CLIMATE
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Fossil Fuel Extraction in Biomass-Rich Areas Calculator (FEBAC)

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1. Fossil fuel emissions

1.1. The case of known reserves: Likely emissions

When reserves are known, the analyst is required to input all available data on reserves including the low estimate (proved, P90), the best estimate (proven + probable, P50), and the high estimate (proven + probable + possible, P10). If only one is available, the analyst should input it in as the **“best estimate."**

The analyst is also required to decide on the R/P ratio being country-based, region-based, or taking the global R/P ratio for the fuel.

<u>If Proved reserves are known:</u>

Ideally, the analyst should have the low estimate (proved reserves) as it is the least uncertain one and the estimate upon which commercial viability is usually decided for a given project. If no other estimate is available, it is important to choose **“no”** for the field, **“Do you have an estimate for non-proved reserves?"** The tool uses the reserves input data to calculate a low-end estimate for reserves for the likely emissions scenario, using equation (1).

$$Efl = p * R * d \tag{1}$$

Where,

Efl	Likely emissions from burning the fossil fuel extracted
p	Percentage depletion of the resource by the scenario analysis year
R	Low-end estimate for reserves
d	Carbon content in fossil fuel

It is important to note that the R/P ratio is used to estimate **“p”** in the equation above. For example, if the R/P ratio is 100 years for a given resource, the project start year is 2025, and the scenario analysis end year is 2100, **“p”** will be equal to **75%**, as we expect that the reservoir/ deposit would still contain reserves by the end of the century. Alternatively, if the scenario analysis end year was 2050, **“p”** will be equal to **25%**, as only 25 years of production will be executed (between the year 2025 and 2050).

<u>If Proved reserves are not known:</u>

If the analyst did not have an estimate for proved reserves, they must choose **“yes”** for the field **“Do you have an estimate for non-proved reserves?”**. If the only estimate was the 2P, the tool assumes a ratio between 2P and 1P of **~1.6** to estimate proved reserves from the **“best estimate,"** giving a 1P estimate of about 65% the 2P reserves.

The likely emissions are calculated from the 1P estimate, using equation (2).

$$Efl = p * Re * d \tag{2}$$

Where,

Efl	Likely emissions from burning the fossil fuel extracted
p	Percentage depletion of the resource by the scenario analysis year
Re	Estimated proved reserves from the 2P
d	Carbon content in fossil fuel

1.2. The case of known reserves: Potential emissions

<u>If Proved reserves are known:</u>

If only proved reserves are available, it is important to choose **“no”** for the field, **“Do you have an estimate for non-proved reserves?”**. The tool uses the proved reserves input data to calculate an average daily fossil fuel production rate by dividing proved reserves by the R/P ratio. Proved reserves are the low estimate and depend on current technical, market, and regulatory conditions. Thus it is plausible to assume that production may resume until the year 2100 if any of the aforementioned conditions change, and more reserves are discovered and moved from the Probable and Possible categories to Proved. Thus, the tool calculates potential emissions from the continued production of fossil fuel using equation (3).

$$Efp = t * s * d \tag{3}$$

Where,

Efp	Potential emissions from burning the fossil fuel extracted
t	Time between project start year and the scenario analysis end year
s	Production rate based on proved reserves and R/P ratio
d	Carbon content in fossil fuel

<u>If Proved reserves are not known:</u>

If the analyst did not have an estimate for proved reserves, they must choose **“yes”** for the field, **“Do you have an estimate for non-proved reserves?”**. If the only estimate was the 2P, the tool assumes a ratio between 2P and 1P of **~1.6** to estimate proved reserves from the **“best estimate,"** giving a 1P estimate of ~63% the 2P reserves. The tool estimates a production rate from the 1P estimate divided by the R/P ratio, and uses this production rate to calculate likely emissions, using equation (4).

$$Efp = t * se * d \tag{4}$$

Where,

Efp	Potential emissions from burning the fossil fuel extracted
t	Time between project start year and the scenario analysis end year
se	Estimated production rate based on the 1P reserves and R/P ratio
d	Carbon content in fossil fuel

1.3. The case of known production forecast: Likely emissions

When the average daily production/ extraction rate is known, the analyst is required to input the production rate and decide on the R/P ratio being country-based, region-based, or taking the global R/P ratio for the fuel.

The tool multiplies the production rate by the R/P ratio to generate a low-end estimate for reserves for the likely emissions scenario, using equation (5).

$$Efl = p * (s * r) * d \tag{5}$$

Where,

Efl	Likely emissions from fossil fuel extraction
p	Percentage depletion of the resource by the scenario analysis end year
s	Production rate input by the analyst
r	R/P ratio
d	Carbon content in fossil fuel

It is important to note that the R/P ratio is used to estimate **“p”** in the equation above. For example, if the R/P ratio is 100 years for a given resource, the project start year is 2025, and the scenario analysis end year is 2100, **“p”** will be equal to **75%**, as we expect that the reservoir/ deposit would still contain reserves by the end of the century. Alternatively, if the scenario analysis end year was 2050, **“p”** will be equal to **25%**, as only 25 years of production will be executed (between the year 2025 and 2050).

1.4. The case of known production forecast: Potential emissions

Fossil fuel emissions

The tool simply assumes that the analyst-input production rate will continue until the scenario analysis end year to estimate the potential emissions from fossil fuel extraction, using equation (6).

$$Efp = t * s * d \tag{6}$$

Where,

Efp	Potential emissions from fossil fuel extraction
t	Time between project start year and the scenario analysis end year
s	Production rate input by the analyst
d	Carbon content in fossil fuel

1.5. The case of known expansion plan: Likely emissions

When a national expansion plan is available to the analyst, the tool allows them to estimate emissions on a national, or on a block level. The difference between the two levels of aggregation is simply in the **“Number of blocks for expansion."** Table 1 explains the difference.

	National-level analysis	**Block-level analysis**
Number of blocks for expansion	**1**	**n**
Reason	The tool calculates reserves and production rates per block. Thus if the analyst wants to analyze the expansion plan for the full country, they are telling the tool to look at the project as a single block, with the caveat that the forest land area should be the sum of all the blocks included in the expansion plan.	If the analyst wants to conduct a block-level analysis, the tool assumes all blocks included in the project have an equal production capacity (a simplifying assumption) and the analyst would need to specify the number of blocks and the exact area of the block in question.

Table 1: Difference in number of block sizes for the known expansion plan case

The analyst is required to input the **“Target production rate,"** the **“Current production rate,"** and the **“Target year to complete expansion,”** which is not to be confused with the **“Project start year."** The analyst is also required to specify the R/P ratio assumption [Country, Regional, World] and specify whether they are considering non-proved reserves or not. Such choice affects likely emissions, but has a minor impact on the potential emissions. The following section explains the difference in calculations.

