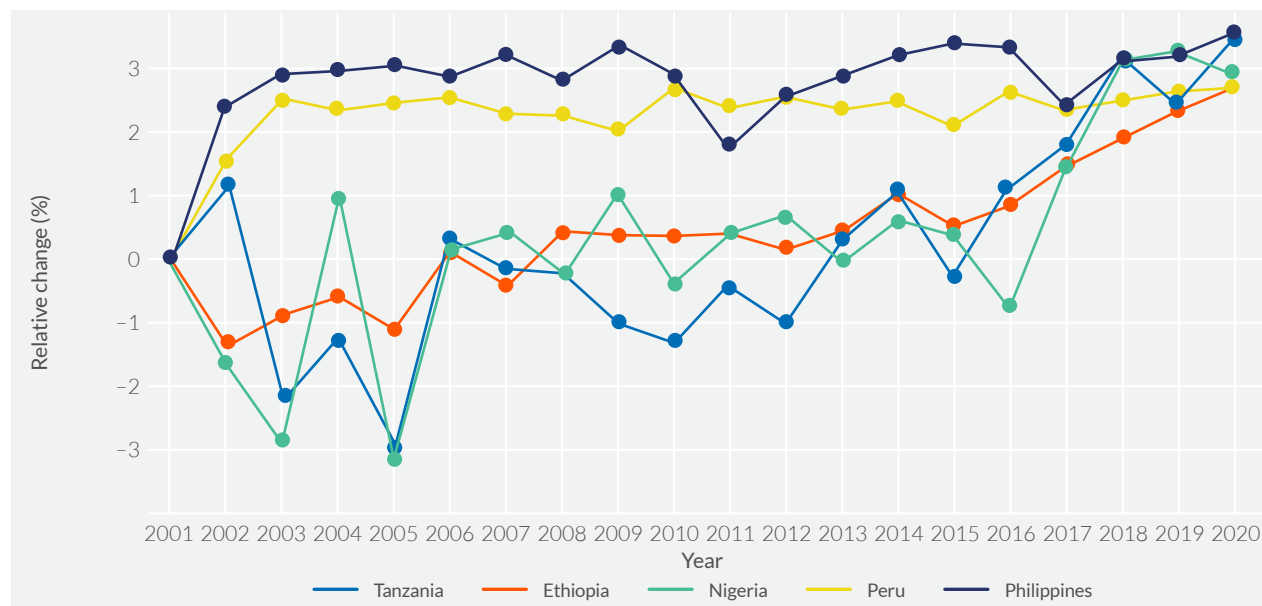


FIGURE 5.3D: TOTAL VEGETATION CARBON STOCK INCREASE BY COUNTRY (IN RELATIVE TERMS)

Top 5 countries increasing their vegetation carbon stock (% change from 2001), 2001–2020



5.2 VEGETATION CARBON STOCK RESULTS DISAGGREGATED BY LAND COVER CLASS

The results were also stratified by land cover class to observe the contribution of each individual class to the vegetation carbon stock.

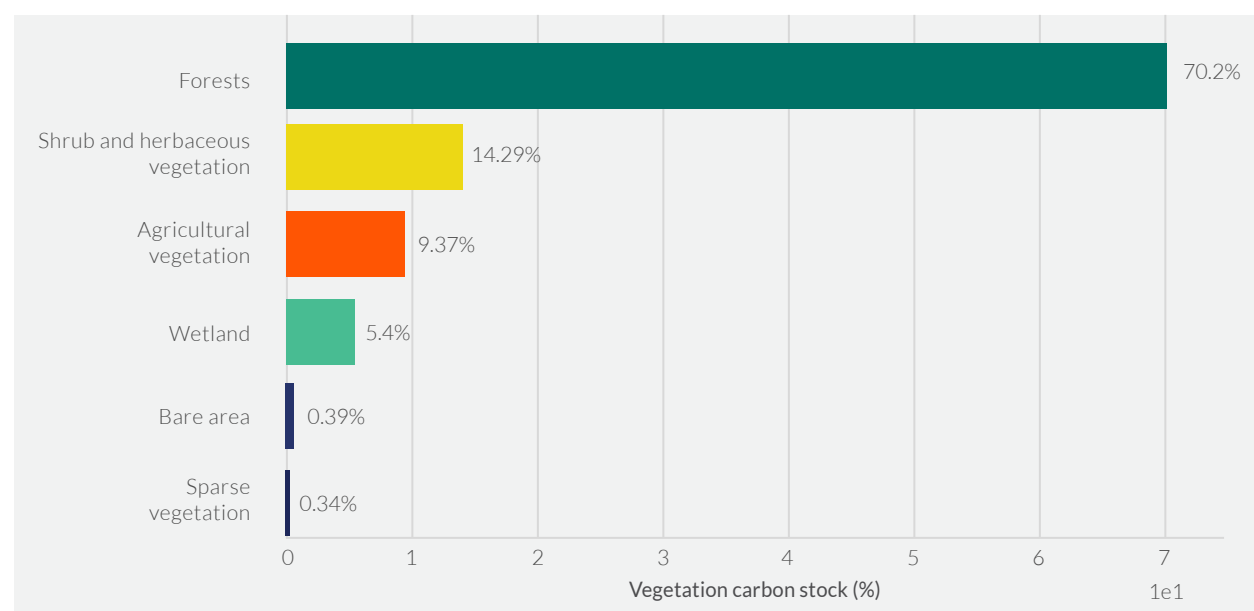
Since the classification of land cover contains 36 classes, which would be cumbersome to visualize, we grouped those into six aggregated classes:

- Agricultural vegetation
- Forest
- Shrub and herbaceous vegetation
- Wetland
- Sparse vegetation
- Bare area.

While artificial surfaces, waterbodies, and permanent snow and ice do not contribute to vegetation carbon storage, the other aggregated classes' contribution over the time series is summarized below. As expected, forest ecosystems are the greatest contributor to global vegetation carbon stocks, accounting for more than 70 percent. Shrub and herbaceous vegetation, which includes grasslands, shrublands, and savannas, accounts for about 14 percent of vegetation carbon stock. Agricultural vegetation covers an extensive area, but its carbon density is much lower, and accounts for about 9 percent. Wetlands are ranked fourth for contribution, accounting for about 5 percent of vegetation carbon stock. Wetland carbon stocks are substantially greater when also accounting for soil organic carbon, which is an important part of wetland carbon stocks. Sparse vegetation and bare area contribute less than 0.5 percent each.

TABLE 5.1: RELATIVE CONTRIBUTION TO VEGETATION CARBON STOCK BY AGGREGATED CLASS OVER THE WHOLE TIME SERIES (2001–2020 TOTAL VEGETATION CARBON STOCK)

AGGREGATED CLASSES	CONTRIBUTION TO GLOBAL VEGETATION CARBON STOCK (%)
Forest	70.50%
Shrub and herbaceous vegetation	14.18%
Agricultural vegetation	9.29%
Wetland	5.31%
Bare area	0.40%
Sparse vegetation	0.33%
Artificial surface	0.00%
Waterbody	0.00%
Permanent snow and ice	0.00%

FIGURE 5.4: DISTRIBUTION OF VEGETATION CARBON (%) IN 2020

The relative contribution of the vegetation carbon stock of the aggregated classes is described in the following sections, which analyze class-level changes in greater detail. Overall, from 2001 to 2020, forest vegetation carbon stocks decrease, while shrub and herbaceous vegetation and agricultural vegetation stocks increase, but not by enough to compensate for forest carbon stock declines. The distribution across categories, though, stays relatively stable over the time series, and only small changes, in relative terms, are observed.

5.2.1 Forest Vegetation Carbon Stock

In the following figure, the vertical scale, representing the vegetation carbon stock, has been compressed to focus on the interval between the maximum and minimum values observed in the time series, so that the bars are not completely flat.

FIGURE 5.5A: FOREST GLOBAL VEGETATION CARBON STOCK (MEGATONNES)

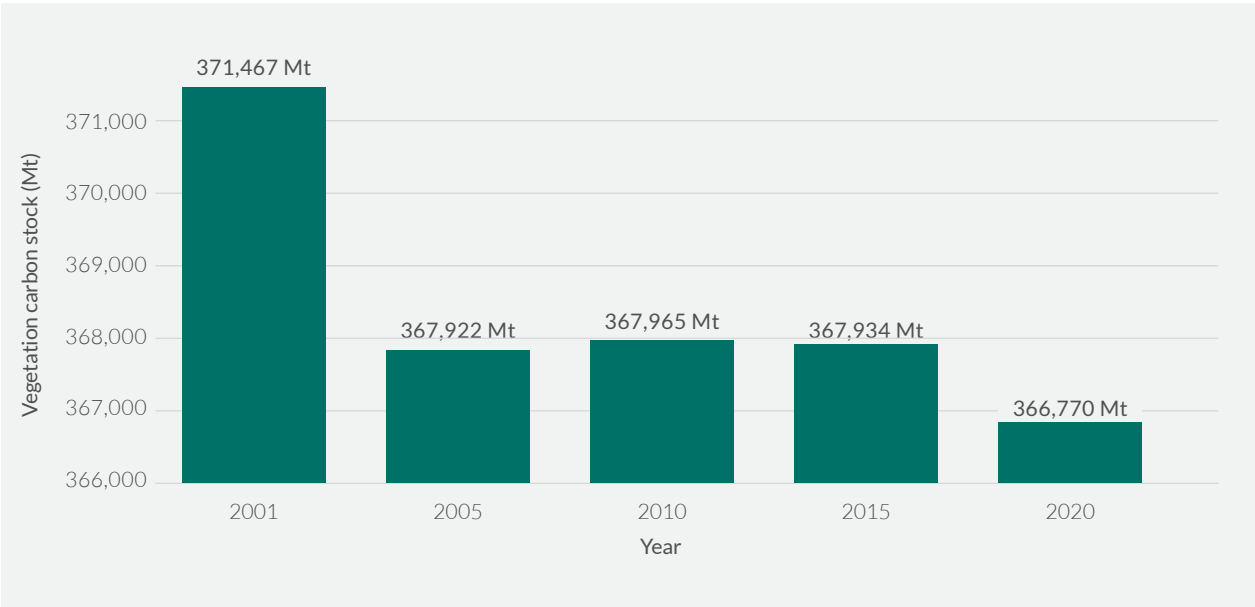
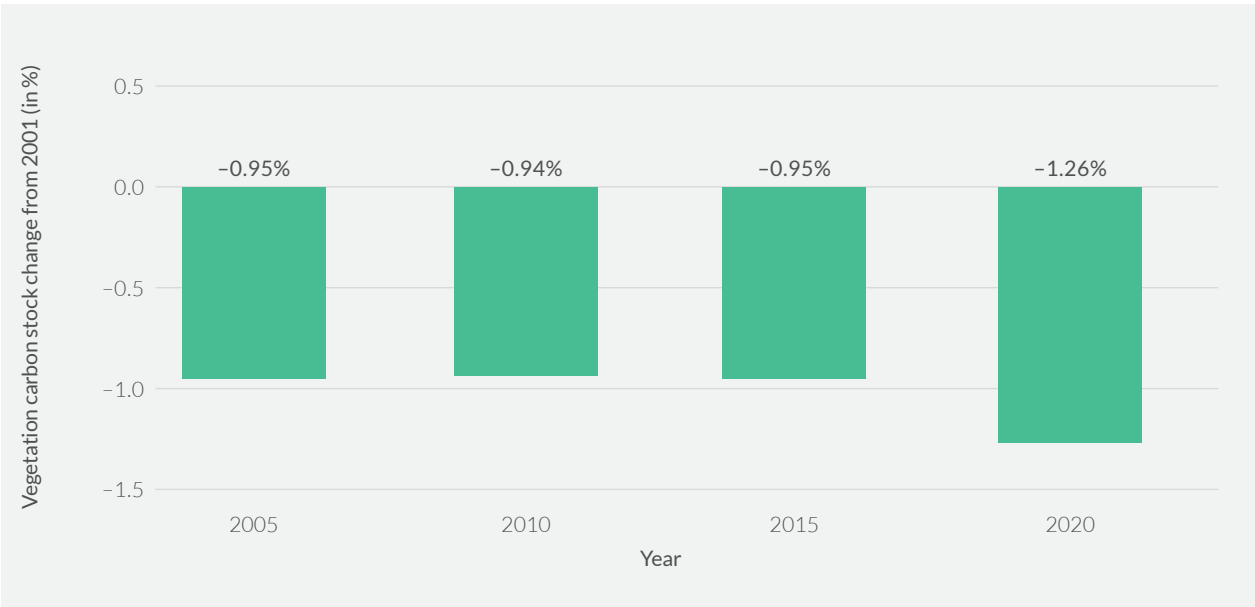


FIGURE 5.5B: FOREST GLOBAL VEGETATION CARBON STOCK (%)



The global forest vegetation carbon stock decreased by almost 1.3 percent over the period analyzed. The greatest decline occurred from 2001 to 2005. Global forest carbon stocks stayed relatively constant from 2005 to 2015 before declining further from 2015 to 2020.

FIGURE 5.5C: CONTRIBUTION TO FOREST GLOBAL VEGETATION CARBON STOCKS FOR 2001–2020 (MEGATONNES)

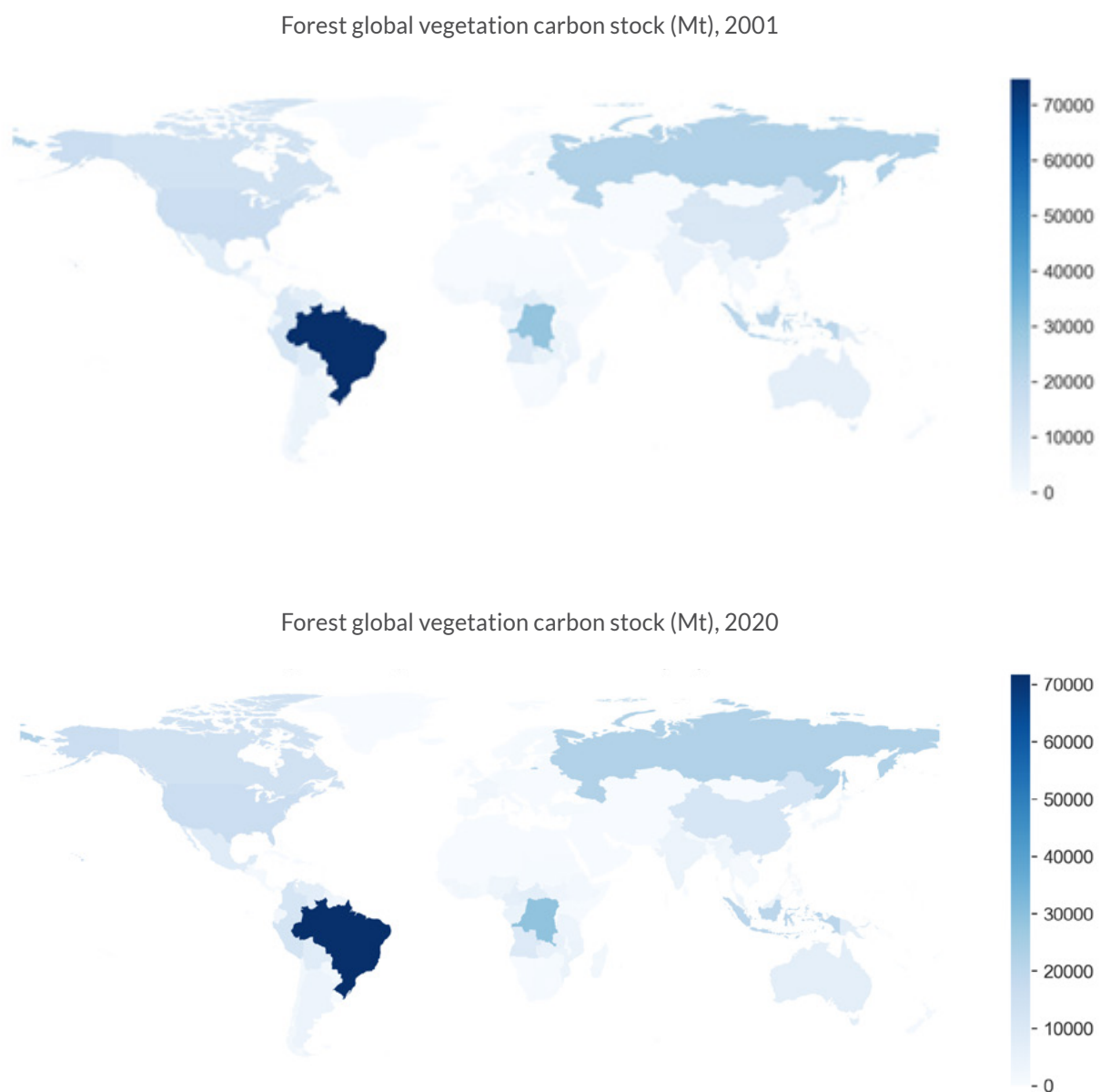


FIGURE 5.5D: FOREST VEGETATION CARBON STOCK DECLINE BY COUNTRY (MEGATONNES)

Top 5 countries decreasing their forest vegetation carbon stock (Mt), 2001–2020

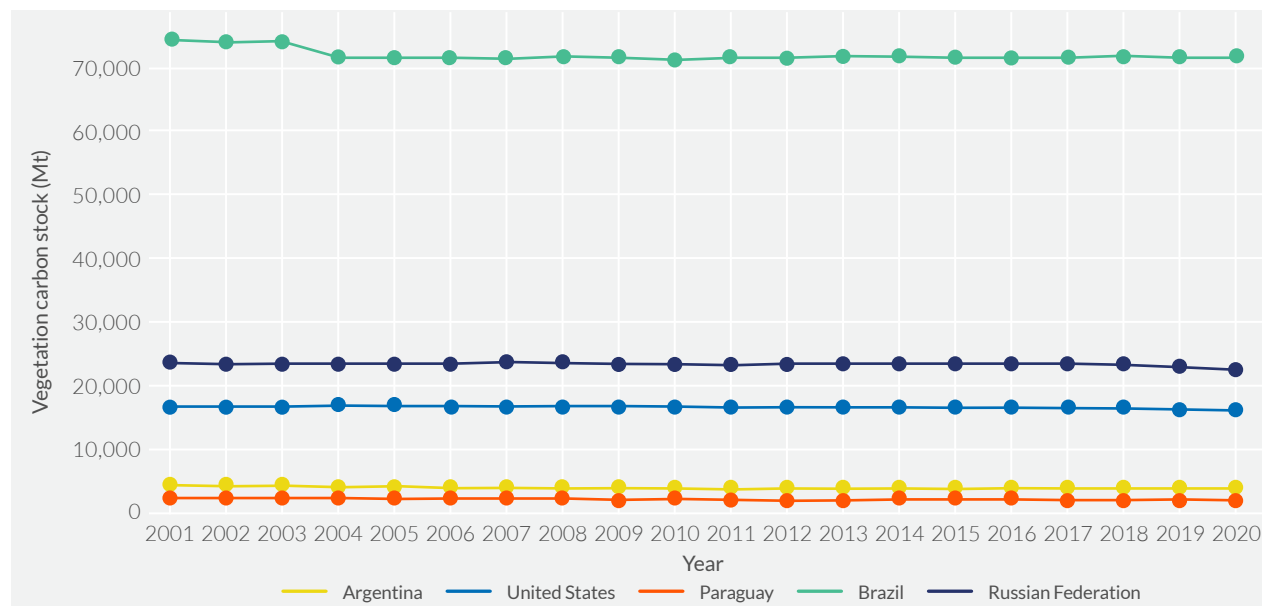
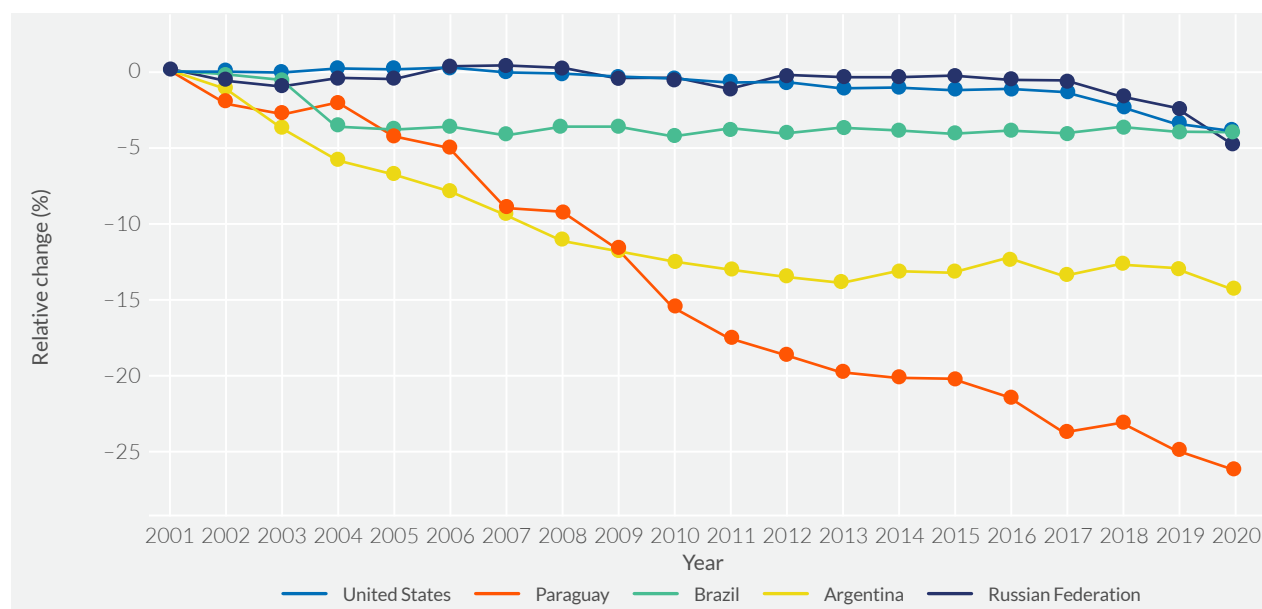