Fossil fuel emissions

If non-proved reserves are not considered:

For the likely emissions scenario, if the analyst was not considering non-proved reserves, the tool estimates proved reserves by multiplying **“Current production rate”** by the R/P ratio. This is to make sure that for countries with available data (i.e. the R/P ratio country configuration does not generate an error), the proved reserves estimate is equal to that from the Statistical Review of World Energy data (SRWED) (Energy Institute, 2025).

Furthermore, the tool assumes that the **“Target production rate”** would accelerate the depletion of the estimated proved reserves. Accordingly, the tool adjusts (reduces) the R/P ratio proportionate to the ratio between **“Current production rate”** and the **“Target production rate,"** to get an adjusted R/P ratio which will be used to calculate the **“Percentage depletion of the resource by the scenario analysis year."**

The tool generates the likely emissions from fossil fuel extraction, using equation (7).

$$Efl = pa * (sc * r) * d \tag{7}$$

Where,

Efl	Likely emissions from fossil fuel extraction
pa	Adjusted percentage depletion of the resource by the scenario analysis end year
sc	Current production rate input by the analyst
r	R/P ratio
d	Carbon content in fossil fuel

If non-proved reserves are considered:

For the likely emissions scenario, if the analyst was considering non-proved reserves, the tool estimates proved reserves by multiplying the **"Average production rate"** by the R/P ratio. This generates a higher estimate for reserves for a given country than in the Statistical Review of World energy data (SRWED) since the R/P ratio is constant but the production rate has increased compared to the **"Current production rate."**

The tool calculates the **"Average production rate"** for the duration of the R/P ratio from the **"Target production rate"** and the **"Current production rate"**. Furthermore, the tool assumes that the R/P ratio stays constant as more reserves will be discovered over the project lifetime. The tool generates the likely emissions from fossil fuel extraction, using equation (8).

$$Efl = p * (sa * r) * d \tag{8}$$

Where,

Efl	Likely emissions from fossil fuel extraction
p	Percentage depletion of the resource by the scenario analysis year
sa	Average production rate calculated from the target production and current production rates
r	R/P ratio
d	Carbon content in fossil fuel

1.6. The case of known expansion plan: Potential emissions

The consideration of non-proved reserves has a minor effect on potential emissions. For potential emissions, it is assumed that the **“Average production rate,"** which is estimated based on the R/P ratio, applies for a limited duration − the R/P ratio − beyond which the **“Target production rate”** becomes the basis for emissions calculation, as shown in equation (9).

For scenarios where the difference between the **“Scenario analysis end year"** and the **“Project start year"** is less than the R/P ratio, the tool takes a MAX (0, --) to prevent the second term in equation (9) from going negative.

$$Efp = [(sa * r) + MAX(0, (tf - ti - r)) * st] * d \tag{9}$$

Where,

Efp	Likely emissions from fossil fuel extraction
sa	Average production rate calculated from the target production and current production rates
r	R/P ratio
tf	Scenario analysis end year
ti	Project start year
st	Target production rate input by the analyst
d	Carbon content in fossil fuel

2. Land emissions

2.1. Land likely emissions

The analyst is required to specify the total area of the block (forest land disturbed by the fossil fuel extraction project), as well as the expected level of disturbance based on a 3-point scale of low, medium, and high disturbance.

The tool calculates likely emissions from forest disturbance using equation (10).

$$Ell = A * q * c \tag{10}$$

Where,

Ell	Likely emissions from forest land disturbance
A	Area of block(s)
q	Cumulative % of the block area disturbed (likely case)
c	Carbon density of forest land

The cumulative percentage of block area disturbed by the fossil fuel activities is based on direct factors including infrastructure such as wells, refineries, and roads as well as road building and indirect factors such as colonization of forest land by migrant workers. The study period of Robertson (2021) was 18 years, which we refer to as the **"maximum land disturbance period."** Therefore, if the analysis period (the difference between the project start year and the scenario analysis end year) is higher than 18 years, the tool only uses the 18 years to estimate likely emissions. If the analysis period is less than 18 years, the tool uses the lower number and multiplies it by the annual rate of disturbance (as a % of total block area).

Carbon density of forest land is an assumption of the tonnage of CO_2 that will be released per hectare of forest land disturbed by a fossil fuel extraction project.

Carbon density is calculated from Carbon stock (Above ground biomass Carbon, Below ground biomass Carbon, and Soil Carbon) per hectare of land multiplied by a degradation fraction, assumed by the tool as 90% of biomass Carbon and a dynamic soil Carbon degradation factor (with a maximum of ~30%) when a given area of forest land is cleared – See **Assumptions** for details.

2.2. Land potential emissions

The tool calculates likely emissions from forest disturbance using equation (11).

$$Elp = A * u * c \tag{11}$$

Where,

Elp	Potential emissions from forest land disturbance
A	Area of block(s)
u	Cumulative % of the block area disturbed (potential case)
c	Carbon density of forest land

The cumulative percentage of block area disturbed by the fossil fuel activities in the potential emissions case relaxes the assumption of the **"maximum land disturbance period"** of 18 years, and enables land disturbance to continue up to the scenario analysis end year. The other terms of the above equation remain unchanged from the likely emissions calculation.

3. Assumptions

3.1. R/P ratio and the rate of fossil fuel depletion

In the fossil fuel industry, the concept of R/P ratio (measured in years) is used to describe the relationship between proved reserves and fossil fuel production on a national/ regional/ global level. It is measured in years, and is simply proved reserves divided by the annual production rate.

R/P ratios can be used to estimate reserves if production rates were known and reserves were unknown. R/P ratios can also be used to estimate whether a known quantity of reserves will be depleted by a specific date, at current reserve levels and under existing economical and technical conditions.

We leveraged the Statistical Review of World energy data (SRWED) (Energy Institute, 2025), which includes data as far back as the 1960s to estimate country-specific reserves-to-production ratios (R/P ratios).

3.1.1. Countries with data on proved reserves and production rates

We calculated the R/P ratios for oil, natural gas, and coal for all countries listed in the SRWED (n=55 for oil, n=56 for gas, n=40 for coal) using the most recent proved reserves (2020) and production rates (2024 for oil & gas, 2020 for coal). This ensures that when the tool is used on a country-level test case, the estimate for reserves and production rates will be consistent with the latest available country-level data.

Thus for country-level data use cases II and III, this approach estimates reserves consistently with the SRWED data.

3.1.2. Countries with no data proved reserves and production rates

For countries with no historical data on proved reserves or fossil fuel production, we calculate regional R/P ratios from the country-level data using a median based approach (to limit the impact of outlier countries in any given region) as described below.

Initially we used an aggregate approach, where the total regional historical reserves were averaged (1980-2020 for oil & gas, 2020 for coal), then divided by the total average regional production rates (1980-2020 for oil & gas, and 2020 for coal) to estimate the regional R/P ratios.

Table 2 outlines our choice for the above timeframes for averaging.

Fossil fuel	Historical timeframe	Comment
Oil	1980-2020	Since reserves data only go as far back as 1980-2020, while production data is from 1965 to 2024.
Gas	1980-2020	Since reserves data only go as far back as 1980-2020, while production data is from 1970 to 2024.
Coal	2020	The only data available in SRWED (Energy Institute, 2025).

Table 2: years of historical data used for estimating regional R/P ratios

The reason for taking the average total historical value is to make use of the extensive data available in the SRWED to estimate regional R/P ratios instead of relying on the most recent single data point. Furthermore, no validation is possible for countries of missing data, for example checking if our R/P ratio generates an accurate reserves estimate if combined with a known country-level production rate (unlike countries with data) so there is no need to limit our estimates to the most recent data point.

However, the distributions of R/P ratios on a global, as well as regional, level are mostly skewed, as shown in the frequency plots for global oil (1980-2020), gas (1980-2020), and coal (2020) in Figure 1.

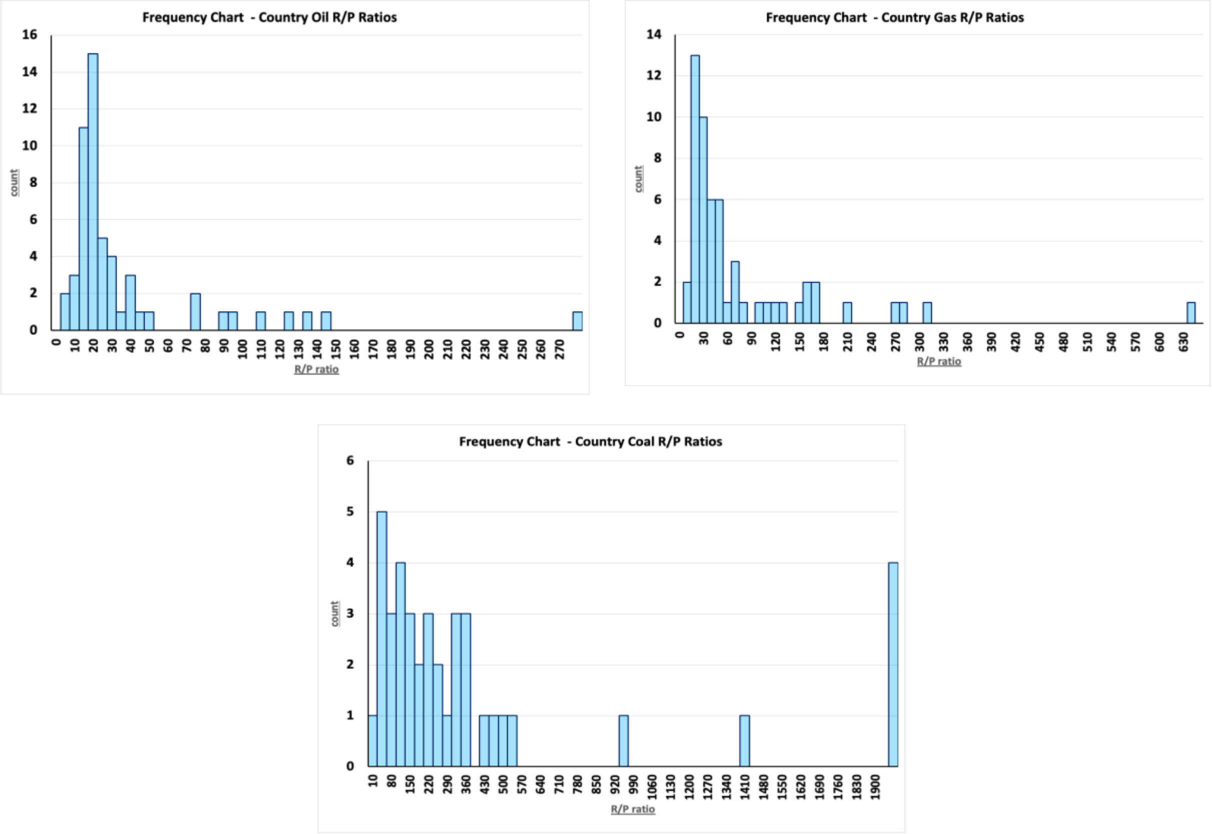


Figure 1: Frequency plots of country R/P ratios from the SRWED

Some outlier countries (e.g. Venezuela for gas in South and Central America and Canada for oil in North America) inflated the regional estimate to an extent that may not be relevant for countries that do not currently produce any fossil fuels. Thus we opted for a median-based approach to err on the side of caution in our estimation of regional R/P ratios.

Figure 2 compares the regional R/P ratios estimated using the total regional approach versus the median country in each region.