FIGURE 5.5E: FOREST VEGETATION CARBON STOCK DECLINE BY COUNTRY (IN RELATIVE TERMS)

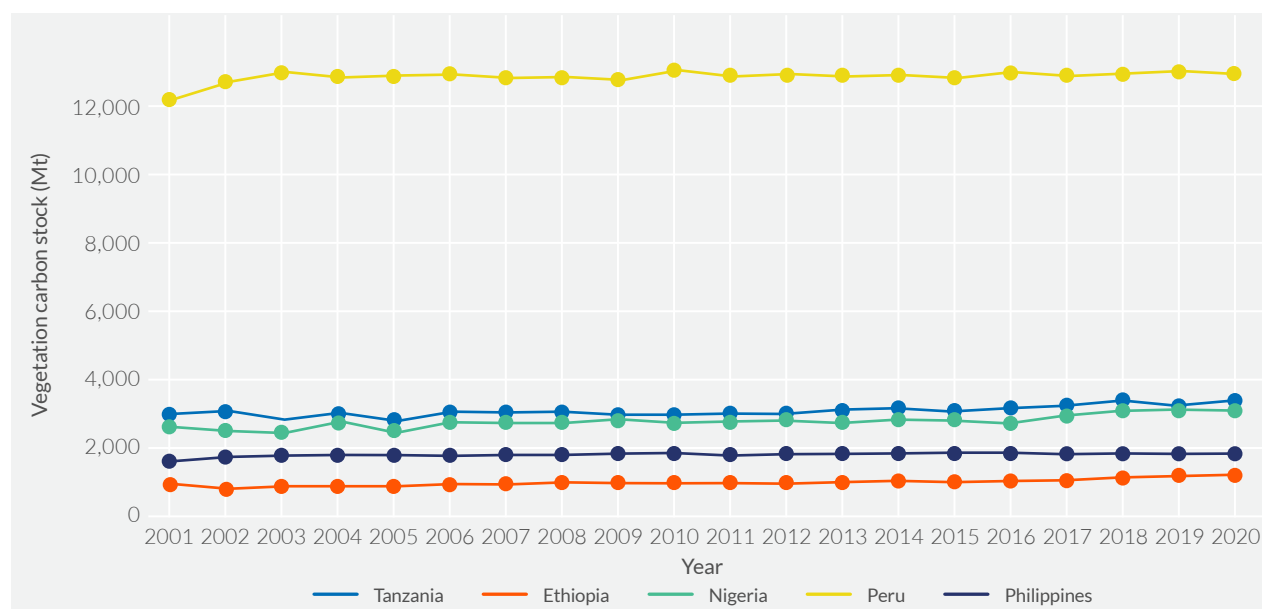
Top 5 countries decreasing their forest vegetation carbon stock (% change from 2001), 2001–2020



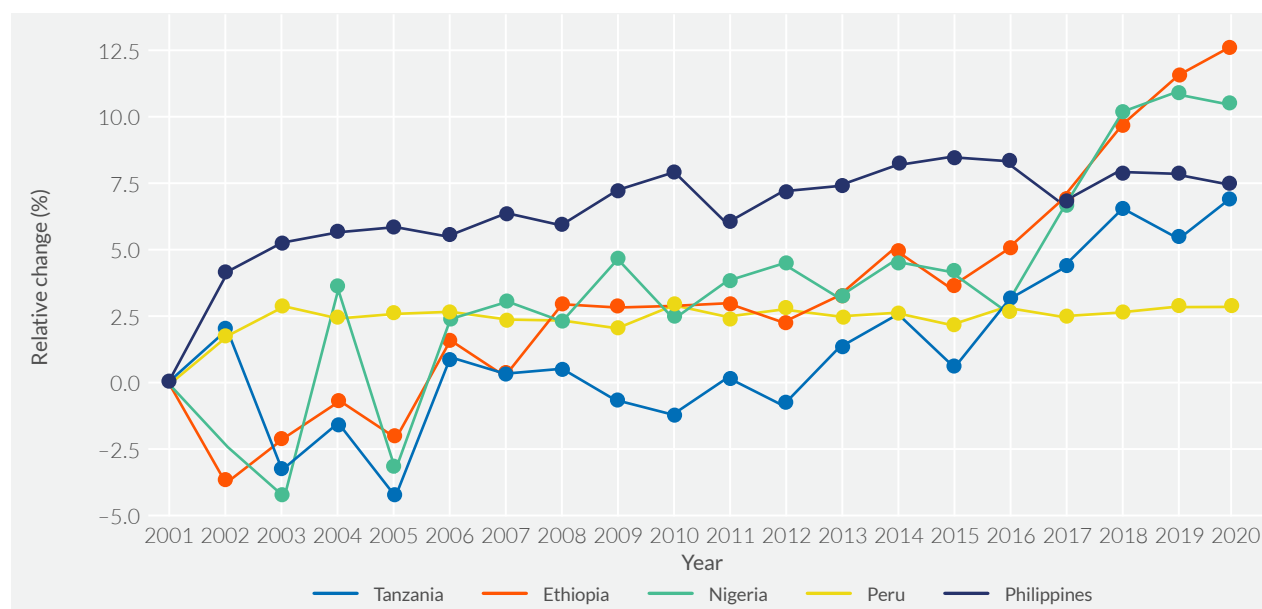
Aside from Argentina, all countries recording the largest declines of forest vegetation carbon stocks also experienced the greatest declines in total vegetation carbon stocks. This shows the importance of forests for vegetation carbon storage.

FIGURE 5.5F: FOREST VEGETATION CARBON STOCK INCREASE BY COUNTRY (MEGATONNES)

Top 5 countries increasing their forest vegetation carbon stock (Mt), 2001–2020

**FIGURE 5.5G:** FOREST VEGETATION CARBON STOCK INCREASE BY COUNTRY (IN RELATIVE TERMS)

Top 5 countries increasing their forest vegetation carbon stock (% change from 2001), 2001–2020



Collectively, Figures 5.3 and 5.5 show that deforestation is the main driver of global vegetation carbon stock loss. As shown in the next section, agricultural and shrub and herbaceous vegetation areas and carbon storage increased from 2001 to 2020, suggesting that these expansions come at the expense of forests.

5.2.2 Shrub and Herbaceous Vegetation Carbon Stock

In the following figure, the vertical scale, representing the vegetation carbon stock, has been compressed to focus on the interval between the maximum and minimum values observed in the

time series, so that the bars are not completely flat.

Figure 5.6A shows a clear trend of constant growth for the carbon stored in shrub and herbaceous vegetation, which increased by slightly less than 1,000 megatonnes, or about 1.35 percent of its initial value in 2001.

FIGURE 5.6A: SHRUB AND HERBACEOUS GLOBAL VEGETATION CARBON STOCK (MEGATONNES)

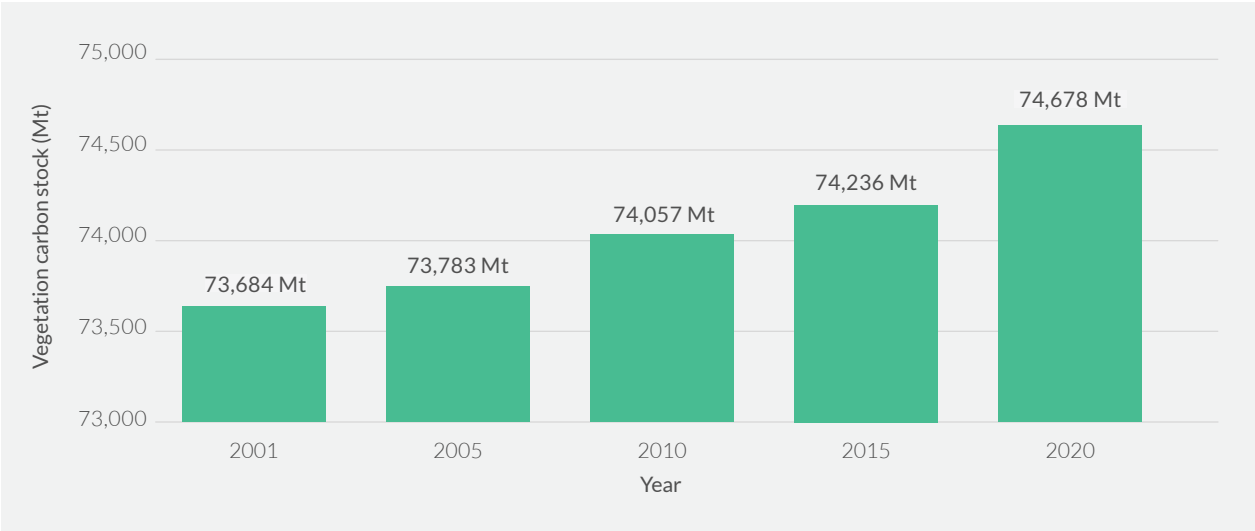
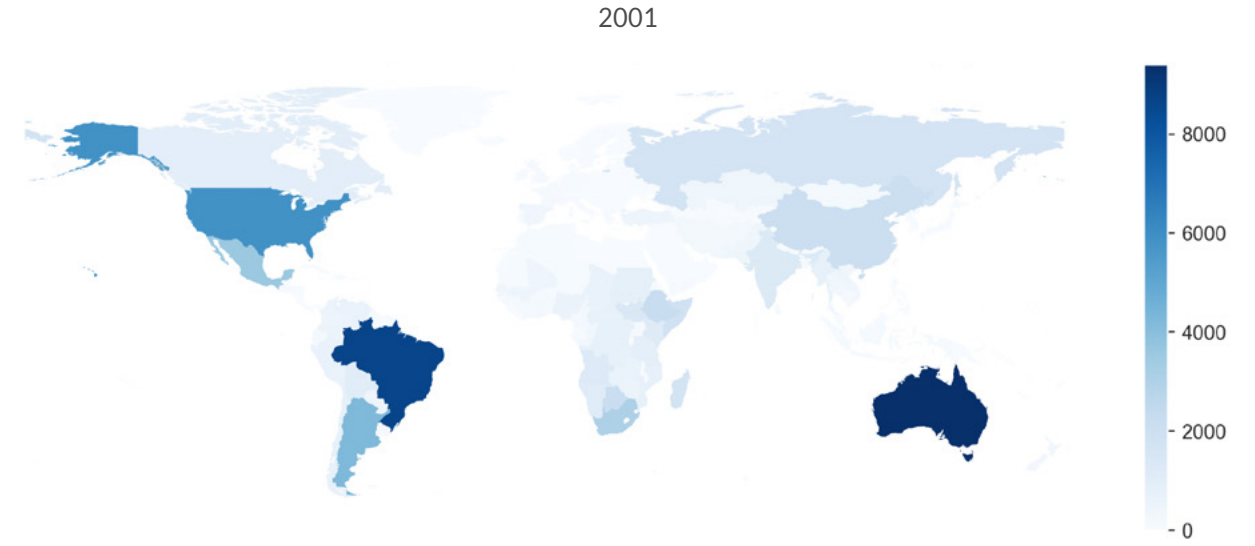


FIGURE 5.6B: SHRUB AND HERBACEOUS GLOBAL VEGETATION CARBON STOCK (MEGATONNES)



A land cover transitional analysis could correctly determine which shrub and herbaceous vegetation expansion has net positive and negative effects on total global vegetation carbon stocks. One must determine which land cover type replaces another in order to interpret the results of changes in the overall carbon stock. As mentioned at the end of the previous section, a positive overall increase in vegetation carbon stock only occurs when the expansion of shrub and herbaceous vegetation

does not replace forests. Because shrub and herbaceous vegetation is largely replacing forests, the above results contribute to an overall decrease of vegetation carbon stock.

Different countries contribute to the vegetation carbon stock for shrub and herbaceous vegetation, notably Australia, Mexico, Argentina, as well as countries in Sub-Saharan Africa and in the Eastern Asia region.

FIGURE 5.6C: CONTRIBUTION TO SHRUB AND HERBACEOUS GLOBAL VEGETATION CARBON STOCK (MEGATONNES)

2020



5.2.3 Agricultural Vegetation Carbon Stock

In the following figure, the vertical scale, representing the vegetation carbon stock, has been compressed to focus on the interval between the maximum and minimum values observed in the time series, so that the bars are not completely flat.

Agricultural vegetation carbon stocks increased globally by about 2 percent or almost 1,000 megatonnes, with nearly all this change occurring between 2001 and 2005. Agricultural vegetation carbon stocks by country are shown in Figures 5.7C–7E.

FIGURE 5.7A: AGRICULTURAL GLOBAL VEGETATION CARBON STOCK (MEGATONNES)

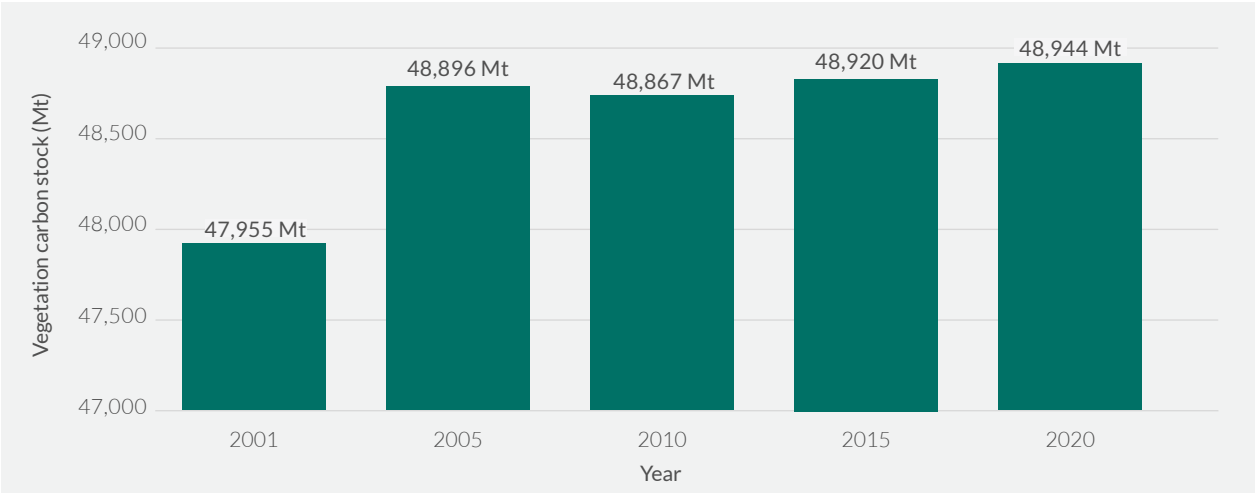


FIGURE 5.7B: AGRICULTURAL GLOBAL VEGETATION CARBON STOCK (%)

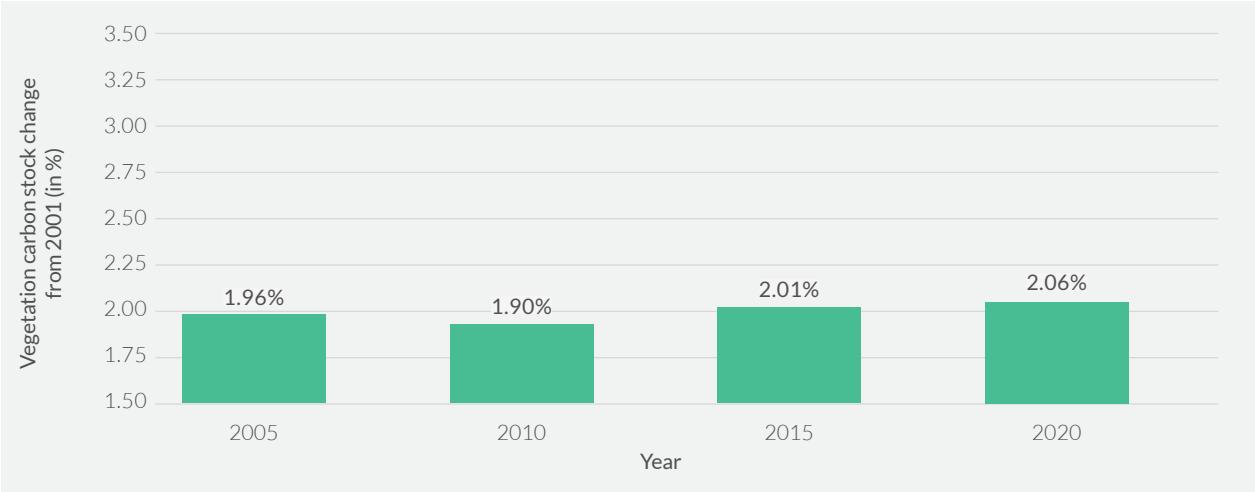


FIGURE 5.7C: CONTRIBUTION TO AGRICULTURAL VEGETATION CARBON STOCK (MEGATONNES)