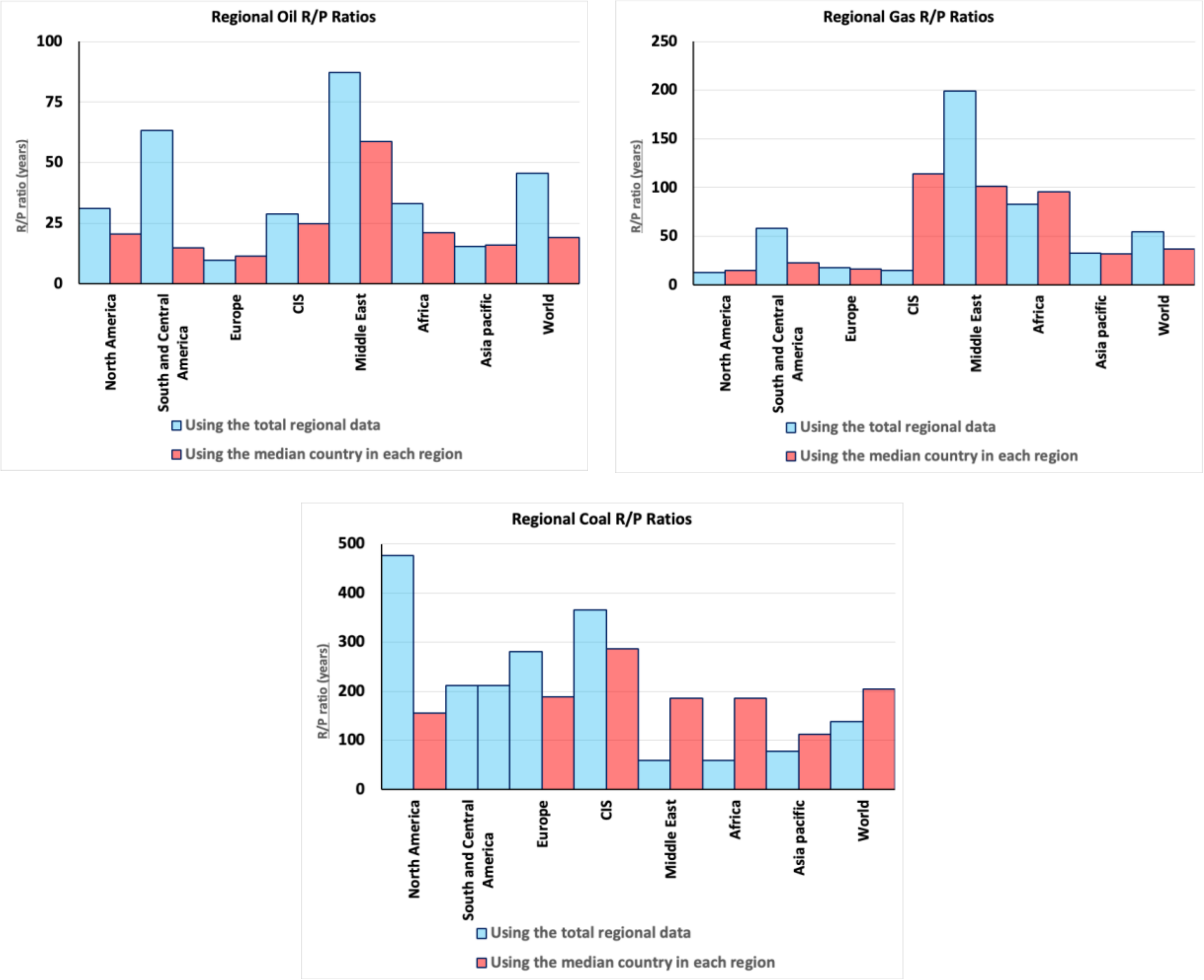


Figure 2: Bar charts of regional R/P ratios using the two approaches outlined (aggregate v median)

It is clear that for oil, the median approach yields smaller R/P ratios in most regions *(which lowers emissions from fossil fuels for Cases II and III - where reserves are estimated from production rates & R/P ratios, but may increase the likely emissions for Case I where R/P ratio is used to calculate depletion of the reserves by the scenario analysis end year).*

However, the median approach yielded higher R/P ratio estimates for some cases, for example where the data is left-skewed. One significant case is that of [South and Central

America, coal] which had outliers with R/P ratios of more than 900 years (due to very low production rates), such that we used the total regional data instead.

Table 3 summarizes the R/P ratios by region for the 3 fossil fuels considered.

Region	Oil (years)	Gas (years)	Coal (years)
North America	21	15	156
South and Central America	15	23	212
Europe	11	16	189
CIS	25	114	286
Middle East	59	101	186
Africa	21	96	186
Asia pacific	16	32	113
World	19	37	205

Table 3: Calculated regional R/P ratios for oil, gas, and coal

3.1.3. Limitation of the approach used to calculate the R/P ratio

We did not extrapolate trends in reserves/ production rates, and thus R/P ratios, although such trends exist in the historical data from (Energy Institute, 2025) as shown in Figure 3.

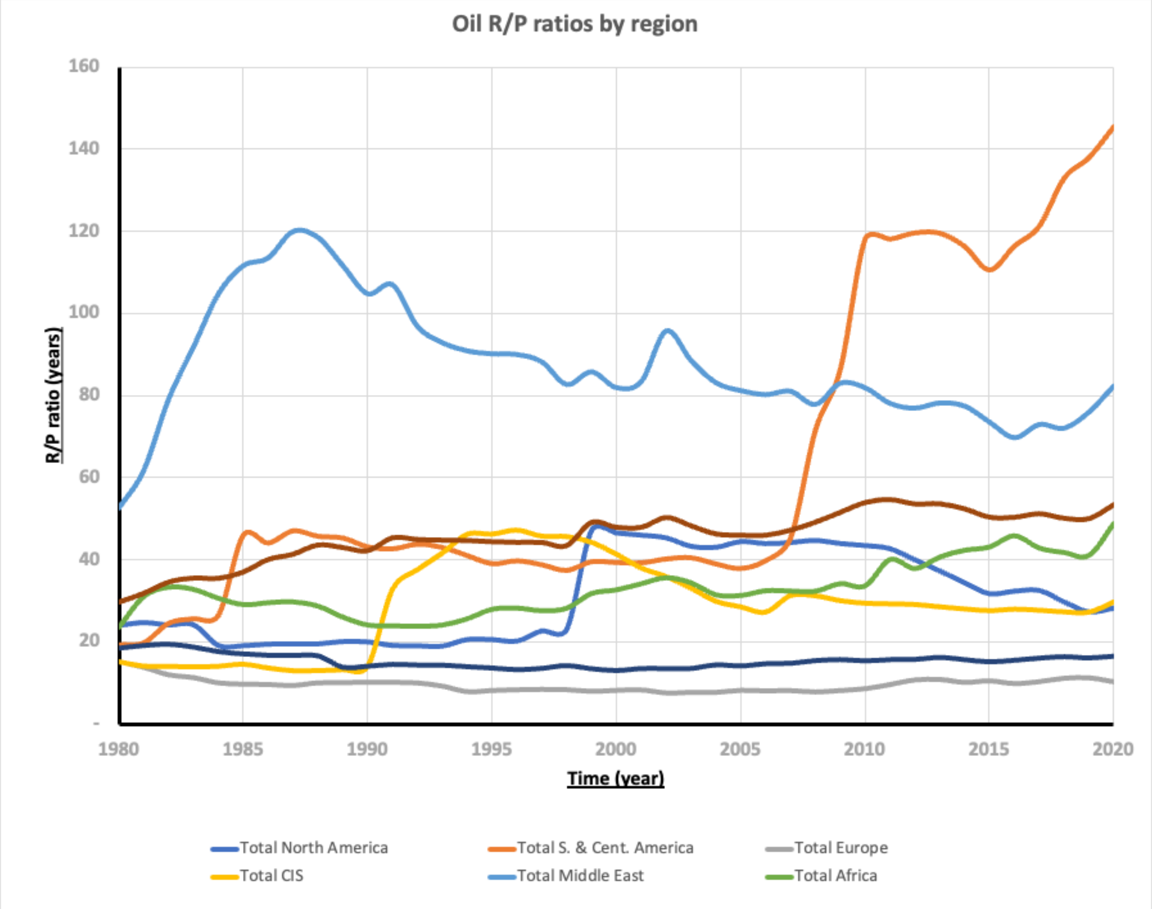


Figure 3: Regional R/P ratios (1980-2020)

This is because there is an additional level of uncertainty in any projections we would make regarding the R/P ratio. We thus take the simplistic approach of the most recent R/P ratio for countries for which we have data, and a cautiously conservative approach to estimating the regional figures for countries with missing data using the median of the 40-year average R/P ratio of countries for which we do have data (to limit the effect of outlier countries on the regional estimates).

Figure 4 demonstrates the approach followed. The dashed lines represent countries from which the regional R/P ratio estimates were calculated. The graph only extends to 2050 to better track historical trends (1980-2020).

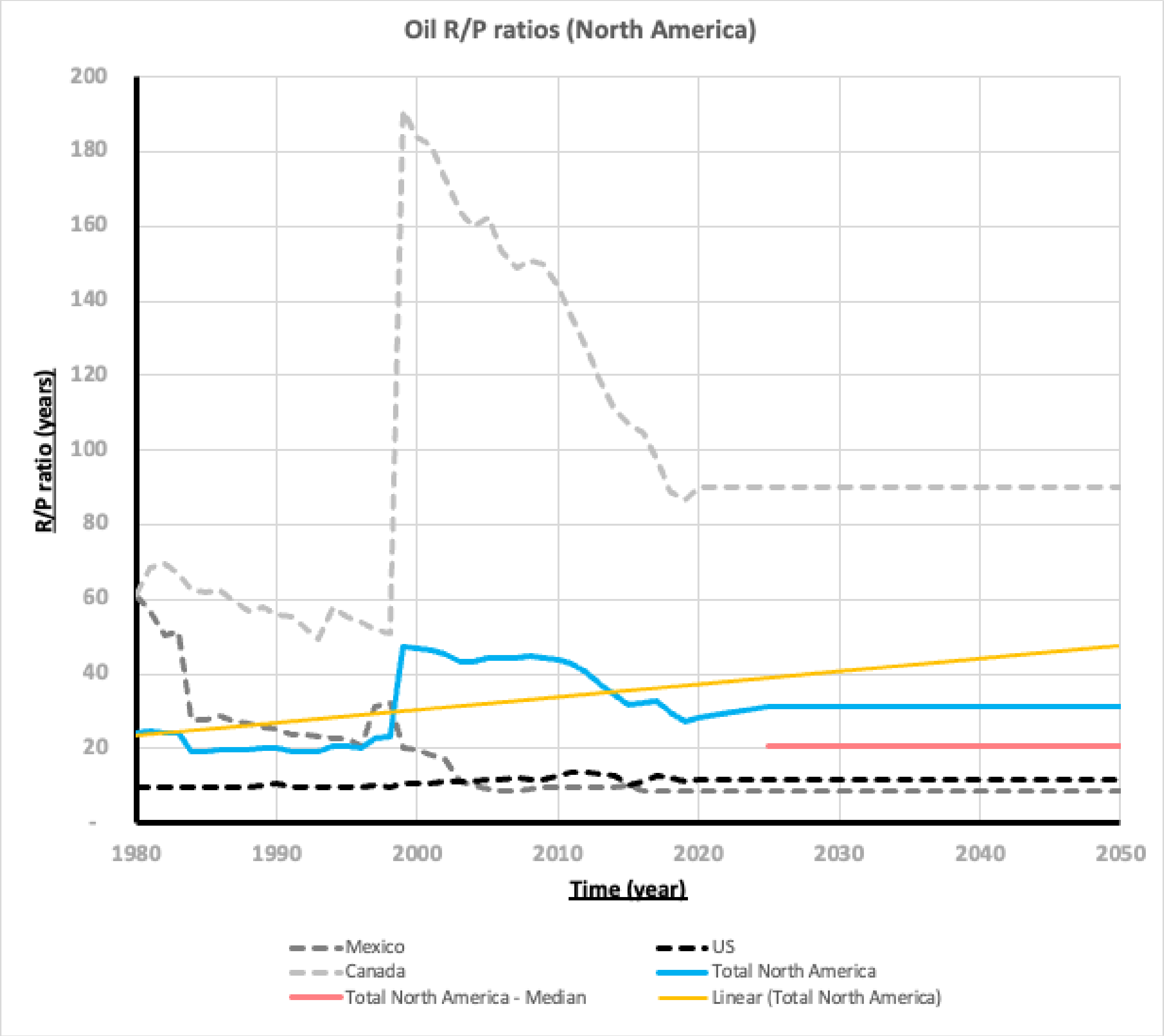


Figure 4: R/P ratios for North America (1980 – 2050)

For use cases where the country of interest is either Canada, Mexico, or the US, we calculate the R/P ratio from the latest reserves estimate (2020) and the latest production estimate (2024). This is to make sure we take the most recent data into our calculations, especially if the analyst is conducting a country-level analysis for where we have reserves/ production data.

In Figure 4, the solid blue line represents the total aggregate approach: where the total reserves of the region (sum of the reserves of the 3 countries) is divided by the total production of the region (sum of the production of the 3 countries), and with the value at 2020 extended until the year 2100. The solid yellow line represents the trend of the regional R/P ratio, calculated using the aforementioned aggregate approach. As mentioned, we opted against taking such trends into account since they are difficult to explain and are highly uncertain.

The solid red line in Figure 4 is the R/P ratio used in the tool, calculated as the median of the 40-year average country data (1980-2020 for oil & gas, 2020 for coal). Figure 4 shows that Canada is an outlier, which raises the mean relative to the median. The US is a relatively stable value and the lowest of the 3 countries (1980-2020), with Mexico being the regional median. The graph also shows how the solid red line is around midway between the highest and lowest R/P ratios for Mexico (1980-2020). Table 4 summarizes the approach followed to estimate the median regional R/P ratio.

Region	Average R/P ratio in years (1980-2020)
Canada	107
Mexico	**21**
US	11
Total North America	31
North America (Median)	**21**

Table 4: forty-year average R/P ratios for North America

Finally, future work can take into account trends in R/P ratio, by making projections for reserves and production rates using historical data. This would complicate the face validity of the results generated by the tool as it would not generate current estimates for reserves but rather the projections.

The next section discusses carbon emissions from fossil fuels.