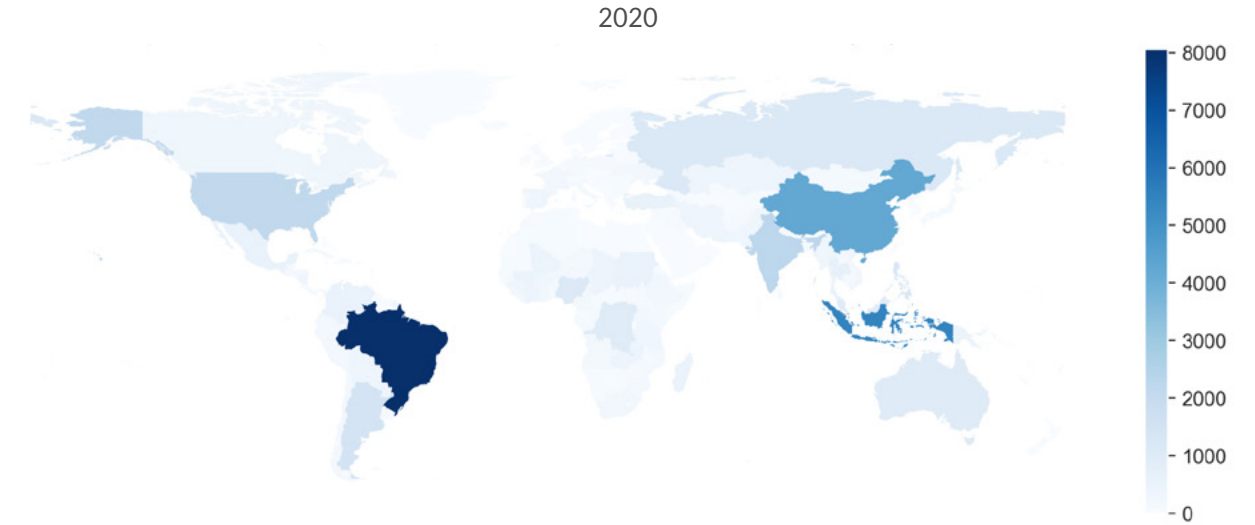
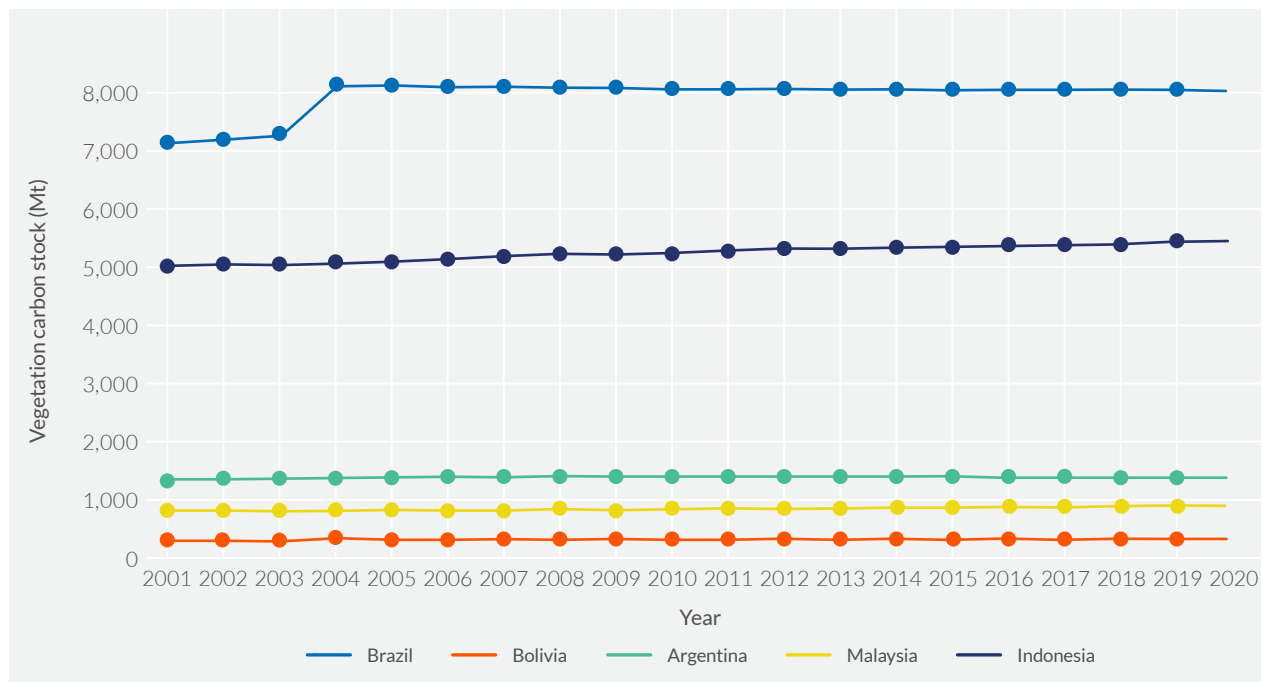
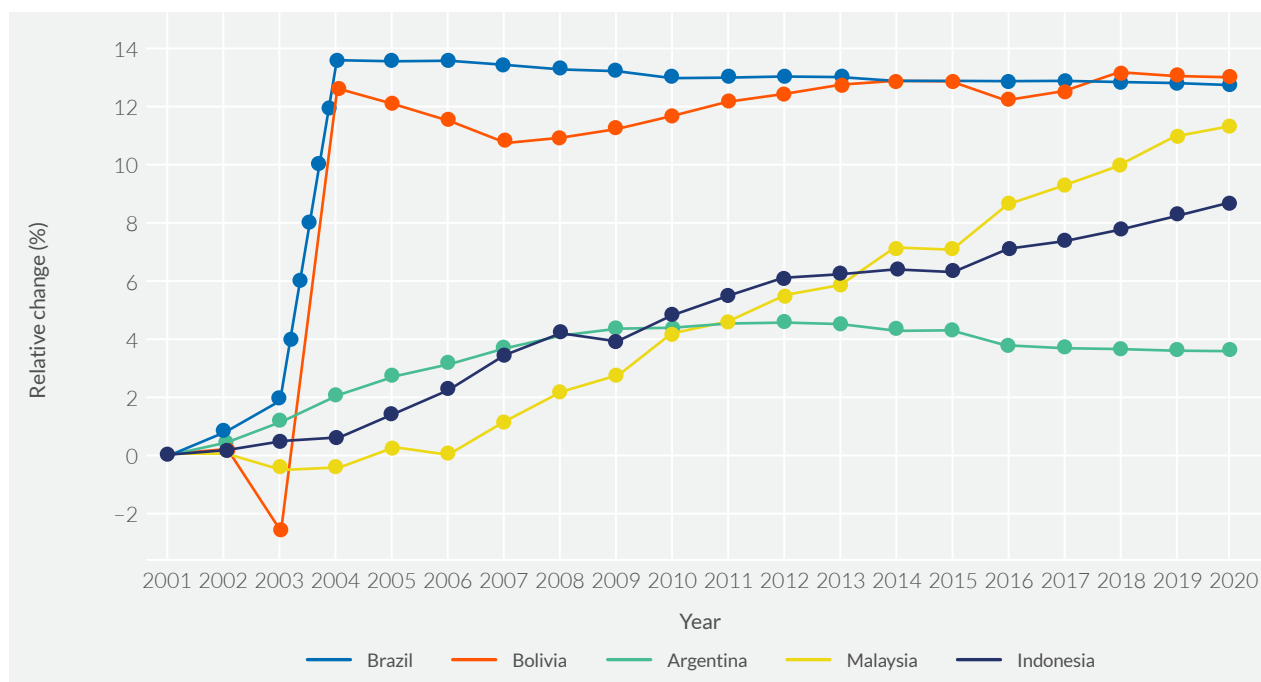


FIGURE 5.7D: AGRICULTURAL VEGETATION CARBON STOCK INCREASE BY COUNTRY (MEGATONNES)

Top 5 countries increasing their agricultural vegetation carbon stock (Mt), 2001–2020

**FIGURE 5.7E:** AGRICULTURAL VEGETATION CARBON STOCK INCREASE BY COUNTRY (IN RELATIVE TERMS)

Top 5 countries increasing their agricultural vegetation carbon stock (% change from 2001), 2001–2020



Intuitively, agricultural vegetation carbon stock increases are usually associated with decreases in the total vegetation carbon stock, because agricultural expansion comes at the expense of land cover types with greater per-area carbon storage. This is clear for the case of Brazil when analyzing graphs of the total decrease of carbon vegetation and the increase of agricultural vegetation. The drop in the first graph, representing forest carbon storage, takes place over the period 2002–2003, the same period in which the latter, illustrating agricultural carbon storage, increases significantly. This is also the case for Bolivia, where a similar trend occurs from 2002 to 2003. Although Bolivia does not rank among the top countries for total vegetation

carbon stock declines, it had the same pattern as Brazil: the extent of agricultural land increased by 10 percent, while agricultural carbon increased by 16 percent. However, agricultural carbon only accounts for about 3 percent of the total carbon stock in the country, and this increase, estimated at 0.5 megatonnes, did not offset the total vegetation carbon stock loss in that year, which was estimated at 1.3 megatonnes.

The opposite effect is observed when natural vegetation replaces agricultural vegetation, which usually stores greater carbon content. So a reduction in this aggregated class can also contribute to an increase in the overall level of vegetation carbon

TABLE 5.2: AGRICULTURAL CARBON STOCK ANALYSIS FOR BOLIVIA OVER THE PERIOD 2002–2003

CARBON STORAGE (t)	MOSAIC NATURAL VEGETATION	MOSAIC CROPLAND	CROPLAND	HERBACEOUS COVER	TREE OR SHRUB COVER	TOTAL AGRICULTURAL CARBON STOCK	TOTAL CARBON STOCK
Year 2003	1,195,260	1,802,835	44,915	127,260	10	3,170,279	106,963,909
Year 2004	1,310,846	2,179,271	52,445	128,545	15	3,671,122	105,633,346
Net change	115,587	376,437	7,530	1,285	5	500,843	-1,330,563
% change	10%	21%	17%	1%	50%	16%	-1%

AREA (km ²)	MOSAIC NATURAL VEGETATION	MOSAIC CROPLAND	CROPLAND	HERBACEOUS COVER	TREE OR SHRUB COVER	TOTAL
Year 2003	15,771.94	21,846.96	8,645.92	24,484.76	1.93	70,751.51
Year 2004	17,088.51	26,019.14	10,103.22	24,732.96	2.9	77,946.73
Net change	1,316.57	4,172.18	1,457.31	248.2	0.97	7,195.23
% change	8%	19%	17%	1%	50%	10%
Vegetation carbon storage density (t/ha)	88	90	5	5	5	

stock. Clearly, a reduction of agricultural carbon stock substituted by the other aggregate classes, such as artificial surface (urbanization) or bare area (desertification), has an even more severe

effect on the overall vegetation carbon stock, since the already relatively low carbon stored in crops disappears completely without being replaced by any type of vegetation.

FIGURE 5.7F: AGRICULTURAL VEGETATION CARBON STOCK DECLINE BY COUNTRY (MEGATONNES)

Top 5 countries decreasing their agricultural vegetation carbon stock (Mt), 2001–2020

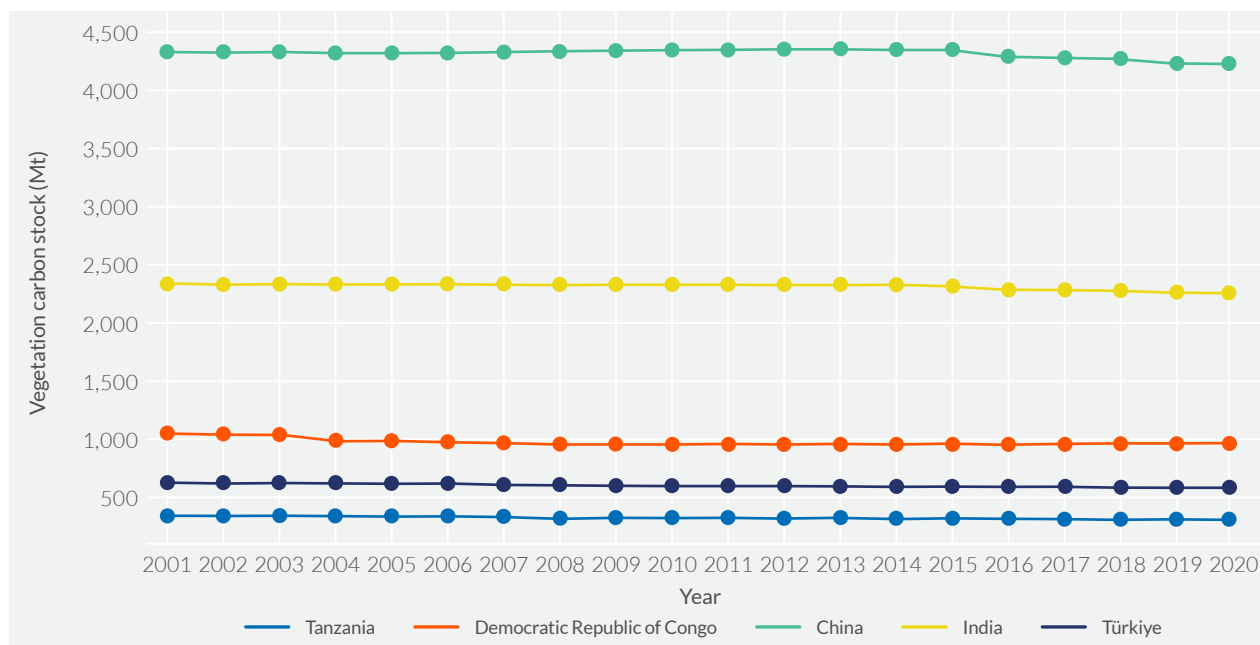
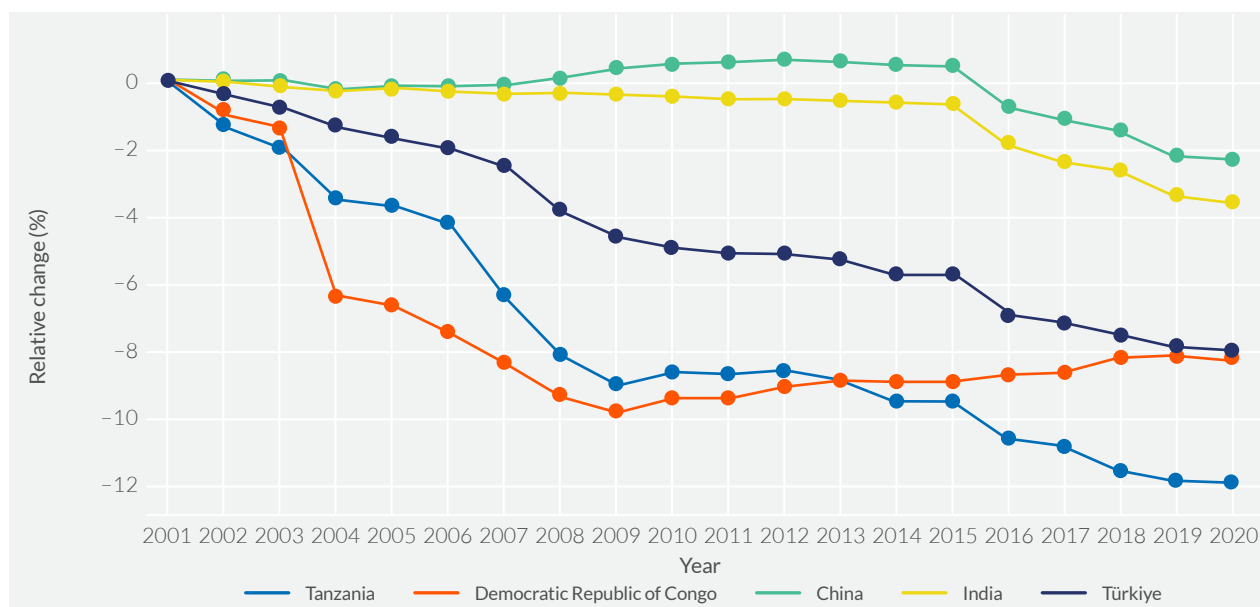


FIGURE 5.7G: AGRICULTURAL VEGETATION CARBON STOCK DECLINE BY COUNTRY (IN RELATIVE TERMS)

Top 5 countries decreasing their agricultural vegetation carbon stock (% change from 2001), 2001–2020



5.2.4 Wetland Vegetation Carbon Stock

In the following figure, the vertical scale, representing the vegetation carbon stock, has been compressed to focus on the interval between the maximum and minimum values observed in the time series, so that the bars are not completely flat.

Wetland vegetation carbon stock does not show

clear temporal trends globally. Carbon stocks were stable from 2000 to 2005 and 2010 to 2015, declined from 2005 to 2010, and increased from 2015 to 2020. This could indicate ecosystem recovery in recent years or accuracy issues in detecting wetlands at global scales. Future work can shed further light on the evolution of wetland vegetation carbon stocks at the global scale.

FIGURE 5.8A: WETLAND GLOBAL VEGETATION CARBON STOCK (MEGATONNES)

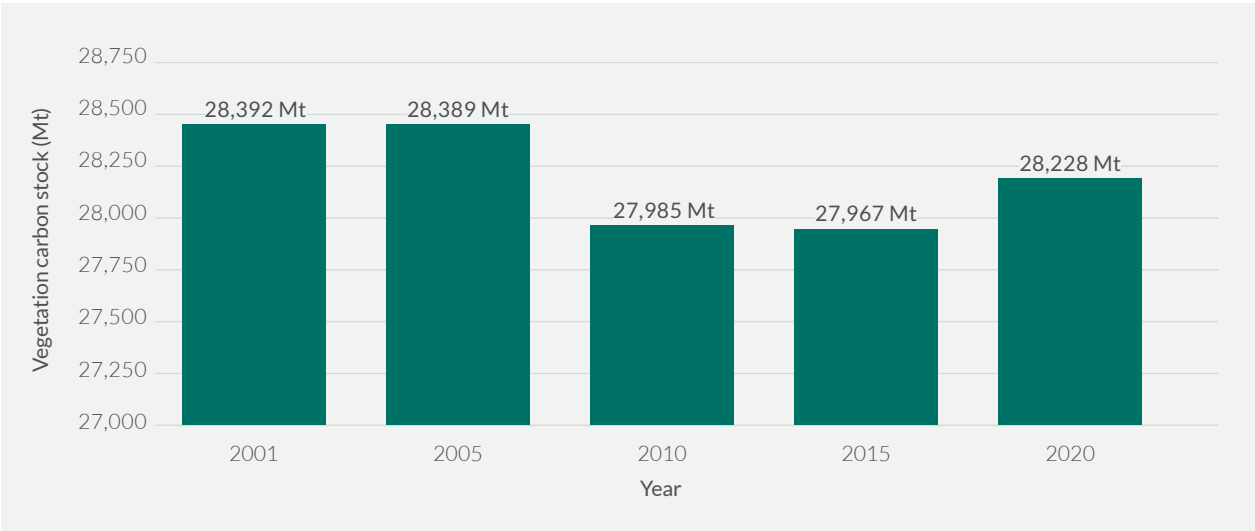
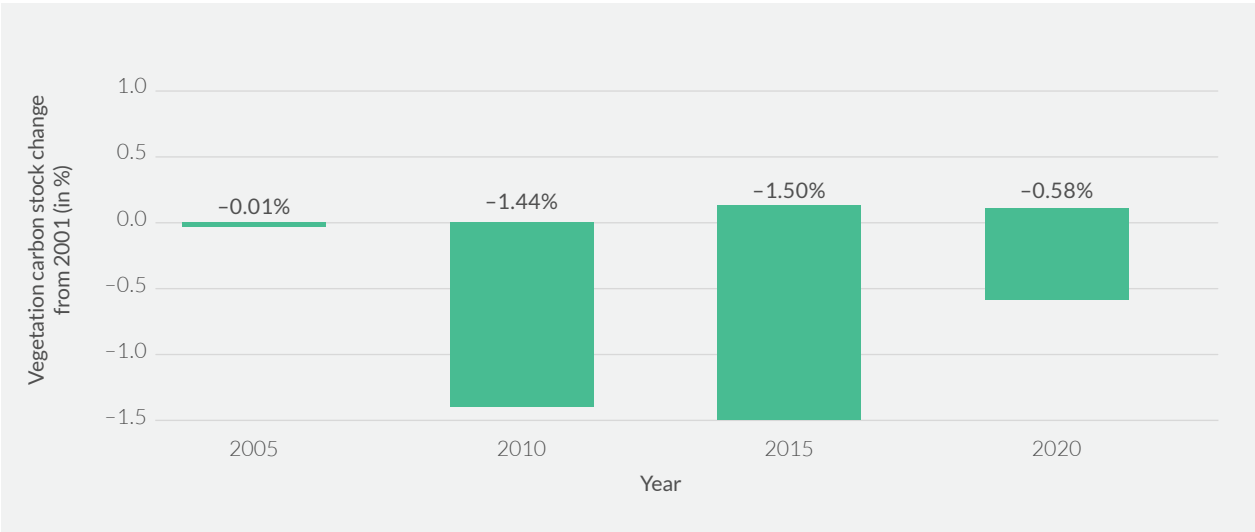


FIGURE 5.8B: WETLAND GLOBAL VEGETATION CARBON STOCK (%)

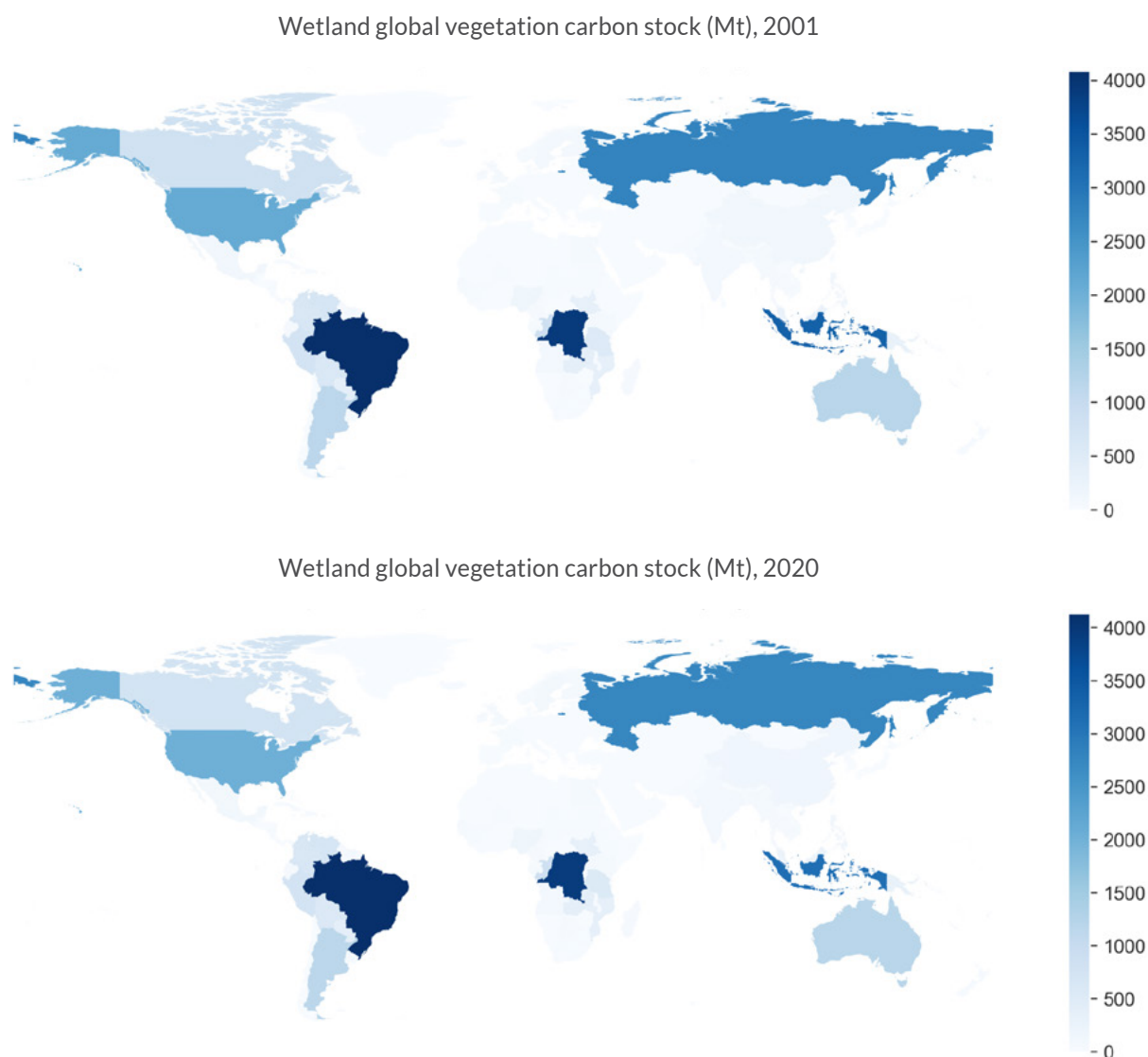


Over the entire period, there is a loss of about 0.6 percent from the 2001 vegetation carbon stock level to the 2020 level. An increase or decrease of this size should have a straightforward positive or negative impact on the overall vegetation carbon stock.