3.2. Estimating Proved reserves from the "Best estimate"

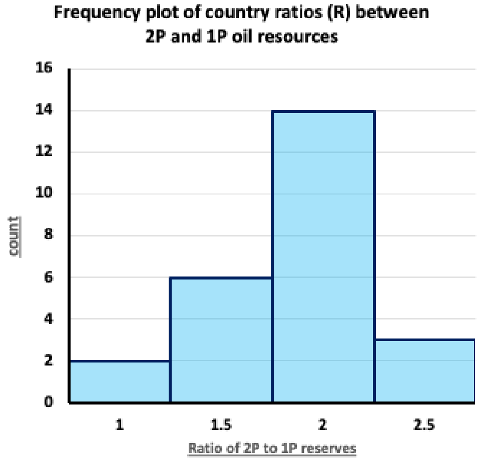
In some rare cases, the analyst will only have a **"Best estimate"** for reserves (sometimes denoted as 2P or P50), and no estimate for **"Proved reserves"** (sometimes denoted as the 1P or P90).

In such cases, we calculate **"Proved reserves"** from the **"Best estimate"** using an aggregate global assumption for the ratio **"R"** between 2P and 1P oil reserves from Rystad Energy's estimates for global 1P and 2P oil reserves (Nysveen & Busby, 2024) estimating **R~1.6**.

Literature such as Bentley et al. (2007) and McGlade & Ekins (2014) suggest a similar ratio when taking the median of country estimates where 2P>1P. These two studies compared 1P estimates to 2P estimates from different independent data sources, resulting in some mismatches such that for some countries 1P>2P, inconsistent with the definition of 2P being the sum of Proved (1P) reserves and Probable reserves.

The Rystad Energy data is more recent, internally consistent (P2>P1 for all countries), and has broader coverage (n=25) thus it was selected as the preferred source. However, we note that the Rystad 1P estimate is much less (449 Billion barrels of oil) than the 1P estimate we use for R/P ratio calculation from Energy Institute's Statistical Review of World Energy Data (1,732 Billion barrels of oil) due to different methodologies and assumptions. Hence, we do not try to compare the magnitude of reserves rather only take the ratio between 2P and 1P from Rystad Energy. Figure 5 shows the distribution of the observations, and descriptive statistics from Nysveen & Busby (2024).

Finally, we assume the estimated ratio applies to gas and coal.



Mean	1.67
Mean (excluding outliers)	1.59
Median	1.63
1st Quartile	1.50
3rd Quartile	1.80
Max	2.50

Figure 5: Distribution and descriptive statistics of country R ratios from Nysveen & Busby (2024)

3.3. Carbon in fossil fuels

We average the results from the US EPA Greenhouse Gas Equivalencies Calculator (US EPA, 2025) and the Greenhouse gas reporting: conversion factors (2025) (UK Department for Energy Security and Net Zero, 2025) to estimate the direct/ combustion emissions for each fossil fuel.

We used the EIA's Lifecycle Upstream Emission Factors 2023 (Pilot Edition) - Database Documentation (International Energy Agency, 2023, p. 30) to estimate upstream emissions associated with the raw material extraction, material and component manufacturing, and transport to capture the lifecycle emissions associated with each fuel. The study estimated 16-20% of the combustion emissions from electricity generation were associated with upstream factors. We do not know the end use of the fossil fuels extracted, thus to err on the side of caution we reduced our estimates of upstream emissions to 8-10% of combustion emissions.

We cross-referenced the assumption for oil (used more as a fuel for transport than for electricity generation) via the International Council on Clean Transportation (ICCT) et al., (2014) and found it to average between 5-12%.

Table 5 shows the direct emissions factor per unit of fossil fuel, and the total emissions factor adding 8-10% of the direct emissions as upstream emissions.

Fossil fuel	Direct emissions factor	Total emissions factor	Unit
Oil	0.433	0.477	Tons CO_2/ barrel
Natural gas	0.002	0.0022	Tons CO_2/ m^3
Coal	2.22	2.39	Tons CO_2/ ton

Table 5: Direct and Total (direct + upstream) emission factors per unit of fossil fuel

3.4. Carbon in forests

3.4.1. Carbon in biomass

Forest biomass can be categorized into above-ground biomass (AGB), and below-ground biomass (BGB). Around 50% of such biomass is Carbon (De Sy et al., 2019). BGB is usually calculated as a fraction of AGB, subject to a root-to-shoot ratio (RSR). RSR differs by biome and geographical region ranging between 19% to more than 40% (Huang et al., 2021, Table S3/ S4).

Saatchi et al. (2011) outlined an approach for estimating BGB from AGB, but we opted for an empirical approach given data availability.

Data from the Global Forest Watch (GFW) (Global Forest Watch, 2024) was utilized to provide the basis for land emissions calculations. We used a forest selection threshold of >30% canopy density.

The GFW Bulk data with global coverage (n=213) was available only for total AGB density (tons/ ha) from Harris et al. (2021), and soil C density (tons/ ha) from Sanderman et al. (2018). However, bulk data was not available for AGB Carbon, and BGB Carbon densities, which required a manual effort to get data for each country. We thus sampled a subset of countries (n=56) corresponding to the major countries with existing oil production to empirically estimate the percentage of AGB Carbon (47%) from AGB, and to estimate regional RSR values as shown in Table 6.

Region	Sampled root-to-shot ratio (RSR)
North America	27%
South and Central America	26%
Europe	29%
CIS	37%
Middle East	48%
Africa	30%
Asia pacific	28%

Table 6: Regional root to shoot ratios from sampled data

The AGB C density calculated was then multiplied by the Regional RSR values to estimate the BGB C density. Figure 6 shows the predicted values of BGB density for the sampled countries (excluding 1 outlier – Oman).

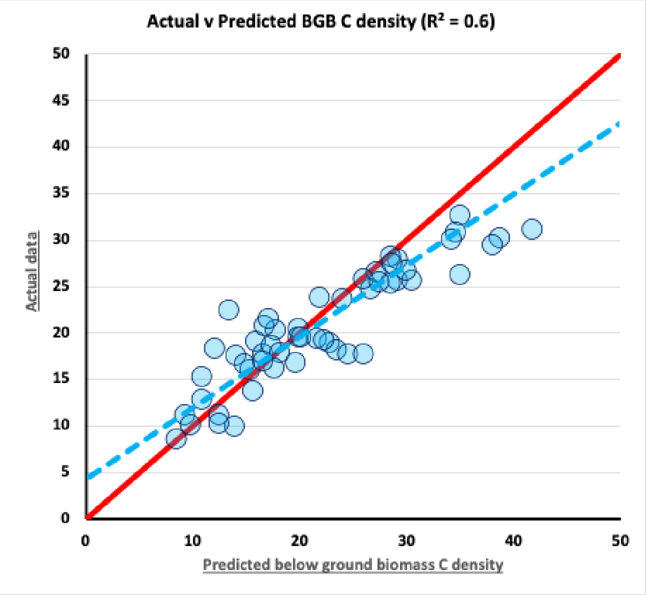


Figure 6: Plot of Predicted v data BGB C density

Having estimated the AGB C and BGB C, we proceeded to calculate Soil C.

3.4.2. Carbon in soil

Bulk data with global coverage (n=214) was available for Soil C density (30 cm soil depth) from Sanderman et al. (2018), which was validated using the sampled subset (n=56) described above.

With the Carbon density of AGB, BGB, and Soil available for each country, the next step was to estimate the proportion of such Carbon we expected to be degraded with deforestation.

3.4.3. Forest land degradation

Literature takes all forest C biomass to be Gross emissions as a result of deforestation (e.g. Harris et al. (2012)). The net emissions are a function of land use post-deforestation. Due to the high uncertainty on the nature of the land disturbance, we adopted the conservative approach to estimate net emissions from forest degradation, as outlined below.

We used the average (3 regions) % Carbon lost due to “All land uses” as the degradation fraction for AGB+BGB from De Sy et al. (2019, Fig. 5), of 90%. This means that for a given Carbon density, 90% of that Carbon will be released as net emissions due to deforestation.

For Soil C degradation, literature presents a range of values. Müller et al. (2024) estimated ~41.2% loss in topsoil (30 cm) Carbon when converting forest land to agricultural land over a period of 30 years. Van Straaten et al. (2015, Fig. S6) estimated a relationship over time of loss in topsoil (10 cm) C of ~32% by studying 3 plantation crops in Cameroon, Indonesia, and Peru. This is in line with the global meta-analysis by Don et al. (2011) estimating the loss in soil organic carbon (SOC) to range between 25–30% when forest land is converted into cultivated land.

Given the time-varying nature of Soil C loss/ emissions, we calculated the annual rate of ~1.4%/ year based on Müller et al. (2024) – 41.2% over 30 years, and ~1.0%/ year based on Van Straaten et al. (2015), taking the lower estimate of both of 1.0%/ year.

Given that most of the loss in Soil C occurs over the 1st 30 years from Van Straaten et al. (2015), we multiply the soil C loss rate (1.0% per year) by the minimum of the duration between the present moment and the scenario analysis end year or 30 years, with a maximum of ~30% Soil C loss and a minimum of ~5% for scenarios up to the year 2030.

3.5. Validation of forest Carbon data

3.5.1. Validation of forest Carbon data with results from literature

We validated our biomass C (not including soil C) emissions against the results of Harris et al. (2012, Table S2) reporting gross C emissions from deforestation in tropical regions.

We calculated the C emissions per unit area from Table S2 in tons/ hectare for the high-end estimate. We then plotted the result against our estimated GROSS C emissions from GFW data for (AGB+BGB) for a subsample (n=73) countries included in Harris et al. (2012). Figure 7 demonstrates that our emissions results are within plausible range.

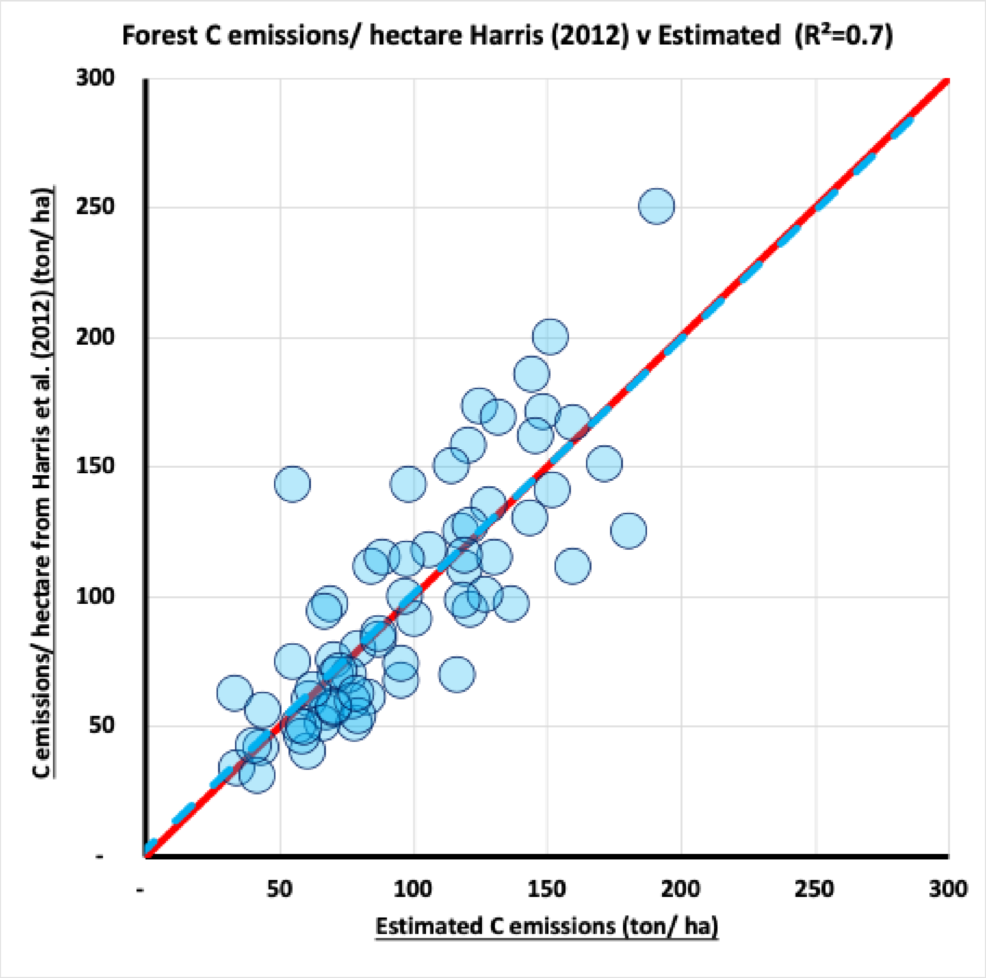


Figure 7: Plot of Country-level forest C emissions density from Harris et al. (2012) against predicted country forest C emissions from the FEBAC tool

Noting that validating our NET emissions against the results of Harris et al. (2012) was not possible because it was not an apples-to-apples comparison as we took a degradation coefficient (~90%) while Harris et al. (2012) did not.

3.5.2. Validation of forest Carbon data with another Global dataset

To validate our estimates for forest carbon data from GFW with more data points, we compared our results to the recently published Global Forest Resources Assessment (FRA) (FAO, 2025b). The below frequency plots (histogram) compare estimates from GFW for AGB Carbon (Figure 8), BGB Carbon (Figure 9), and Soil Carbon (Figure 10) to those of the FRA. It is worth noting that the FRA data was published shortly after our work on this project was concluded.