Notably, the above results exclude the contribution to the carbon stock from soil organic carbon, which accumulates greatly in the wetland subsoil and plays an important role in global carbon stocks. The accumulation is caused by sediment trapping

by wetland vegetation roots and rhizomes. Such matter decomposes slowly due to anaerobic and poorly drained wetland soils. Thus, this category contributes more significantly to the total carbon stock, but the vegetation carbon model does not capture this effect. The next generation of carbon stock models could account specifically for this phenomenon, completing the information on soil organic carbon, and increasing figures for wetlands, which are underestimated when only considering vegetation carbon stock.

FIGURE 5.8C: CONTRIBUTION TO WETLAND GLOBAL VEGETATION FOR 2001–2020



5.3 SOIL ORGANIC CARBON RESULTS DISAGGREGATED BY LAND COVER CLASS

The results for soil organic carbon in 2020, disaggregated by land cover class, are produced as additional information to this work. Since there are no data available to produce a long time series, the most recent results, obtained using the best techniques, are summarized in the tables <https://data.integratedmodelling.org/dataset/soil-organic-carbon-stock-2020>.

The disaggregation by land cover class has been obtained by superimposing the soil organic carbon and the 2020 ESA-CCI land cover maps. The latter map (ESA-CCI dataset) was used as a geographical reference to identify which land cover class would correspond to carbon stocks in the soil organic carbon, but since the two products superimposed

are inherently different and unrelated, these results must be carefully interpreted. Inconsistencies are expected due to the very different geographical scales and the methodologies used to build them. While soil organic carbon has been estimated by interpolating soil samples collected on the ground, the ESA-CCI dataset is being obtained from the interpretation of satellite images. Moreover, the ESA-CCI land cover map is not a source of information used in computing soil organic carbon, whereas it was a primary input in the computation of the vegetation carbon stock.

Nevertheless, the disaggregation of this map can provide useful information when correctly interpreted, and the results of the aggregation of all land cover classes' contributions to soil organic carbon for a country can more confidently be considered the correct estimates for that region.

6 Comparative Assessment of Vegetation Carbon Stock Results

6.1 INTRODUCTION

In line with the good practices from the 2006 IPCC guidelines (volume 1, chapter 6) on implementing quality assurance, quality control, and verification, this section provides a comparative assessment of model results with country-specific information. The IPCC recognizes: “Discrepancies between alternative methods do not necessarily imply that the inventory data are in error. When analyzing discrepancies, it is important to consider that there may be large uncertainties associated with the alternative calculations themselves.”

This section, which presents the results of the comparative assessment, aims to:

- Enhance the understanding of the model's outputs
- Identify potential areas for future improvement
- Contribute to future developments in the monitoring, reporting, and verification of emissions and removals from the land-based sector.

Model results were compared with publicly available country-specific forest-related information included in submissions by countries under international reporting frameworks. In addition to the quality assurance and quality control procedures implemented by the countries before submitting

their information, national submissions undergo expert reviews or technical assessments before the international reporting frameworks make the country submissions publicly available.

For developing countries, the comparative assessment used information included in the last submission of forest reference emissions levels under the UN REDD+²⁴ program. For developed countries, the main data source was the latest GHG inventory submission under the UNFCCC.²⁵ Moreover, information from FAO's Global Forest Resources Assessments²⁶ was used in the comparison for certain parameters or used as an auxiliary data source when the other sources lacked information needed for the comparison.

The assessment focuses on four countries: Gabon, Mexico, Finland, and Papua New Guinea. These countries were selected based on the availability of country-specific data under the international reporting frameworks (with a view to covering different ecoregions) and reporting capacities. Attention was also given to two criteria: country area and degree of forest heterogeneity.²⁷ The use of these criteria is intended to facilitate the understanding of the effects, and potential artifacts, that the country area and different forest types considered in national submissions might have on the data comparison.

²⁴ <https://redd.unfccc.int>

²⁵ <https://unfccc.int/ghg-inventories-annex-i-parties/2022>

²⁶ <https://www.fao.org/forest-resources-assessment/fra-2020/country-reports/en/>

²⁷ Based on expert judgement.

Despite the attempt to minimize artifacts, the impact of some elements cannot be filtered out. And, as with any other comparison, the meaningfulness of results is a function of the comparability of the elements that are being compared. In this comparative assessment, the degree of comparability of areas and carbon stocks is also closely linked to the internal consistency across time and space of the sources used to obtain country data for this section.

The scientific community has recently given attention to the challenges of comparing forest-related information and the need to bridge differences when setting science-based strategies to combat the adverse effects of climate change, using comparable background information (Grassi et al. 2018).

A case-by-case analysis of the results, which goes beyond the purpose of this section, may point out specific drivers of differences. Common reasons for the differences in forest information across data sources, which could help to correctly interpret the results, include the following:

- **Definition of forest:** In principle, most countries count on an official forest definition, which should determine the areas classified as “forest land” by the forest monitoring systems. In practice, these official definitions are often modified to fulfill the reporting requirements of international reporting frameworks. In some cases, these definitions are also modified because they are not technically feasible to implement due to the current methods used by countries to obtain forest information (for example, minimum area adopted for defining forest versus minimum mapping units used in the land monitoring system). The use of different forest definitions in a single country is often the main driver of differences when the information for the same parameter is compared across official submissions.

- **Land use versus land cover:** Whether national forest monitoring systems are land cover- or land use-oriented impacts the real meaning of the forest land information. A good example is when the extent of deforested areas is overestimated by including unstocked areas (resulting from management practices) where, although the forest coverage is reduced, the land use has not changed and the forest on the land is expected to regenerate.
- **Consistency of forest monitoring systems:** In line with the comment above, how countries identify and classify lands across time and space also has an impact on the meaning of the forest information reported. Implementing different methods across a time series of data hampers the internal consistency of the information. An example of this effect is when a country uses remote-sensing products with different resolutions to produce a time series of forest areas.

Although this list is not comprehensive, it shows real examples from country submissions to international frameworks, highlighting the challenges of comparing forest information. In some cases, the lack of transparency in the submissions also impedes a full understanding of the information needed to better grasp differences among data sources.

Therefore, the results of this comparative assessment should not be used as an indicator of the transparency, accuracy, consistency, comparability, and completeness of any of the datasets involved, including our model results.

6.2 COMPARATIVE ASSESSMENT OF AREAS

Table 6.1 includes information on the total area of countries selected (Gabon, Mexico, Finland, and Papua New Guinea) for this assessment. Further information on areas and other parameters used in this section for each country can be found in Appendix 1 of this report. Information on country areas refers to the year 2020 when available, or to the most updated reference found in the data sources. It is expected that the total country area remains constant over time. In practice, comparing country areas across national submissions can reveal different values for the extension of the national territories due to boundary disputes.

In some cases, natural effects may change total country area (for example, coastal erosion), but the differences would be captured only when comparing references over a long time span. Commonly, technical issues are found that explain the differences in national areas. For example, a single country may report inconsistent land area across the years for the same submission of

information or across different submissions, when the land representation system used for the datasets is different, or when the scope of the information is not the same. For example, a country may include or exclude information related to small islands, overseas territories, or territories occupied in a particular submission.

The differences found when comparing total country area among datasets are acceptable as their potential impact on the model results is minimal. In all cases, the total area used in the model differs from national submissions by less than 5 percent.

In addition, while official information on total area submitted by countries is inconsistent among data sources, the model runs with a constant and consistent total country area for the entire time series. Nevertheless, information on country area represents the sum of different land classes. As such, the value from each dataset intrinsically balances out the effect of using inconsistent definitions of the land classes among data sources. By contrast, a consistent classification of lands plays a key role in comparing areas when only one category is involved.

TABLE 6.1: COMPARISON OF INFORMATION ON TOTAL COUNTRY AREA SUBMITTED BY COUNTRIES WITH MODEL DATA

COUNTRY	TOTAL AREA (KILOHECTARES)			COMPARISON	
	FAO-FRA	REDD+ / UNFCCC	MODEL RESULTS	AVERAGE VALUE OF OFFICIAL SUBMISSIONS	DIFFERENCE (%) MODEL VS. AVERAGE OF OFFICIAL DATA SOURCES
Gabon	25,767	26,767	26,511	26,267	1%
Mexico	194,395	194,078	196,854	194,236	1%
Finland	30,391	33,843	33,375	32,117	4%
Papua New Guinea	45,286	46,100	46,600	45,693	2%

Table 6.2 compares the forest areas included in official submissions by countries with model results. The table also includes parameters to facilitate the interpretation of the comparison in terms of the level and trend of results.

TABLE 6.2: COMPARISON OF INFORMATION ON FOREST AREA SUBMITTED BY COUNTRIES WITH MODEL DATA

FOREST AREA (KILOHECTARES)							
GABON	2000	2010	DELTA	2015	DELTA	2020	DELTA
FAO-FRA	23,700	23,649	-0.2%	23,590	-0.3%	23,531	-0.3%
Forest land	23,700	23,649	-0.2%	23,590	-0.3%	23,531	-0.3%
Other woody lands	0	0	NA	0	NA	0	NA
REDD+ (*)	23,663	23,600	-0.3%	23,546	-0.2%	23,523	-0.1%
Model	23,896	23,823	-0.3%	23,817	0.0%	23,830	0.1%

(*) Values included in table 6 of the Forest Reference Level submission. The value in the last column refers to the year 2018.

MEXICO	2000	2010	DELTA	2015	DELTA	2020	DELTA
FAO-FRA	88,906	86,932	-2.2%	86,216	-0.8%	85,525	-0.8%
Forest land	68,381	66,943	-2.1%	66,331	-0.9%	65,692	-1.0%
Other woody lands	20,525	19,989	NA	19,885	NA	19,833	-0.3%
REDD+ (*)	101,269	99,561	-1.7%	98,061	-1.5%	97,711	-0.4%
Model	76,796	75,973	-1.1%	75,617	-0.5%	75,464	-0.2%

(*) Values included in table 26 of the Forest Reference Level submission. The value in the last column refers to the year 2016.

FINLAND	2000	2010	DELTA	2015	DELTA	2020	DELTA
FAO-FRA	23,269	23,031	-1.0%	23,155	0.5%	23,155	0.0%
Forest land	22,446	22,242	-0.9%	22,409	0.8%	22,409	0.0%
Other woody lands	823	789	NA	746	NA	746	0.0%
UNFCCC-GHGI (*)	22,106	21,943	-0.7%	21,885	-0.3%	21,849	-0.2%
Model	22,317	22,517	0.9%	22,491	-0.1%	21,816	-3.0%

(*) Values included in the 2022 GHGI submission (CRF table 4.1 for specific years).

TABLE 6.2: CONT.

PAPUA NEW GUINEA	2000	2010	DELTA	2015	DELTA	2020	DELTA
FAO-FRA	36,278	36,179	-0.3%	36,024	-0.4%	35,856	-0.5%
Forest land	36,278	36,179	-0.3%	36,024	-0.4%	35,856	-0.5%
Other woody lands	0	0	NA	0	NA	0	NA
REDD+ (*)	36,051	36,051	0.0%	36,051	0.0%	36,051	0.0%
Model	40,659	41,257	1.5%	41,282	0.1%	41,114	-0.4%

(*) Values included in figure 7.1 of the Forest Reference Level submission. The values refer to the year 2013.

For most of the case studies, the comparison shows that the model matches the country data. However, it also raises some differences that would need to be individually analyzed to explain their origin, for instance, the forest area reported by Papua New Guinea to FAO and under REDD+ and the area classified as forest in this country by the model. Nevertheless, a preliminary analysis of these results suggests that, as acknowledged by the countries, different forest definitions drive differences in forest areas across their submissions. For this reason, the semantic differences between the model's land cover classes encoded as "forest land" and national forest definitions seem to have a significant impact on the result of this comparison and could, at least partly, explain the differences in forest areas.

This problem could be greatly reduced if each country could provide specific information on how the land cover classes in the global dataset differ from the national definition of forest or their land cover classification. In practical terms, this problem cannot be solved due to the intrinsic nature of the global data, which provide a global perspective that is insufficiently detailed to distinguish those characteristics.

6.3 ISSUES WITH LAND CLASSIFICATION SYSTEMS

The model uses information from the ESA-CCI to classify land cover. This data source allows the construction of worldwide complete and consistent time-series information on land cover classes across time and space.

The land classification of the ESA-CCI does not explicitly assign classes under a "forest land" category. For this comparative assessment, it was necessary to merge the area of certain ESA-CCI land cover classes to derive the area of a theoretical forest land category. To ensure a consistent comparison of the model information on forest land area with the country data, it was decided to always use the sum of areas for the same ESA-CCI classes considered forest lands without considering the country being compared. This approach aims to avoid the uncertainties of a subjective selection of ESA-CCI classes, based on which country is compared.

Therefore, the only criteria used to select the ESA-CCI land cover classes that conform with the area of the forest land used in this comparative assessment is the likelihood of them satisfying

the minimum threshold values that are commonly used by countries for classifying forest lands. When selecting the land cover classes, special attention was given to the canopy cover value included in the legend of the ESA-CCI classification system.

Table 6.3 provides the forest definitions used by countries in their reporting under the REDD+ program or in their GHG inventory submission to the UNFCCC. It also includes the ESA-CCI land cover classes that were classified as forest land for the purpose of comparing model data on forest areas with country data.

Table 6.3 also indicates whether the forest definition used by countries in their submissions to REDD+ or the UNFCCC is consistent with the one used for their reporting under the FAO-FRA. The inclusion of this information aims to improve the understanding of differences among data sources included in other tables of this section, and increase awareness of the challenges of comparing data sources on forest-related information (Grassi, Conchedda, et al. 2022; Grassi, Schwingshackl, et al. 2022).

TABLE 6.3: COMPARISON OF FOREST DEFINITION USED BY COUNTRIES WITH MODEL DATA

COUNTRY	FOREST DEFINITION	DATA SOURCE	CONSISTENCY WITH FAO-FRA
Gabon	Tree formation covering at least 30 percent of the soil over more than 1 hectare and more than 20 meters wide, with trees at least 5 meters high at maturity, but not subject to any agricultural practice. It does not include land that is predominantly under agricultural or urban land use.	UN REDD+	Not consistent
Mexico	Forest lands with canopy cover greater than 10 percent, with woody species over 4 meters high or capable of reaching that height, and with a minimum surface of 1 hectare.	UN REDD+	Not consistent
Finland	The definition of forest that Finland employed for FAO's FRA is applied in the GHG inventory to define forest land. The FAO definition for forest in FRA 2005 was: "Land spanning more than 0.5 hectares with trees higher than five meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use." This definition was used for national data in the 2005 FRA report except for the requirement of the minimum area of 0.5 hectares.	UNFCCC	Mostly consistent
Papua New Guinea	Land spanning more than 1 hectare, with trees higher than 3 meters and a canopy cover of more than 10 percent. This excludes land that is predominantly under agricultural or urban land use.	REDD+	Not consistent

COUNTRY	FOREST DEFINITION	DATA SOURCE	CONSISTENCY WITH FAO-FRA
MODEL	The following ESA-CCI land cover classes are used to represent the most likely alignment with areas considered forest by the countries: Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%) Tree cover, broadleaved, evergreen, closed to open (>15%) Tree cover, broadleaved, deciduous, closed to open (>15%) Tree cover, broadleaved, deciduous, closed (>40%) Tree cover, broadleaved, deciduous, open (15–40%) Tree cover, needleleaved, evergreen, closed to open (>15%) Tree cover, needleleaved, evergreen, closed (>40%) Tree cover, needleleaved, evergreen, open (15–40%) Tree cover, needleleaved, deciduous, closed to open (>15%) Tree cover, needleleaved, deciduous, closed (>40%) Tree cover, needleleaved, deciduous, open (15–40%) Tree cover, mixed leaf type (broadleaved and needleleaved) Mosaic tree and shrub (>50%) / herbaceous cover (<50%) Tree cover, flooded, fresh or brackish water Tree cover, flooded, saline water	ESA-CCI ²⁸	NA

6.4 COMPARATIVE ASSESSMENT OF CARBON STOCKS IN VEGETATION

The model provides global estimates of vegetation carbon stocks for terrestrial ecosystems using a multi-layer lookup table for merging geographically explicit information that is needed to correctly assign aboveground biomass values to lands. Specifically, the table allows one to merge information on land cover classes, ecofloristic regions, and geographical zones, which is then used to assign aboveground biomass stocks.

Information on aboveground biomass is obtained from the default values included in the 2006 IPCC

guidelines (Table 4.7). Further details on this methodology are provided in section 2, which also includes information on the methods for estimating belowground biomass and carbon stocks in vegetation.

This section includes 2006 IPCC default values for aboveground biomass in forests used in the model in an attempt to compare the model outcomes with country data.

It should be noted that most countries have in place national forest inventories that provide field measurements of tree parameters, which are used to retrieve information on aboveground biomass, belowground biomass, and carbon stocks. This information, based on field measurements, is,

²⁸ <https://cds.climate.copernicus.eu/cdsapp#/dataset/satellite-land-cover?tab=overview>

in principle, more representative of the natural conditions of the countries than the IPCC default values because it intrinsically captures the effects of national circumstances, such as management practices, natural disturbances, and ecosystem features, on the vegetation carbon stocks.

However, using default aboveground biomass values from the 2006 IPCC guidelines allows a globally comparable and consistent treatment of the data that would be difficult to achieve using country-specific information.

Moreover, the interpretation of the results of comparing this information should consider the different stratifications of forest land used by countries as compared with the model approach. Countries often implement random sampling or systematic approaches in their national forest inventories that allow them to retrieve information on biomass stocks disaggregated by forest types, or for strata based on biological characteristics of the vegetation or ecozones. This difference in stratification by countries and the model approach

prevents a one-to-one comparison of information on aboveground biomass among data sources.

Bearing all this in mind, it is recommended that the comparison of model data with country data should focus solely on aboveground biomass information, which is the main contributor to forest carbon stock, disregarding the comparison of information on other parameters involved in estimating land-based emissions and removals, for which a dedicated case-by-case comparative analysis would be needed to obtain meaningful results.

The information in Table 6.4 below includes (i) aboveground biomass values used in the model, as included in the 2006 IPCC guidelines, and (ii) country-specific information on aboveground biomass, or in-house estimates for aboveground biomass retrieved from information included in country submissions, in order to enhance the comparability of model data with country-specific information. The result of this comparison must consider the discussion provided above on the challenges and artifacts of comparing forest-related information.

TABLE 6.4: 2006 IPCC DEFAULT VALUES FOR FOREST ABOVEGROUND BIOMASS USED BY THE MODEL

ABOVEGROUND BIOMASS IN FORESTS				
DOMAIN	ECOLOGICAL ZONE	CONTINENT	ABOVEGROUND BIOMASS (tonnes d.m ha ⁻¹)	REFERENCES
Tropical	Tropical rain forest	Africa	310 (130–510)	IPCC 2003
		North and South America	300 (120–400)	Baker et al. 2004a; Hughes et al. 1999
		Asia (continental)	280 (120–680)	IPCC 2003
		Asia (insular)	350 (280–520)	IPCC 2003
	Tropical moist deciduous forest	Africa	260 (160–430)	IPCC 2003
		North and South America	220 (210–280)	IPCC 2003
		Asia (continental)	180 (10–560)	IPCC 2003
		Asia (insular)	290	IPCC 2003

ABOVEGROUND BIOMASS IN FORESTS				
DOMAIN	ECOLOGICAL ZONE	CONTINENT	ABOVEGROUND BIOMASS (tonnes d.m ha ⁻¹)	REFERENCES
Tropical	Tropical dry forest	Africa	120 (120–130)	IPCC 2003
		North and South America	210 (200–410)	IPCC 2003
		Asia (continental)	130 (100–160)	IPCC 2003
		Asia (insular)	160	IPCC 2003
	Tropical shrubland	Africa	70 (20–200)	IPCC 2003
		North and South America	80 (40–90)	IPCC 2003
		Asia (continental)	60	IPCC 2003
		Asia (insular)	70	IPCC 2003
	Tropical mountain systems	Africa	40–190	IPCC 2003
		North and South America	60–230	IPCC 2003
		Asia (continental)	50–220	IPCC 2003
		Asia (insular)	50–360	IPCC 2003
Subtropical	Subtropical humid forest	North and South America	220 (210–280)	IPCC 2003
		Asia (continental)	180 (10–560)	IPCC 2003
		Asia (insular)	290	IPCC 2003
	Subtropical dry forest	Africa	140	Subei et al. 2001
		North and South America	210 (200–410)	IPCC 2003
		Asia (continental)	130 (100–160)	IPCC 2003
		Asia (insular)	160	IPCC 2003
	Subtropical steppe	Africa	70 (20–200)	IPCC 2003
		North and South America	80 (40–90)	IPCC 2003
		Asia (continental)	60	IPCC 2003
		Asia (insular)	70	IPCC 2003
	Subtropical mountain systems	Africa	50	Montès et al. 2002
		North and South America	60–230	IPCC 2003
		Asia (continental)	50–220	IPCC 2003
		Asia (insular)	50–360	IPCC 2003
Temperate	Temperate oceanic forest	Europe	120	–
		North America	660 (80–1,200)	Hessl et al. 2004; Smithwick et al. 2002
		New Zealand	360 (210–430)	Hall et al. 2001
		South America	180 (90–310)	Gayoso and Schlegel 2003; Battles et al. 2002

ABOVEGROUND BIOMASS IN FORESTS				
DOMAIN	ECOLOGICAL ZONE	CONTINENT	ABOVEGROUND BIOMASS (tonnes d.m ha ⁻¹)	REFERENCES
Temperate cont.	Temperate continental forest	Asia, Europe (≤20y)	20	IPCC 2003
		Asia, Europe (>20y)	120 (20–320)	IPCC 2003
		North and South America (≤20y)	60 (10–130)	IPCC 2003
		North and South America (>20y)	130 (50–200)	IPCC 2003
	Temperate mountain systems	Asia, Europe (≤20y)	100 (20–180)	IPCC 2003
		Asia, Europe (>20y)	130 (20–600)	IPCC 2003
		North and South America (≤20y)	50 (20–110)	IPCC 2003
		North and South America (>20y)	130 (40–280)	IPCC 2003
Boreal	Boreal coniferous forest	Asia, Europe, North America	10–90	Gower et al. 2001
	Boreal tundra woodland	Asia, Europe, North America (≤20y)	3–4	IPCC 2003
		Asia, Europe, North America (>20y)	15–20	IPCC 2003
	Boreal mountain systems	Asia, Europe, North America (≤20y)	12–15	IPCC 2003
		Asia, Europe, North America (>20y)	40–50	IPCC 2003

7 Summary and Next Steps

This analysis provides results at the global level for aboveground and belowground vegetation carbon stock covering the period 2001–2020. It prioritizes the comparability of the outcome, providing consistent global results by using relatively long time series of global data and adopting an approach aligned with the 2006 IPCC guidelines.

These results offer a global overview of the vegetation carbon stock trends by country and by land cover class, but are not meant to be used to derive information or to be directly compared against results for a specific country, which are obtained using different data, on different spatial and temporal scales, and for different purposes. The results obtained are in line with country-level estimates and do not show unexpected trends. Nevertheless, the changes in the outputs for each country are driven by the landscape changes observed in the global datasets used, and are not

meant to deduce net carbon fluxes from lands or other emissions of non-CO₂ gases.

Future results will integrate more details without jeopardizing the comparability of the countries' results. New items will include:

- The 2019 IPCC refinement.
- Further stratification of the ecological variables considered to estimate carbon vegetation stock.
- The uncertainty range as per the IPCC guidelines.
- More advanced forest aging and post-fire dynamics.

The current results also include information on soil organic carbon, which are not comparable with each other due to the different methodologies used in their calculation. These results will be made comparable in case the necessary information becomes available.

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Appendix 1: Country-specific background information used for the comparative assessment included in section 6

This appendix contains further information on each of the countries analyzed to compare the results produced in the study against other global data assessments.

1. Gabon: [Modified submission of the REDD+ Forest Reference Level, 2021](#)

Gabon's submission of the Forest Reference Level under the UN REDD+ program does not provide information on aboveground biomass. Instead, information on carbon stocks by hectares is provided for different forest types and carbon pools.

To facilitate the comparison of the information submitted by Gabon with the aboveground biomass stocks used in the model, the default IPCC carbon fraction (0.47) for converting the dry matter of biomass into carbon stocks was used. The tables below show the information on carbon stock as provided by Gabon and in-house estimates of aboveground biomass stocks retrieved from the country's information.

Forest Type	Disturbance History	Above Ground		Below Ground	Dead Organic Matter (Deadwood & Litter)		Soil Carbon		Above and Below-ground		Total Ecosystems		Source
		Trees >10cm DBH		Living Roots	Total DOM		0-100cm						
		Mean	U	Mean	Mean	U	Mean	U	Mean	U	Mean	U	
Old-growth	Undisturbed	151.6	12%	35.6	23.5	16%	161.3	41%	187.2	12%	372.0	19%	NRI (Poulsen et al. 2020)
Logged	Undetermined	172.8	11%	40.6	42.8	14%	127.1	10%	213.4	11%	383.3	7%	NRI (Poulsen et al. 2020)
Secondary	Undetermined	95.6	22%	22.5	26.8	31%	98.3	7%	118.0	22%	243.2	11%	NRI (Poulsen et al. 2020)
Forest (average old growth, logged, secondary)	Undetermined	141.7	9%	33.3	32.2	11%	125.1	14%	175.0	9%	332.3	7%	NRI (Poulsen et al. 2020)
Mangrove	Undisturbed	111.8	20%	37.0	18.9	18%	254.6	11%	148.8	19%	422.3	9%	(Kauffman and Bhomia 2017) https://data.cifor.org/dataverse/swamp
Colonizing	Undisturbed	47.2	21%	11.1	Data not available		72.3	2%	58.3	21%	130.6	104%	(Chiti et al. 2018; Cuni-Sanchez et al. 2016)

U = Uncertainty

FOREST TYPE	ABOVEGROUND (t C/ha)	ABOVEGROUND (t dry matter/ha) (IN-HOUSE ESTIMATES)
Old-growth forest	151.6	322.55
Logged	172.8	367.66
Secondary	95.6	203.40
Forest (average old growth, logged, secondary)	141.7	301.49
Mangrove	111.8	237.87
Colonizing	47.2	100.43

2. Mexico: [Modified submission of the REDD+ Forest Reference Level, 2021](#)

Mexico's submission of the Forest Reference Level under the UN REDD+ program does not provide information on aboveground biomass. Instead, information on carbon stocks for aboveground biomass, by hectare, is provided for different forest types.

To facilitate the comparison of the information submitted by Mexico with the aboveground biomass stock values used in the model, the default IPCC carbon fraction (0.47) for converting the dry matter of biomass into carbon stocks was used. The tables below show the information on carbon stock of aboveground biomass as provided by Mexico and in-house estimates of dry matter in aboveground biomass retrieved from the country's information.

Sub-estrato	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
CalMed – 10x20 – TF	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.78	0.78
CalMed – 20x20 – TF	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
CalMed – 5x5 – TF	8.86	8.86	8.86	8.86	8.86	8.86	8.86	8.86	8.86	8.86	8.86	8.86	8.86	8.86	8.36	8.36	8.36
DesAN – 10x10 – TF	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.69	1.69	1.69
DesAN – 20x20 – TF	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
DesAN – 5x5 – TF	4.79	4.79	4.79	4.79	4.79	4.79	4.79	4.79	4.79	4.79	4.79	4.79	4.79	4.79	4.79	4.78	4.78
ElevSM – 10x10 – TF	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.63	4.59	4.59
ElevSM – 20x20 – TF	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.47	1.47	1.47	1.47	1.47
ElevSM – 5x5 – TF	9.71	9.71	9.71	9.71	9.71	9.71	9.70	9.70	9.70	9.70	9.70	9.70	9.70	9.70	9.67	9.67	9.67
GraPla – 10x10 – TF	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77
GraPla – 20x20 – TF	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.49	0.49	0.49	0.49	0.49	0.49
GraPla – 5x5 – TF	9.77	9.77	9.77	9.77	9.77	9.77	9.77	9.77	9.77	9.77	9.77	9.77	9.77	9.77	9.77	9.77	9.77
SCH – 10x10 – TF	12.52	12.52	12.52	12.52	12.52	12.52	12.52	12.52	12.52	12.52	12.48	12.48	12.48	12.48	12.47	12.34	12.26
SCH – 20x20 – TF	3.74	3.74	3.74	3.74	3.74	3.74	3.74	3.74	3.70	3.67	3.67	3.67	3.67	3.62	3.59	3.56	3.35
SCH – 5x5 – TF	24.87	24.87	24.87	24.87	24.87	24.86	24.82	24.71	24.61	24.50	24.42	24.36	24.28	24.20	24.12	24.05	23.97
SCS – 10x10 – TF	9.37	9.37	9.37	9.37	9.37	9.37	9.37	9.34	9.33	9.33	9.29	9.27	9.25	9.25	9.23	9.18	9.16
SCS – 20x20 – TF	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.92	1.92	1.90	1.90	1.89	1.88
SCS – 5x5 – TF	15.24	15.24	15.24	15.24	15.24	15.22	15.21	15.20	15.18	15.18	15.16	15.11	15.10	15.05	15.04	14.99	14.94
SiTeM – 10x10 – TF	10.43	10.43	10.43	10.43	10.43	10.43	10.41	10.41	10.41	10.41	10.41	10.36	10.36	10.33	10.33	10.33	10.33
SiTeM – 20x20 – TF	7.59	7.59	7.59	7.59	7.59	7.59	7.59	7.59	7.59	7.59	7.59	7.57	7.56	7.56	7.56	7.56	7.56
SiTeM – 5x5 – TF	26.46	26.46	26.46	26.46	26.46	26.45	26.43	26.43	26.41	26.38	26.36	26.30	26.24	26.21	26.15	26.11	26.05

SiTeM – Sierras Templadas
TF – Tierras Forestales

GraPla – Grandes Planicies
SCH – Selvas Cálido-Húmedas
SCS – Selvas Cálido-Secas

CalMed – California Mediterránea
DesAN – Desiertos de América del Norte
ElevSM – Elevaciones Semiáridas Meridionales

ABOVEGROUND BIOMASS (TON DRY MATTER) (IN-HOUSE ESTIMATES RETRIEVED FROM CARBON STOCK INFORMATION INCLUDED IN THE REDD+ MODIFIED FOREST REFERENCE EMISSIONS LEVELS SUBMISSION, 2021)																	
Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
California Mediterranea - 10 x 10 - TF	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.66	1.66
California Mediterranea - 20 x 20 - TF	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
California Mediterranea - 5 x 5 - TF	18.85	18.85	18.85	18.85	18.85	18.85	18.85	18.85	18.85	18.85	18.85	18.85	18.85	18.85	17.79	17.79	17.79
Desiertos de America del Norte - 10 x 10 - TF	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62
Desiertos de America del Norte - 20 x 20 - TF	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Desiertos de America del Norte - 5 x 5 - TF	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19
Elevaciones Semiáridas Meridionales - 10 x 10 - TF	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.85	9.77	9.77
Elevaciones Semiáridas Meridionales - 20 x 20 - TF	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.13	3.13	3.13	3.13	3.13
Elevaciones Semiáridas Meridionales - 5 x 5 - TF	20.66	20.66	20.66	20.66	20.66	20.66	20.64	20.64	20.64	20.64	20.64	20.64	20.64	20.64	20.57	20.57	20.57
Grandes Planicies - 10 x 10 - TF	3.79	3.79	3.79	3.79	3.79	3.79	3.79	3.79	3.77	3.77	3.77	3.77	3.77	3.77	3.77	3.77	3.77
Grandes Planicies - 20 x 20 - TF	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.04	1.04	1.04	1.04	1.04	1.04
Grandes Planicies - 5 x 5 - TF	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79
Selvas Calido-Humedas - 10 x 10 - TF	26.64	26.64	26.64	26.64	26.64	26.64	26.64	26.64	26.64	26.64	26.55	26.55	26.55	26.55	26.53	26.26	26.09
Selvas Calido-Humedas - 20 x 20 - TF	8.23	8.23	8.23	8.23	8.23	8.23	8.23	8.23	8.09	7.79	7.79	7.79	7.79	7.68	7.62	7.55	7.11
Selvas Calido-Humedas - 5 x 5 - TF	53.17	53.17	53.17	53.17	53.17	53.13	53.04	52.81	52.55	52.30	52.11	51.98	51.77	51.60	51.38	51.26	51.06
Selvas Calido-Secas - 10 x 10 - TF	19.94	19.94	19.94	19.94	19.94	19.94	19.94	19.87	19.87	19.87	19.79	19.74	19.70	19.64	19.62	19.51	19.47
Selvas Calido-Secas - 20 x 20 - TF	4.28	4.28	4.28	4.28	4.28	4.28	4.28	4.28	4.28	4.28	4.28	4.17	4.17	4.15	4.13	4.13	4.11
Selvas Calido-Secas - 5 x 5 - TF	32.36	32.36	32.36	32.36	32.36	32.32	32.30	32.30	32.26	32.23	32.19	32.06	32.04	31.94	31.85	31.74	31.64
Sierras Templadas - 10 x 10 - TF	22.30	22.30	22.30	22.30	22.30	22.30	22.23	22.23	22.23	22.23	22.23	22.15	22.11	22.04	22.04	22.04	22.04
Sierras Templadas - 20 x 20 - TF	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.09	16.09	16.09	16.09	16.09
Sierras Templadas - 5 x 5 - TF	56.30	56.30	56.30	56.30	56.30	56.28	56.23	56.23	56.19	56.15	56.11	56.02	55.91	55.85	55.74	55.68	55.62

3. Finland: 2022 GHG inventory submission under the UNFCCC

To ensure consistency of the data source used to obtain country-specific information for Finland for other sections of this comparative assessment, the 2022 GHG inventory submission was first consulted for aboveground biomass stocks of the country's forests. However, due to Finland's method for estimating forest-related GHG emissions and removals, the GHG inventory submission does not include information on aboveground biomass stocks, which is publicly available in FAO's Global Forest Resources Assessments for the country.

The table below provides information on forest aboveground biomass stocks in Finland, as included in the 2020 FAO-FRA country report.

FRA CATEGORIES	FOREST BIOMASS (tonnes/ha)								
	1990	2000	2010	2015	2016	2017	2018	2019	2020
Aboveground biomass	43.86	49.14	53.64	59.77	59.77	59.77	59.77	59.77	59.77
Belowground biomass	13.05	15.20	16.51	17.31	17.31	17.31	17.31	17.31	17.31
Deadwood	1.37	1.37	1.49	1.49	1.49	1.49	1.49	1.49	1.49

4. Papua New Guinea: Modified submission of the national REDD+ Forest Reference Level, 2017

In its submission of the Forest Reference Level under the UN REDD+ program, Papua New Guinea includes explicit information on aboveground biomass by forest type, which is further divided into classes according to different anthropogenic impacts on those forest types. This information is included in the table below to facilitate the comparison of the country data with the aboveground biomass stocks used in the model.

FOREST TYPE	HUMAN IMPACT	ABOVEGROUND BIOMASS			BELOWGROUND BIOMASS	
		SOURCE	ECOLOGICAL ZONE AS PER IPCC GUIDELINES	DRY MATTER (tonnes/ha)	DRY MATTER (tonnes/ha)	ROOT TO SHOOT RATIO
Low altitude forest on plains and fans	Primary	Fox et al. (2010)	Tropical rainforest	223	83	0.37
	Logged			146	54	0.37
	Other disturbances			146	54	0.37
Low altitude forest on uplands	Primary			223	83	0.37
	Logged			146	54	0.37
	Other disturbances			146	54	0.37
Littoral forest	Primary			223	83	0.37
	Logged			146	54	0.37
	Other disturbances			146	54	0.37
Seral forest	Primary			223	83	0.37
	Logged			146	54	0.37
	Other disturbances			146	54	0.37
Swamp forest	Primary			223	83	0.37
	Logged			146	54	0.37
	Other disturbances			146	54	0.37
Lower montane forest	Primary	IPCC Guidelines (2006)	Tropical mountain system	140	38	0.27
	Logged			92	25	0.27
	Other disturbances			92	25	0.27
Montane forest	Primary			140	38	0.27
	Logged			92	25	0.27
	Other disturbances			92	25	0.27
Mountain coniferous forest	Primary			140	38	0.27
	Logged			92	25	0.27
	Other disturbances			92	25	0.27
Dry seasonal forest	Primary		Tropical dry forest	130	36	0.28
	Logged			85	24	0.28
	Other disturbances			85	24	0.28
Woodland	Primary			130	36	0.28
	Other disturbances			85	24	0.28
				85	24	0.28
Savanna	Primary			130	36	0.28
	Other disturbances			85	24	0.28
				85	24	0.28
Scrub	Primary		Tropical shrubland	70	28	0.4
	Other disturbances			46	18	0.4
Mangrove	Primary		Tropical wet mangrove	192	94	0.49
	Other disturbances			126	62	0.49
Forest plantation	Primary		Tropical rainforest (plantation)	150	56	0.37
	Other disturbances			98	36	0.37

Appendix 2: Aligning the terrestrial results produced in ARIES with the carbon contribution of mangrove ecosystems

THE DIFFICULTY OF INTEGRATING MANGROVE AND VEGETATION CARBON STORAGE RESULTS

The current results include the carbon contribution of mangrove ecosystems estimated using the model currently available in ARIES and described in the second segment of the report.

This section shows how the vegetation and mangrove carbon stock results could be aligned to allow future comparison or facilitate a potential integration of these outputs. However, given the important contribution of mangroves to the global carbon budget, the World Bank commissioned Silvestrum Climate Associates to estimate the carbon stock of mangroves separately.²⁹ Given the focus of this analysis, datasets specifically developed to observe changes in these ecosystems were used, which use inconsistent assumptions to those in this global assessment approach. This section discusses the implication of merging these two different data sources to ensure that integrating these data does not affect the consistency of the final result.

To integrate the different data sources, the data must be consistent across spatial and temporal scales.

The integration of current approaches is technically feasible but beyond the scope of this work. Doing so would primarily require reconciling issues related to spatio-temporal scale, since the mangrove carbon storage results are provided at a much higher spatial resolution than those for terrestrial carbon stock. On the other hand, the input data³⁰ used to identify the mangrove areas cover only the years 1996, 2010, 2015, and 2020, while the results of the terrestrial carbon stock cover a complete time series of annual information for the period 2001–2020.

If the two datasets were to be combined, priority should be given to the layers estimating mangroves carbon stock due to the higher spatial resolution of the original information used as input in the model. To fill the gaps in the time series, a linear interpolation approach could be applied. To avoid double-counting, the interpolated vegetation carbon stock that overlaps with the observed mangroves would be excluded. The overlapping values would be neglected for all years in which overlapping areas are observed until a more recent observation confirms that the overlap no longer exists. This approach would minimize error, assuming that the spatial extent of mangroves stays constant in between available spatially explicit information.

29 CWON Technical Report 2024: Estimating Global Carbon Storage in Mangrove Ecosystems.

30 <https://geowetlands.org/knowledge-base/datasets/global-mangrove-watch-gmw-v3-0/>

While this approach is achievable from a purely mathematical perspective, the final result would be difficult to defend. Most of the numeric value resulting from this approach would result from aggregation error rather than carbon stock. It is a well-known phenomenon in geography that results will change, often substantially, at different spatial resolutions. Sensitivity analyses can be used to understand the divergence in results obtained using coarser and finer-scale models, but they fall outside the scope of this work. Therefore, accounting separately for the overall vegetation carbon stock, and for mangrove carbon storage, results in the best approach, at least until there is a clear and recognized way to compute carbon stock at comparable resolutions.

RECONCILING SOIL ORGANIC CARBON AMONG DATA SOURCES

As indicated above, ISRIC—World Soil Information³¹ provides information on soil organic carbon at different depths up to 200cm. Information on soil organic carbon in mangrove areas, as provided by Silvestrum, is given to a depth of 100cm. Techniques to infer the carbon contents at different depths for a given value are available. If setting the carbon content at a unique depth is seen as a way to align data sources, such processing of the data would in principle be feasible. However, using the data as originally provided in each dataset is seen as a more realistic option because (i) it covers a wider range of options for satisfying user demand, and (ii) it avoids introducing new uncertainties associated with processing two outcomes from different data sources.

³¹ <https://www.isric.org/explore/soilgrids>

Appendix 3: Large yearly differences in the vegetation carbon stock not explained by land cover changes

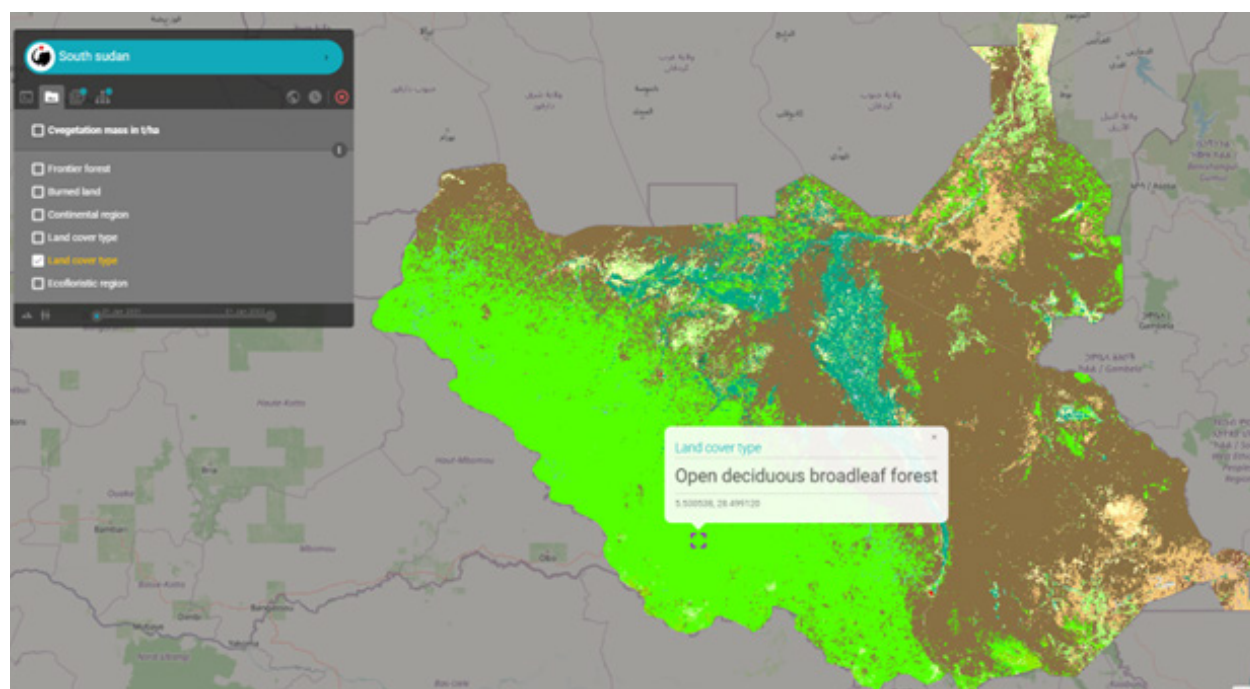
Over the time series, there are cases where the vegetation carbon stock of a unique land cover class contributes significantly to the overall change in the vegetation carbon stock for that country. Intuitively, this might be due to large yearly fluctuation of the extent of that land cover in the ESA-CCI dataset, which drives the reduction in carbon stock. Some large deviations can be caused by:

1. Large areas burnt in a given year, with fire as an important influence on vegetation carbon storage.
2. Data gaps in the presence of fire for large, fire-prone areas, which make it challenging to accurately estimate the vegetation carbon stock.

The impact of fire in regions where fires are abundant in the year observed leads to a loss of vegetation carbon stock. But, given the variables involved in the model, the final results analysis is not always straightforward. An example is provided to help the reader interpret the results correctly.

Between 2001 and 2002, in South Sudan, the vegetation carbon stock of open deciduous broadleaf forests³² decreased by 5.5 megatonnes of CO₂. This loss corresponds to more than 98.5 percent of the total vegetation carbon stock decrease in that year in that country. In the same year though, the change in the extent of the open deciduous broadleaf forest cover is less than 0.15 percent.

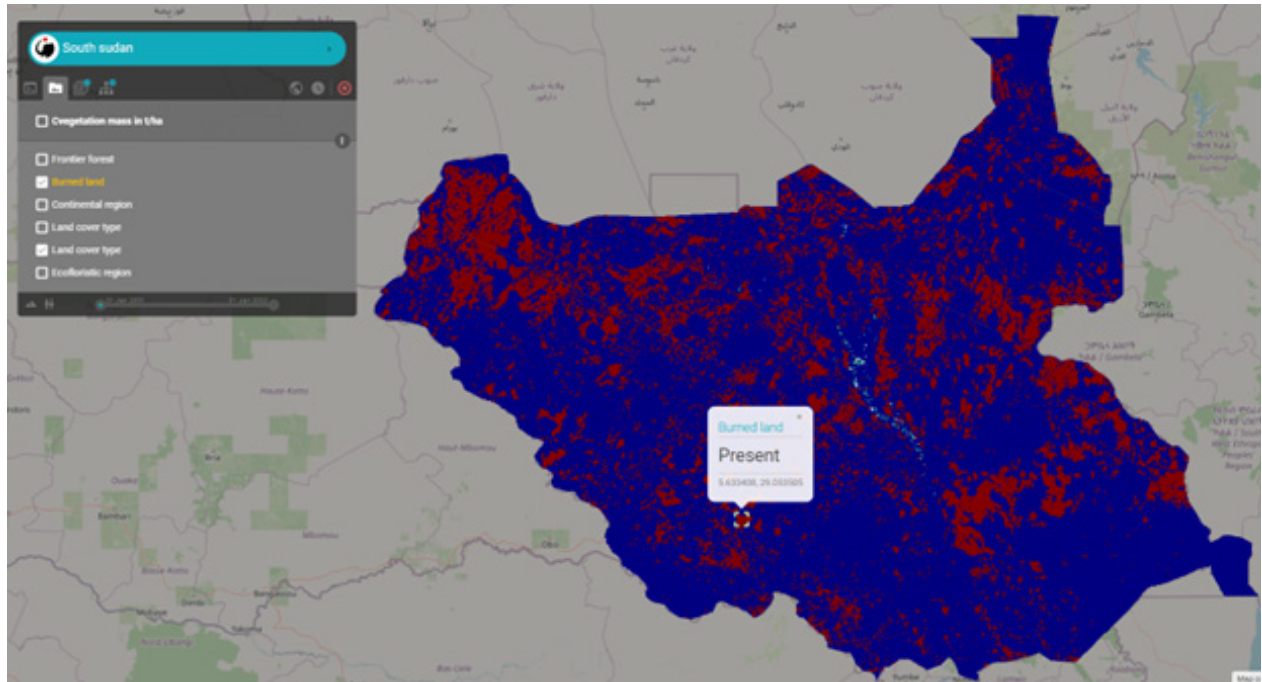
FIGURE A3.1: LAND COVER MAP OF SOUTH SUDAN



However, large areas of deciduous forests burned in 2001.

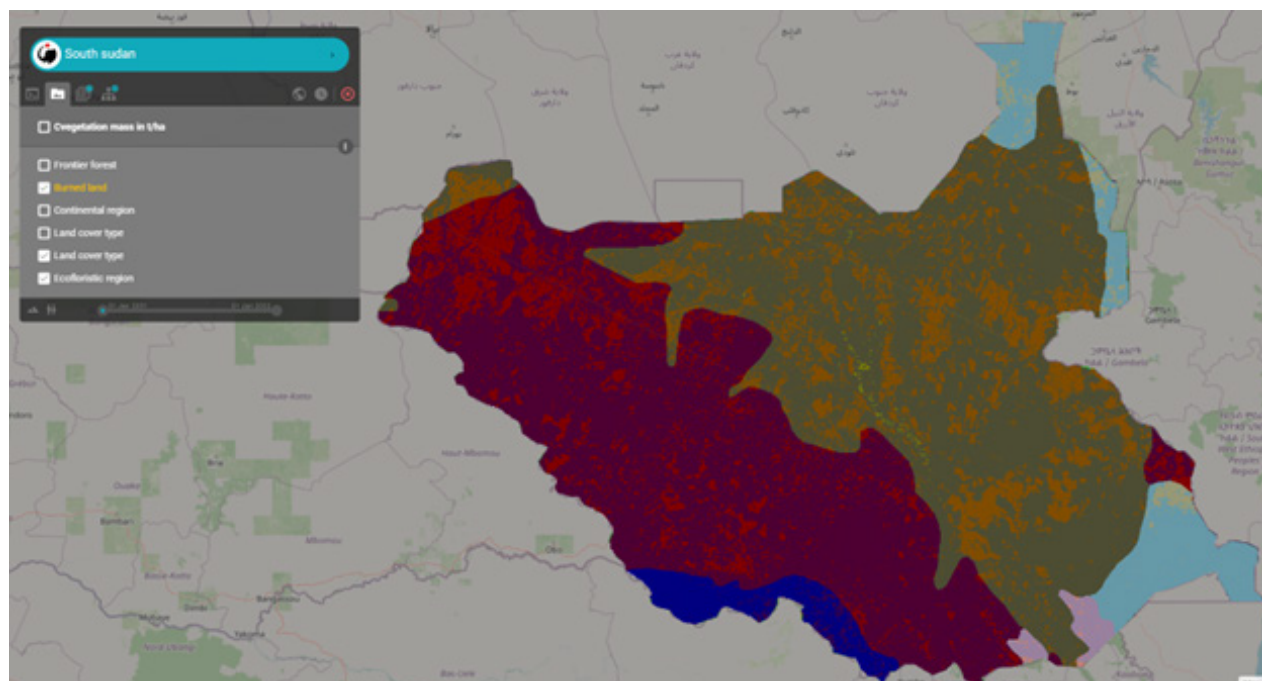
³² These forests are classified as tree cover, needleleaved, deciduous, open (15–40 percent) in the ESA-CCI dataset (code 82).

FIGURE A3.2: PRESENCE OF BURNED LAND IN SOUTH SUDAN



In this model, the combination of other inputs, including land cover class and the ecofloristic region, determines the carbon storage lost due to fire (more sophisticated models account for burn severity in modeling carbon emissions from fires, but global burn severity products do not exist in time series adequate to support CWON).

FIGURE A3.3: OVERLAY OF LAYERS OF PRESENCE OF BURNED LAND AND ECOFLORISTIC REGIONS IN SOUTH SUDAN



For example, when subjected to fire, open deciduous forests in the African tropical moist deciduous region are estimated to lose half of their carbon content, dropping from 152 tonnes per hectare to 76 tonnes per hectare.

FIGURE A3.4: AREA COVERED BY THE TROPICAL MOIST DECIDUOUS FOREST ECOFLORISTIC REGION IN SOUTH SUDAN

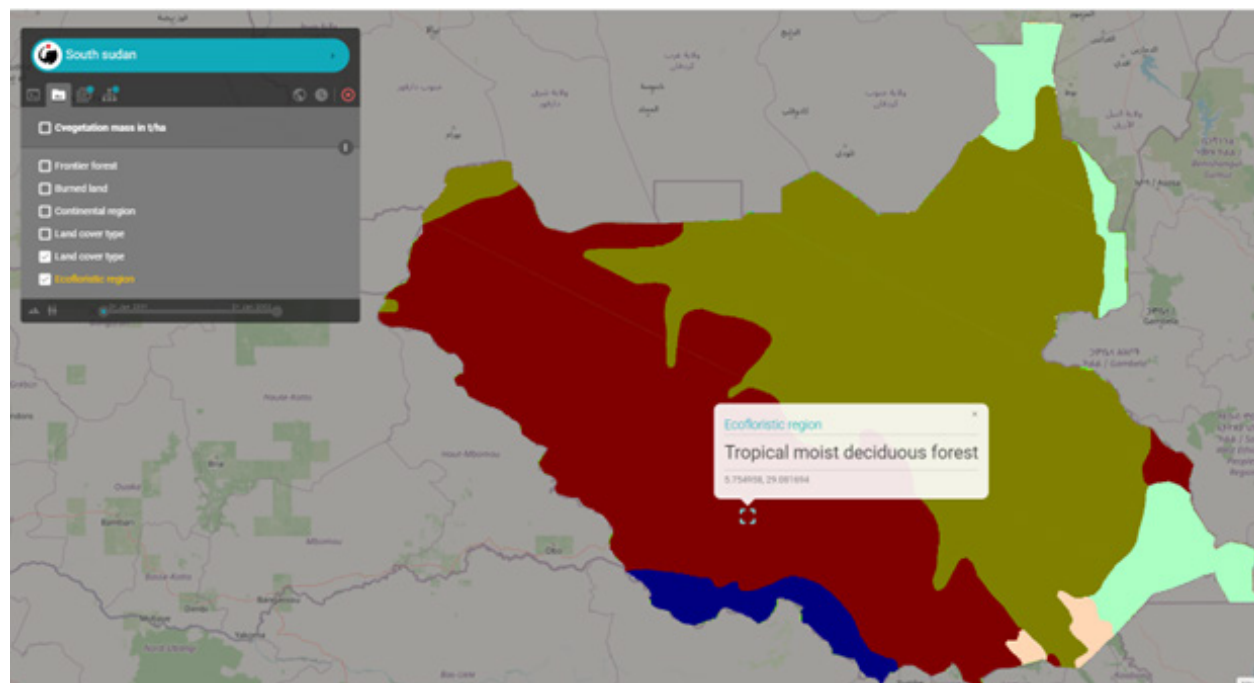
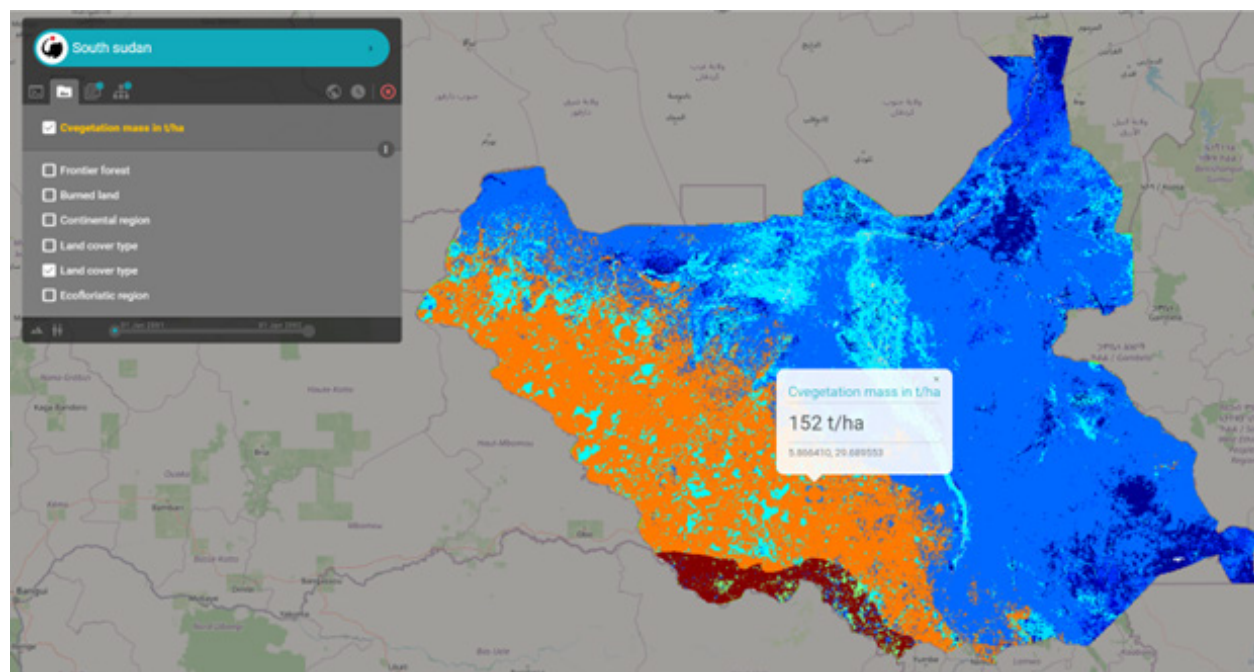
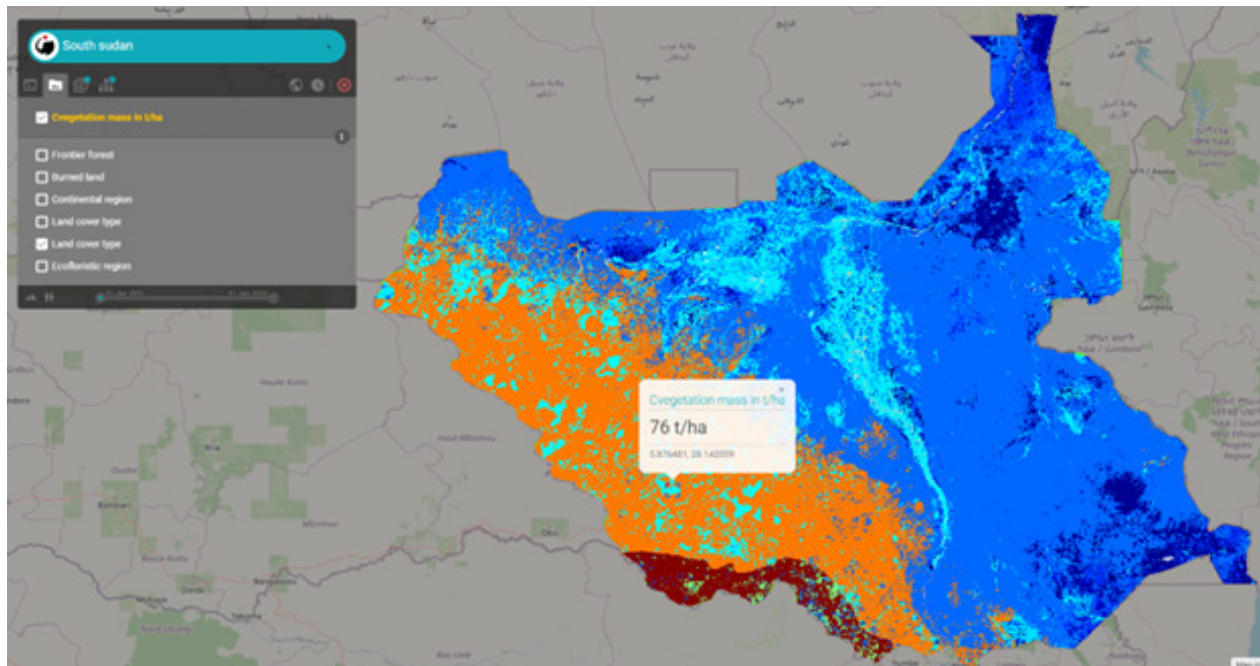


FIGURE A3.5: CARBON STOCK ESTIMATED FOR A NON-BURNED AREA IN TROPICAL MOIST DECIDUOUS FOREST ECOFLORISTIC REGION IN SOUTH SUDAN



The light blue regions located in the south-central part of South Sudan are those burned by fire.

FIGURE A3.6: CARBON STOCK ESTIMATED FOR A BURNED AREA IN TROPICAL MOIST DECIDUOUS FOREST ECOFLORISTIC REGION IN SOUTH SUDAN



The same proportional loss of carbon stock is observed for deciduous forests in the African tropical rainforest region that burned; stocks in burned areas decreased from 200 tonnes per hectare to 100 tonnes per hectare.

FIGURE A3.7: AREA COVERED BY THE TROPICAL RAINFOREST ECOFLORISTIC REGION IN SOUTH SUDAN

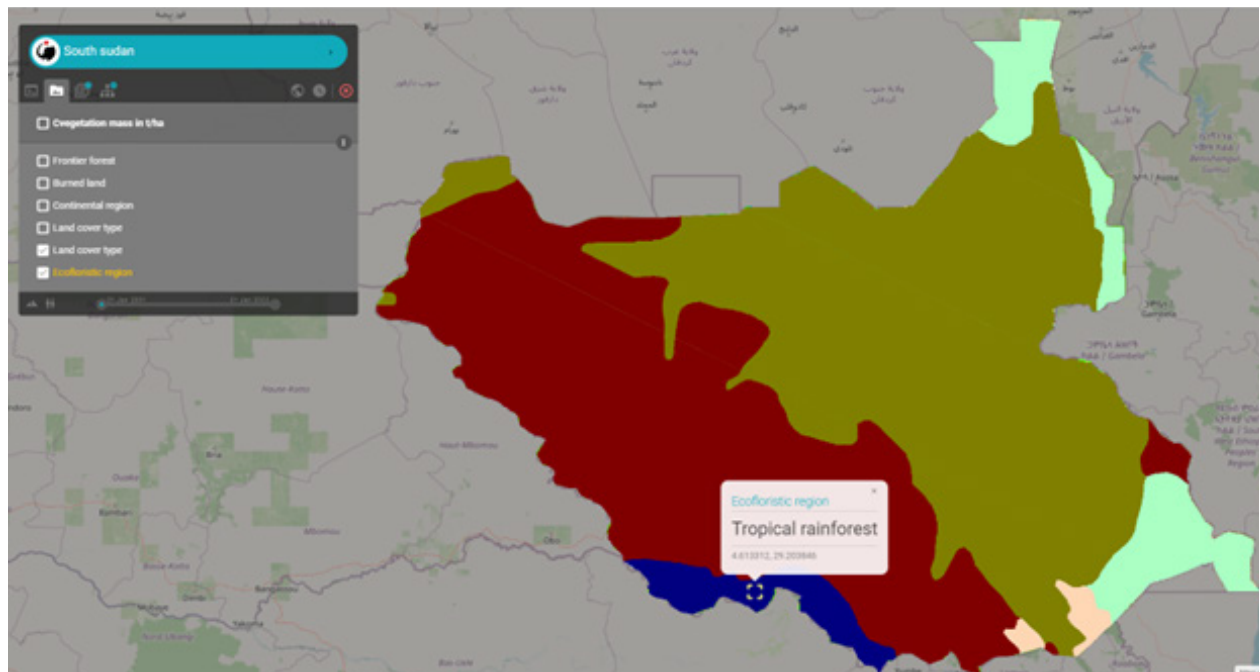


FIGURE A3.8: CARBON STOCK ESTIMATED FOR A NON-BURNED AREA IN TROPICAL RAINFOREST ECOFLORISTIC REGION IN SOUTH SUDAN

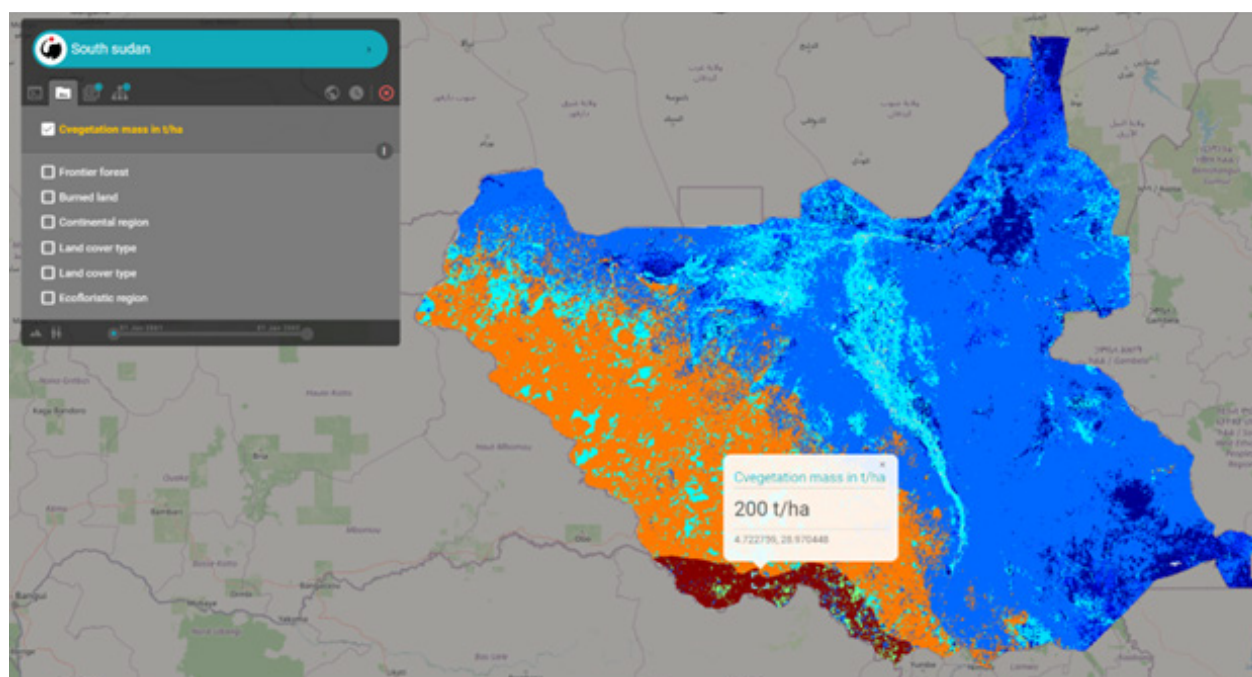
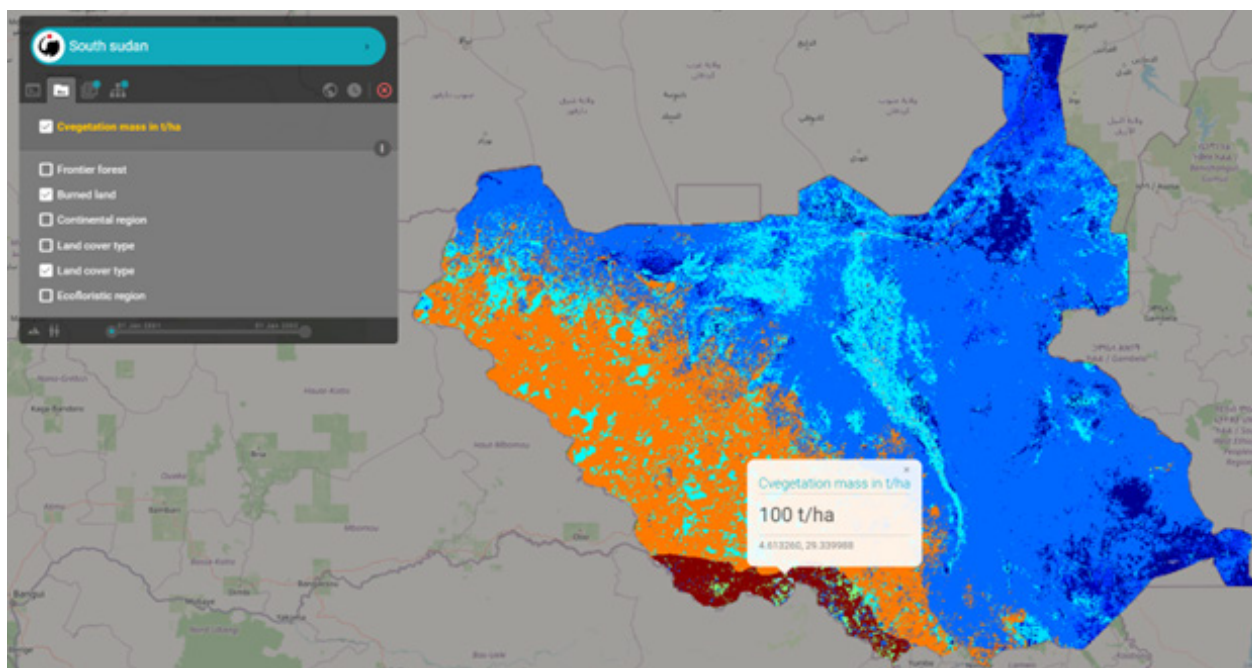


FIGURE A3.9: CARBON STOCK ESTIMATED FOR A BURNED AREA IN TROPICAL RAINFOREST ECOFLORISTIC REGION IN SOUTH SUDAN



The same type of forests located in the African tropical mountain system ecofloristic region are affected more severely by fire, and the model estimates a much greater loss, dropping from 152 tonnes per hectare to 15 tonnes per hectare—about 90 percent of initial carbon stock in relative terms.

FIGURE A3.10: AREA COVERED BY THE TROPICAL MOUNTAIN SYSTEM ECOFLORISTIC REGION IN SOUTH SUDAN

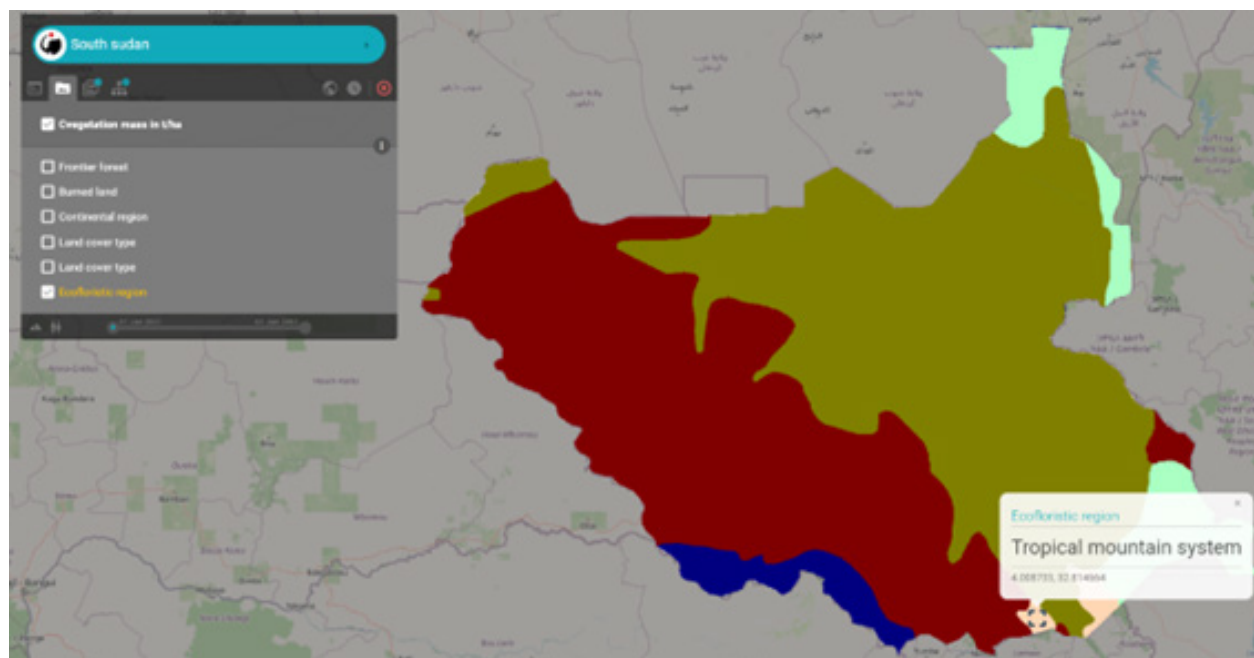


FIGURE A3.11: CARBON STOCK ESTIMATED FOR A NON-BURNED AREA IN TROPICAL MOUNTAIN SYSTEM ECOFLORISTIC REGION IN SOUTH SUDAN

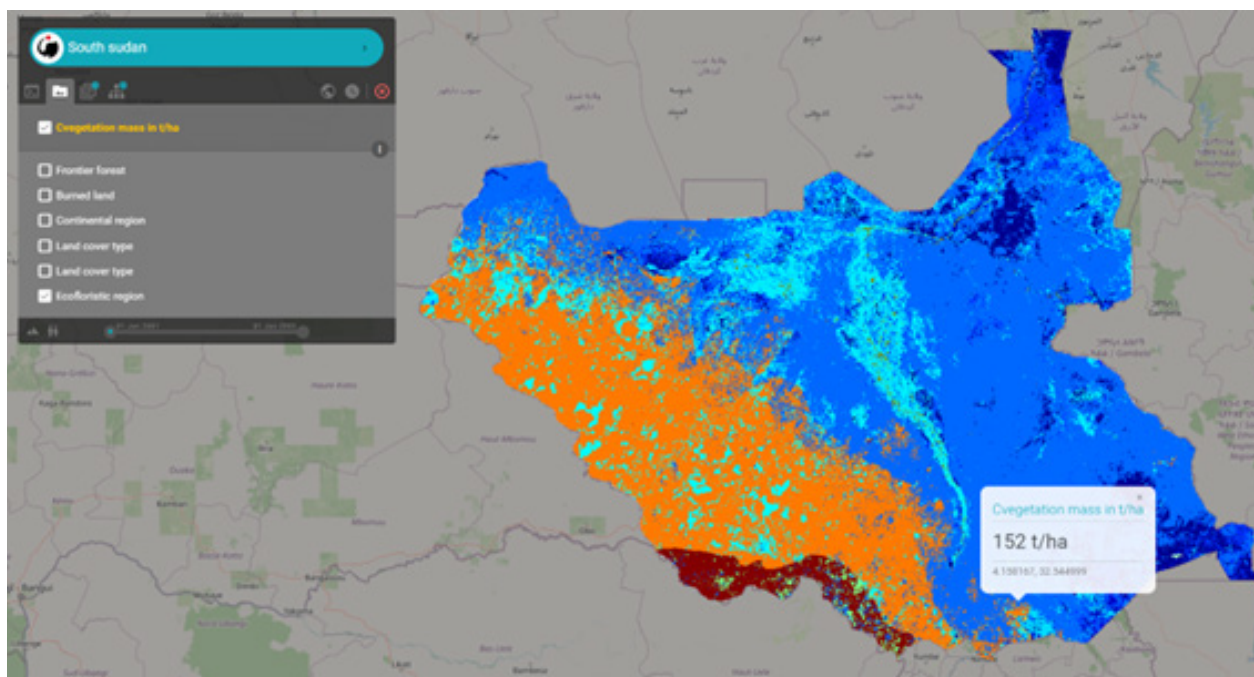
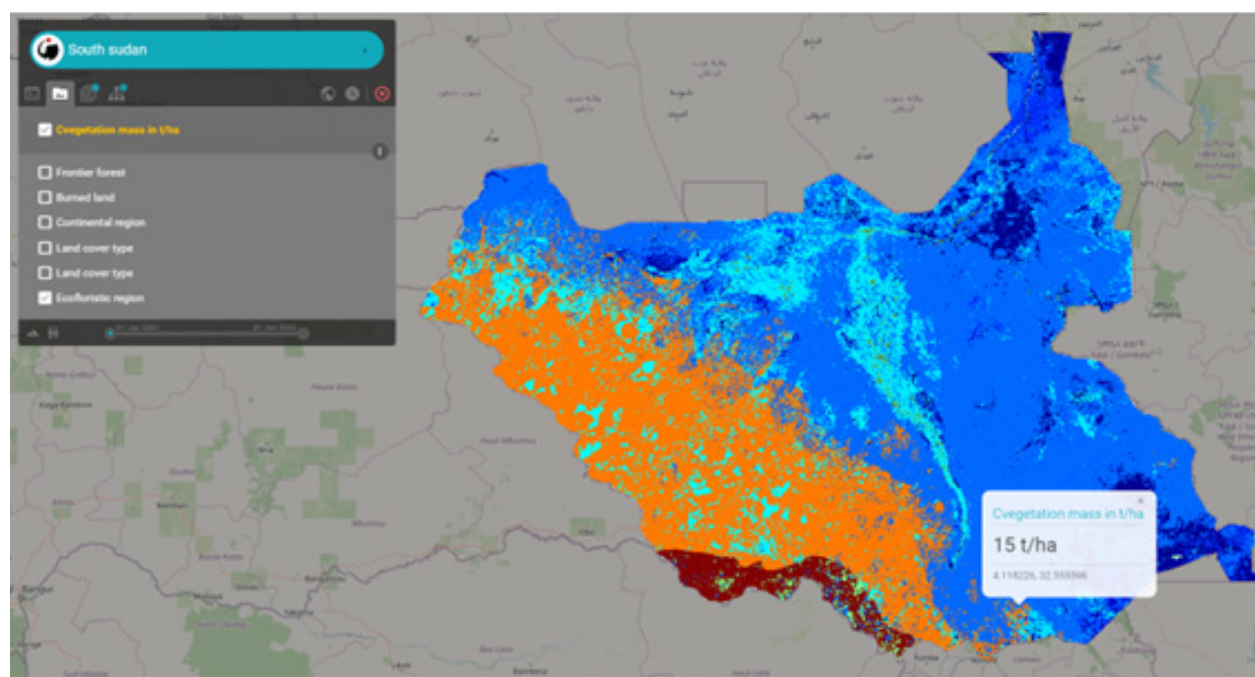


FIGURE A3.12: CARBON STOCK ESTIMATED FOR A BURNED AREA IN TROPICAL MOUNTAIN SYSTEM ECOFLORISTIC REGION IN SOUTH SUDAN



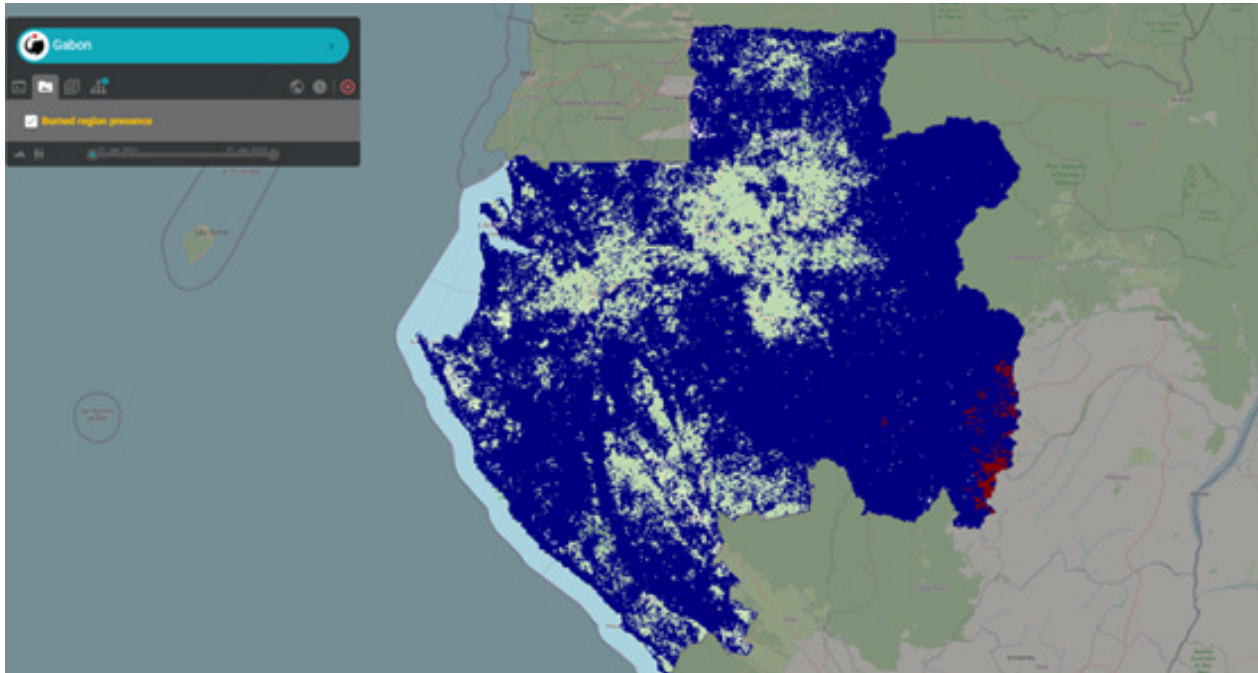
The above examples illustrate how reductions in carbon stock can be caused by burned vegetation as well as changes in the extent of land cover, and the magnitude of the change also depends on the ecofloristic region in which the change takes place.

Another concern relates to how the model treats a lack of information on the presence of fire. In most cases, only a few limited areas are not covered by the data, but when data gaps are extensive in areas where fires play an essential role, modeled changes

may result from missing data. A significant example was the increase shown in vegetation carbon stock in Gabon between 2001 and 2002. Almost 99 percent of this total increase could be attributed to data that showed higher stocks of Gabon's broad-leaved evergreen forests,³³ which had actually declined in extent during that time by 10,000 hectares due to fires, corresponding to a 0.04 percent reduction from the previous year. This counterintuitive output is due to the missing information on the presence of fires.

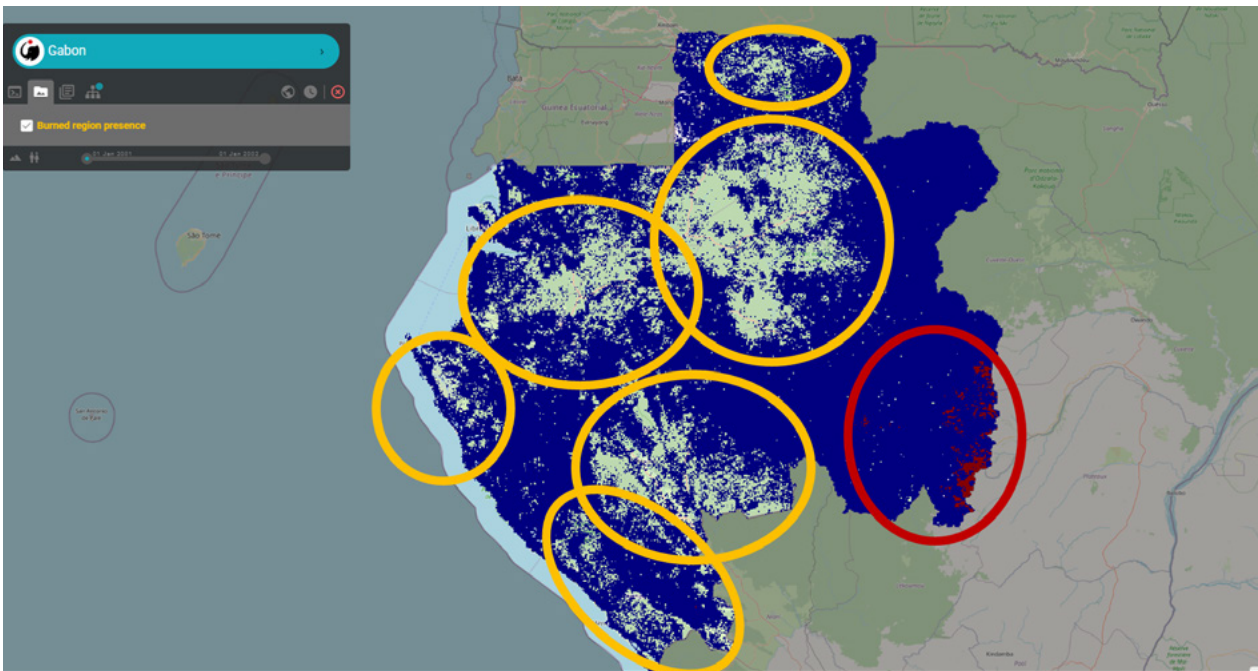
33 Equivalent to the tree cover, broadleaved, evergreen, closed to open (>15 percent) class in the ESA-CCI classification, identified with the code 50.

FIGURE A3.13: PRESENCE OF BURNED LAND IN GABON



In the maps above, red corresponds to burned areas, blue to unburned areas, and pale green areas (highlighted with yellow circles in the image below) to data gaps in the MODIS burned area product, most likely due to persistent cloud cover.³⁴

FIGURE A3.14: PRESENCE OF BURNED LAND IN GABON WITH LEGEND



³⁴ https://lpdaac.usgs.gov/documents/875/MCD64_User_Guide_V6.pdf/section 3.13 Metadata.

A simple fix for this situation would be to assume that the areas with no data experienced no fires, but domain experts strongly discouraged this approach, because this assumption would be difficult to defend and would deviate from the original methodology proposed by Gibbs and Reusch. Indeed, data gaps for fire presence only affect model results in regions prone to fire. Thus, forest ecosystems are the most affected by this lack of information, whereas the effect on other ecosystems is relatively insignificant.

Data gaps for burned areas can also lead to an increase in vegetation carbon stock between two observed years. For example, comparing vegetation carbon stocks in Gabon in 2002 and 2003, the extent of data gaps is much smaller, and so the unburned area increases significantly, which in turn leads to a significant increase in 2003 vegetation carbon stock, as there is enough evidence to assume that a large extent of the region was not burned in that year.

FIGURE A3.15: GABON 2002: PRESENCE OF FIRE

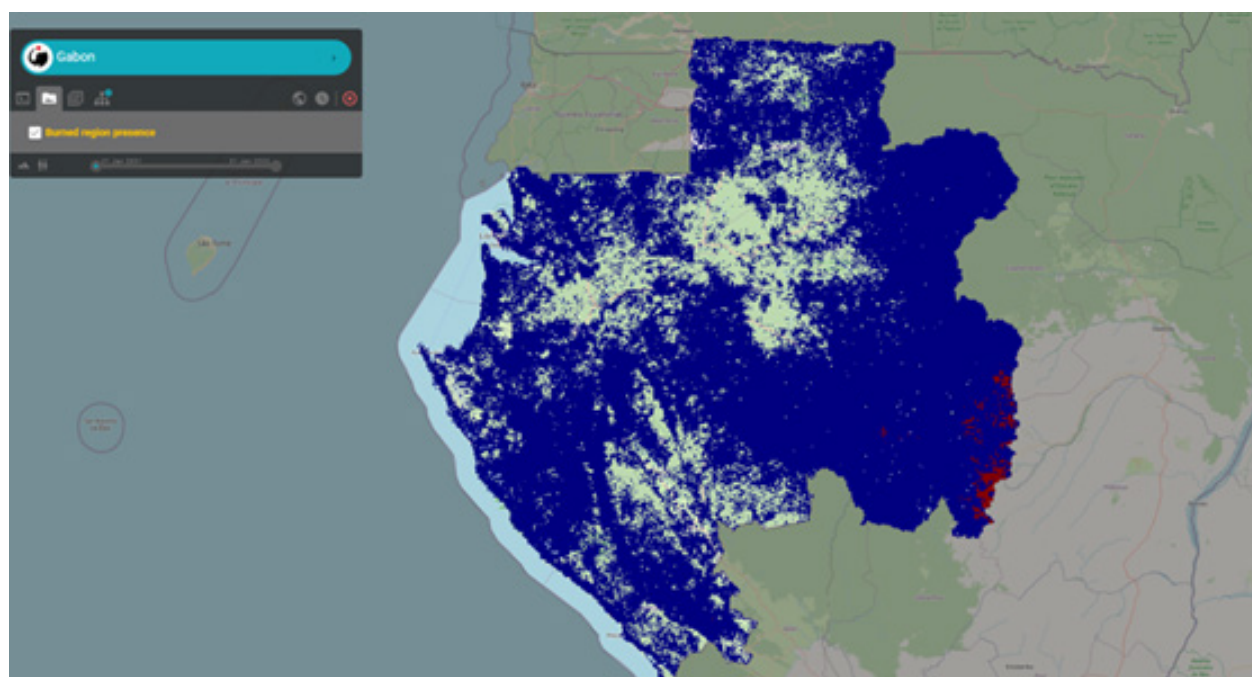
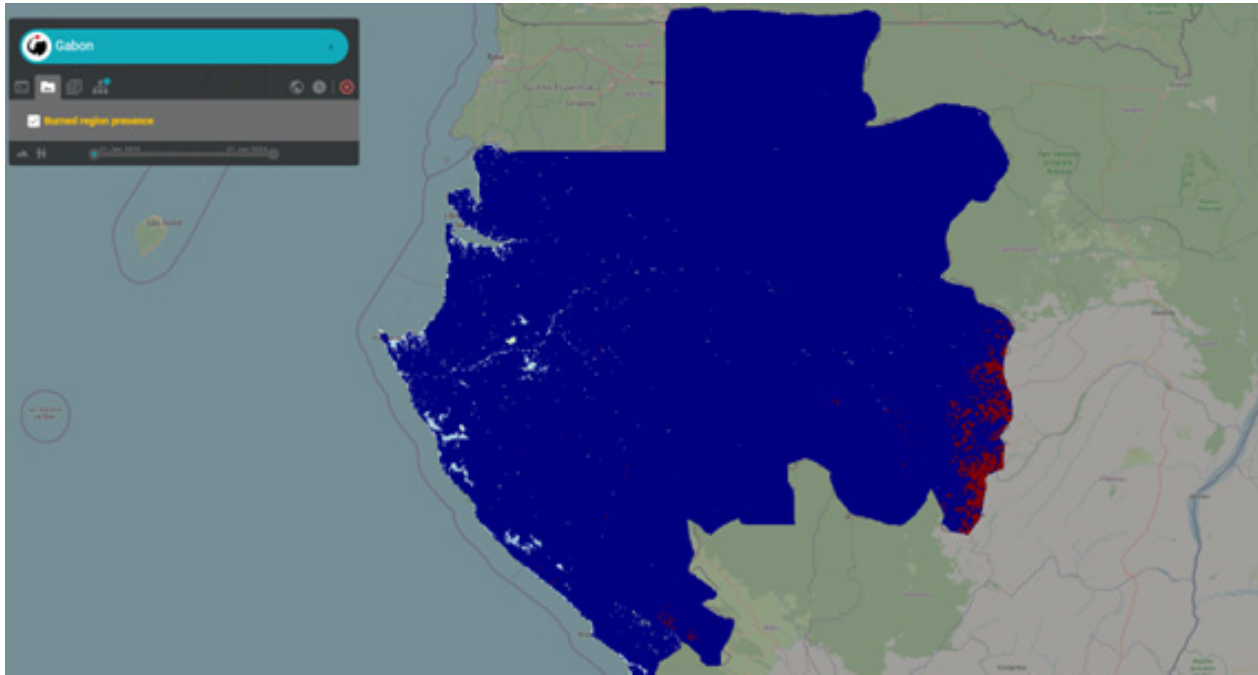


FIGURE A3.16: GABON 2003: PRESENCE OF FIRE



For the above reasons, such cases have been flagged in the results, so that the user can accurately interpret these changes, which are based on the availability of information, rather than changes in the ecological characteristics of the forests over a single year.

Planned model improvements related to forest aging and post-fire dynamics will improve results for such cases and smooth out these issues whenever sufficient information exists to provide more accurate outputs. As such, large changes, such as the case shown above, should be observed less frequently in the future.

Appendix 4: Report of the causes of large changes in vegetation carbon stock of individual land cover classes

For full transparency of the results, the table below shows the main driver of all the large changes observed for a land cover class, over each period observed in the time series. The cases report such information for any change in the vegetation carbon stock of a land cover class that accounted for a significant increase or decrease in the total vegetation carbon stock in a country, as shown in the equation below:

$$|(LC_{1t_2} - LC_{1t_1}) / \text{Tot.VCSt}_1| > 3\%$$

where:

- LC_{1t_2} is the contribution to the vegetation carbon stock of the land cover class #1 at time 2
- LC_{1t_1} is the contribution to the vegetation carbon stock of the land cover class #1 at time 1
- Tot.VCSt_1 is the total vegetation carbon stock from all LC classes at time 1.

For each case in which a single class is directly responsible for a change in the country's total carbon stock (loss or increase) of at least 3 percent, the reason for that change is explicitly reported in the tables below.

TABLE A4.1: ANALYSIS OF LARGE DEVIATION

LEGEND	FIRE OCCURRENCE	LOSS OF VEGETATION CARBON STOCK DUE TO FIRES
	No data (fire)	Lack of data (fire)
	LC change	Loss of vegetation carbon stock due to land cover change
	Fire*	Fire occurrence + lack of data (fire)
	LC change*	Land cover change + lack of data (fire)

TIME PERIOD	2001–2002				
LAND COVER/ COUNTRY	HERBACEOUS COVER	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	TREE COVER, FLOODED, SALINE WATER
South Sudan				-11%	
Gabon		24%			
Equatorial Guinea		10%			
São Tomé and Príncipe		-9%			
Congo		4%			
Central African Republic				-3%	
Togo				-4%	
Guinea				-3%	
Ghana				-5%	
Côte d'Ivoire				-6%	
Benin				-8%	
Dominica		11%			
Grenada		13%			
Saint Kitts and Nevis		9%			
Montserrat (UK)		5%			
Panama		11%			
Colombia		5%			
Singapore					-5%
Monaco	-5%				
Papua New Guinea		6%			
Vanuatu		3%			
Wallis and Futuna (Fr.)		4%			
American Samoa (US)		6%			
Saint Vincent and the Grenadines		10%			
Curaçao (Neth.)			3%		
Sint Eustatius (Neth.)		8%			
Saint-Martin (Fr.)		5%			

TIME PERIOD	2002–2003					
LAND COVER CLASS/ COUNTRY	SHRUB- LAND	SHRUB OR HERBACEOUS COVER, FLOODED, FRESH/SALINE/ BRACKISH WATER	MOSAIC CROPLAND (>50%)/NATURAL VEGETATION (TREE, SHRUB, HERBACEOUS COVER) (<50%)	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	TREE COVER, NEEDLELEAVED, EVERGREEN, CLOSED TO OPEN (>15%)
Uganda			-4%			
São Tomé and Príncipe		53%				
Central African Republic			-6%			
Senegal			8%			
Benin			3%			
Grenada		3%				
Montserrat (UK)				4%		
Panama		6%				
Ecuador		7%				
Monaco	-6%				-3%	
Wallis and Futuna (Fr.)		5%				
Saint Vincent and the Grenadines		8%				
Sint Eustatius (Neth.)				6%		-6%

TIME PERIOD	2003–2004				
LAND COVER CLASS/ COUNTRY	SHRUB OR HERBACEOUS COVER, FLOODED, FRESH/SALINE/ BRACKISH WATER	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	TREE COVER, FLOODED, SALINE WATER
Uganda			4%		
São Tomé and Príncipe		-13%			
Central African Republic			5%		
Togo			4%		
Senegal			-5%		
Nigeria			4%		
Ghana			9%		
Côte d'Ivoire			5%		
Benin			3%		
Bolivia		-4%			
Vanuatu	-9%	17%			
Sint Eustatius (Neth.)				5%*	-6%

TIME PERIOD	2004–2005			2005–2006			
LAND COVER CLASS/ COUNTRY	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	TREE COVER, NEEDLELEAVED, EVERGREEN, CLOSED TO OPEN (>15%)
South Sudan						8%	
Uganda			-6%			14%	
São Tomé and Príncipe	18%			5%			
Togo			-6%			4%	
Nigeria			-4%			3%	
Ghana			-7%				
Côte d'Ivoire			-5%				
Benin			-7%			5%	
Cambodia		4%*			-3%*		
Guernsey (UK)							-3%
American Samoa (US)	-3%						

TIME PERIOD	2006–2007			2007–2008		
LAND COVER CLASS/ COUNTRY	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	TREE COVER, NEEDLELEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	MOSAIC TREE AND SHRUB (>50%)/ HERBACEOUS COVER (<50%)
South Sudan		-3%				
Uganda		-8%				
São Tomé and Príncipe	-13%			10%		
Guinea-Bissau					4%*	
Benin					3%	
Ecuador	-3%			3%		
Macau; SAR						-3%
UN Buffer Zone in Cyprus			-6%			4%

TIME PERIOD	2008–2009		2009–2010		2010–2011		
LAND COVER CLASS/ COUNTRY	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	TREE COVER, NEEDLELEAVED, EVERGREEN, CLOSED TO OPEN (>15%)
South Sudan						-3%	
Uganda		4%		-3%		5%	
São Tomé and Príncipe	-7%		7%		-13%		
Central African Republic		5%					
Togo						-3%	
Ghana						-4%	
Montserrat (UK)							3%*
Panama	-4%						
Ecuador					4%*		

TIME PERIOD	2011–2012			2012–2013		
LAND COVER CLASS/ COUNTRY	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	SHRUB OR HERBACEOUS COVER, FLOODED, FRESH/SALINE/BRACKISH WATER	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	SHRUB OR HERBACEOUS COVER, FLOODED, FRESH/SALINE/BRACKISH WATER
Uganda		-3%				
São Tomé and Príncipe	-17%			27%		
Central African Republic		4%				
Togo		5%				
Guinea-Bissau		-4%*			4%*	
Ghana		4%				
Ecuador				-6%*		
Macau; SAR			20%			-6%
Sint Maarten (Neth.)						-3%
Saint-Barthélemy (Fr.)	-5%			4%		
Saint-Martin (Fr.)	-3%					

TIME PERIOD	2013–2014					
LAND COVER CLASS/ COUNTRY	HERBACEOUS COVER	TREE OR SHRUB COVER	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	SHRUBLAND	SHRUB OR HERBACEOUS COVER, FLOODED, FRESH/SALINE/ BRACKISH WATER
Mauritius	8%					
São Tomé and Príncipe			-10%			
Côte d'Ivoire				3%		
Antigua and Barbuda			-7%			
Aruba (Neth.)					-4%	
Palau	7%	6%				
Sint Maarten (Neth.)						-3%
Saint-Barthélemy (Fr.)			-4%			

TIME PERIOD	2014–2015		2015–2016		
LAND COVER CLASS/ COUNTRY	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)
South Sudan		4%			-4%
São Tomé and Príncipe	12%		-8%		
Senegal		4%			-4%
Guinea					-6%
Ecuador	6%*				
Kuril islands				-5%*	

TIME PERIOD	2016–2017		2017–2018
LAND COVER CLASS/ COUNTRY	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	SHRUBLAND	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)
Guinea	4%		
Aruba (Neth.)		-4%	
Ecuador			-5%
Saint-Barthélemy (Fr.)			-4%

TIME PERIOD	2018–2019				
LAND COVER CLASS/ COUNTRY	MOSAIC NATURAL VEGETATION (TREE, SHRUB, HERBACEOUS COVER) (>50%)/ CROPLAND (<50%)	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	TREE COVER, MIXED LEAF TYPE (BROADLEAVED AND NEEDLELEAVED)	MOSAIC TREE AND SHRUB (>50%)/ HERBACEOUS COVER (<50%)
South Sudan			8%		
São Tomé and Príncipe		18%			
Monaco				-8%	4%
No Man's Land Area	-3%				3%

TIME PERIOD	2019–2020				
LAND COVER CLASS/ COUNTRY	TREE OR SHRUB COVER	TREE COVER, BROADLEAVED, EVERGREEN, CLOSED TO OPEN (>15%)	TREE COVER, BROADLEAVED, DECIDUOUS, OPEN (15–40%)	MOSAIC TREE AND SHRUB (>50%)/ HERBACEOUS COVER (<50%)	SHRUB OR HERBACEOUS COVER, FLOODED, FRESH/SALINE/ BRACKISH WATER
South Sudan			-8%		
Ghana			-4%		
Macau; SAR					-6%
Monaco				-4%	
Palau	11%				
Wallis and Futuna (Fr.)		7%			

Appendix 5: Report of the causes of large relative changes in vegetation carbon stock of individual land cover classes

Over the time series generated, there are large relative changes within each land cover class. The contribution of a land cover class to the vegetation carbon stock of a country can disappear or experience large changes in relative terms over just a single year. Those changes, however, are always associated with land cover classes whose extent was underrepresented in that context, thus small absolute changes in the underlying data (such as ESA-CCI land cover change or the availability of the information on burned land) could lead to significant relative changes. This is unsurprising, even though time-series products should be built to avoid such situations. However, it is challenging to maintain perfect consistency when producing global maps covering such a long period of time.

This appendix lists the cases in which large relative changes (for an individual land cover class contribution to vegetation carbon stock) take place, and the reason for each case:

- Djibouti: Mosaic cropland (<50 percent) increase of 200 percent in 2018: *ESA CCI LC change*
- UAE: Mosaic cropland (<50 percent) drops to zero in 2006: *ESA CCI LC change*
- Brazil: Tree cover mixed leaf type peaks and valleys between 2001 and 2005, then steady:
Burned land (NO DATA)
- Iceland: Tree cover mixed leaf type switching between hundreds and zeros: *ESA-CCI LC change and Burned land (NO DATA)*
- Central African Republic: Tree cover mixed leaf type drops to zero after 2003:
ESA-CCI LC change
- Niger: Tree cover, broadleaved, deciduous, closed to open (>15 percent) goes from zero to thousands after 2014: *ESA-CCI LC change*
- Eritrea: Tree cover, broadleaved, deciduous, closed to open (>15 percent) goes from zero to thousands after 2017: *ESA-CCI LC change*
- Ecuador: Tree cover, broadleaved, deciduous, closed to open (>15 percent) rapidly increases after 2016:
ESA-CCI LC change

- Rwanda: Tree cover, needleleaved, evergreen, closed to open (>15 percent) constant but with several valleys:
ESA-CCI LC change
- Argentina: Tree cover, needleleaved, evergreen, closed to open (>15 percent) constant with a valley in 2018:
Burned land (NO DATA)
- Mozambique: Tree cover, needleleaved, evergreen, closed to open (>15 percent) large value in 2001 then all zeros: *ESA-CCI LC change*
- Angola: Tree cover, needleleaved, evergreen, closed to open (>15 percent) large value in 2001 and 2002 then all zeros: *ESA-CCI LC change*
- Kenya: Tree cover, needleleaved, evergreen, closed to open (>15 percent) rapid drop to zero:
ESA-CCI LC change
- Nicaragua: Tree cover, needleleaved, deciduous, closed to open (>15 percent) high peaks in 2006 and 2010:
ESA-CCI LC change
- Honduras: Tree cover, needleleaved, deciduous, closed to open (>15 percent) rapid increase in 2007:
ESA-CCI LC change
- Malaysia: Tree cover, needleleaved, deciduous, closed to open (>15 percent) all zeros after 2006:
ESA-CCI LC change
- Belize: Tree cover, needleleaved, deciduous, closed to open (>15 percent) all zeros after 2012:
Burned land (NO DATA)