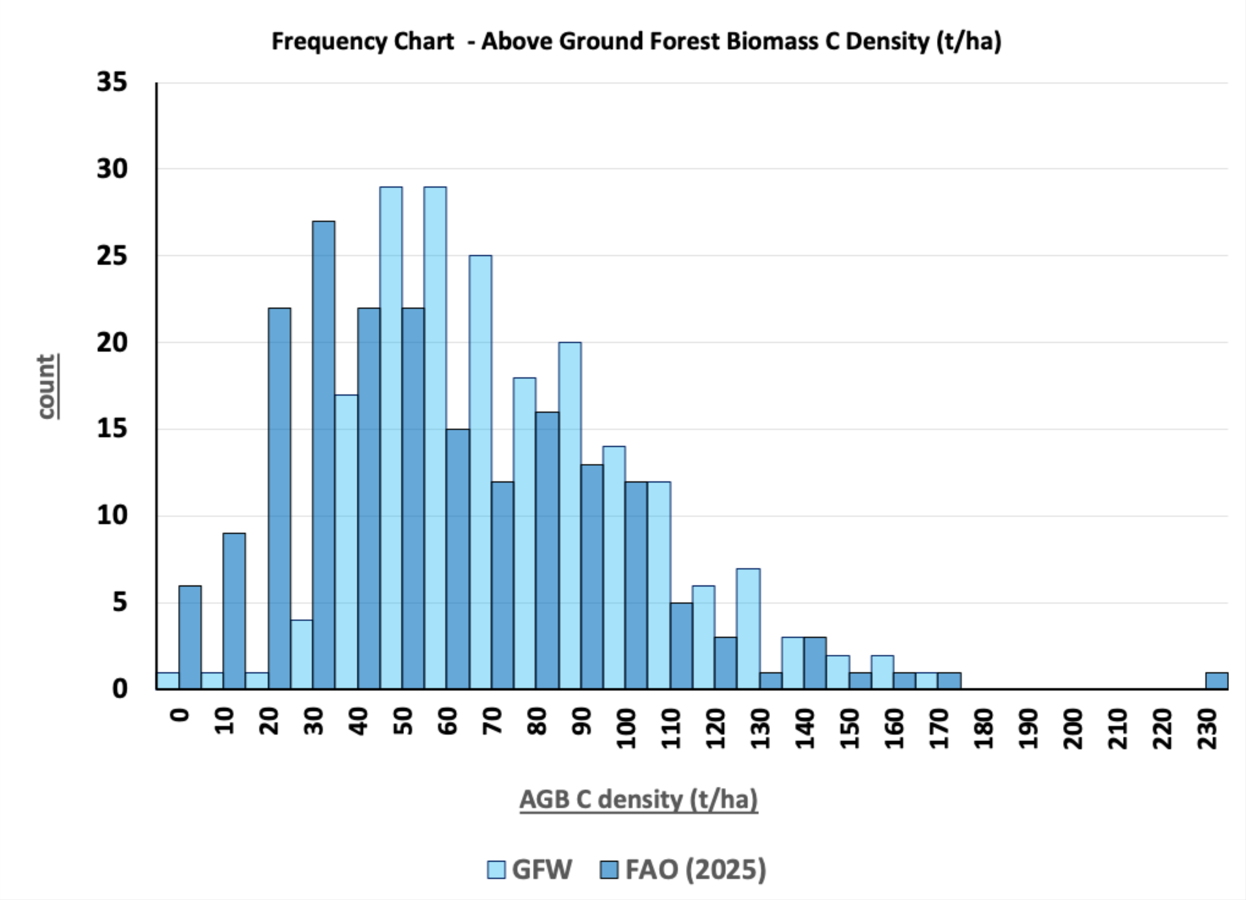


Figure 8: Frequency plot of country-level forest AGB C density data for GFW (2024) and FAO (2025)

The frequency plots demonstrate that the forest Carbon density on a country level is comparable between GFW and FRA, albeit GFW shows a higher mean and the FRA shows higher spread of observations. This shows in the descriptive statistics of the two datasets in Table 7. It is worth noting that there were missing values in FRA for Biomass Carbon and Soil Carbon data, thus only the countries with data in both datasets were considered in the comparison (n=192) for AGB and BGB Carbon, and (n=67) for Soil Carbon.

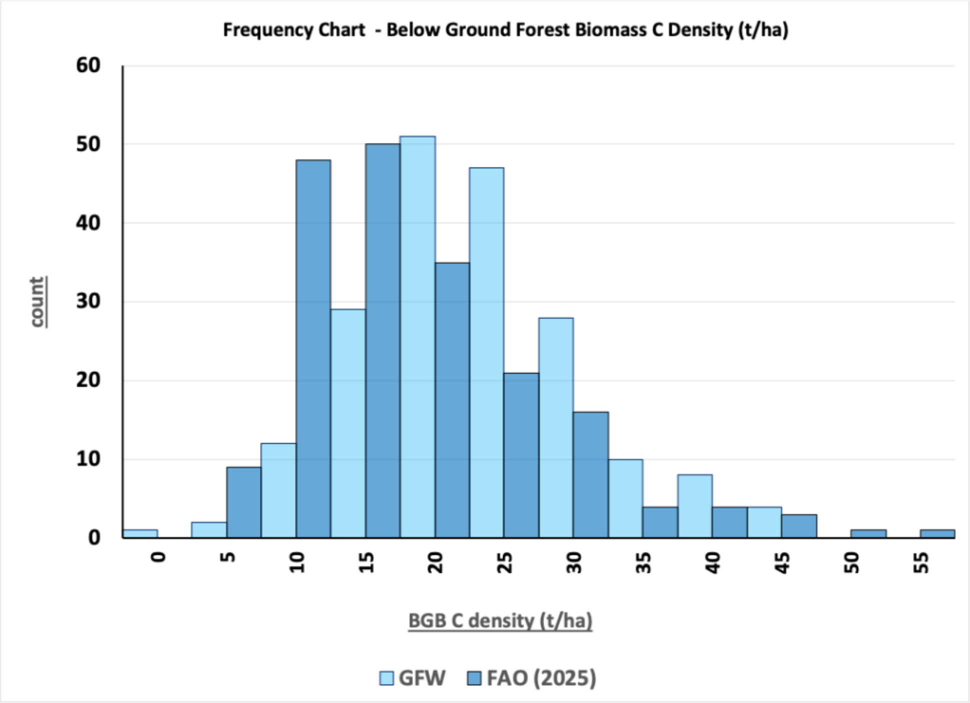


Figure 9: Frequency plot of country-level forest BGB C density data for GFW (2024) and FAO (2025)

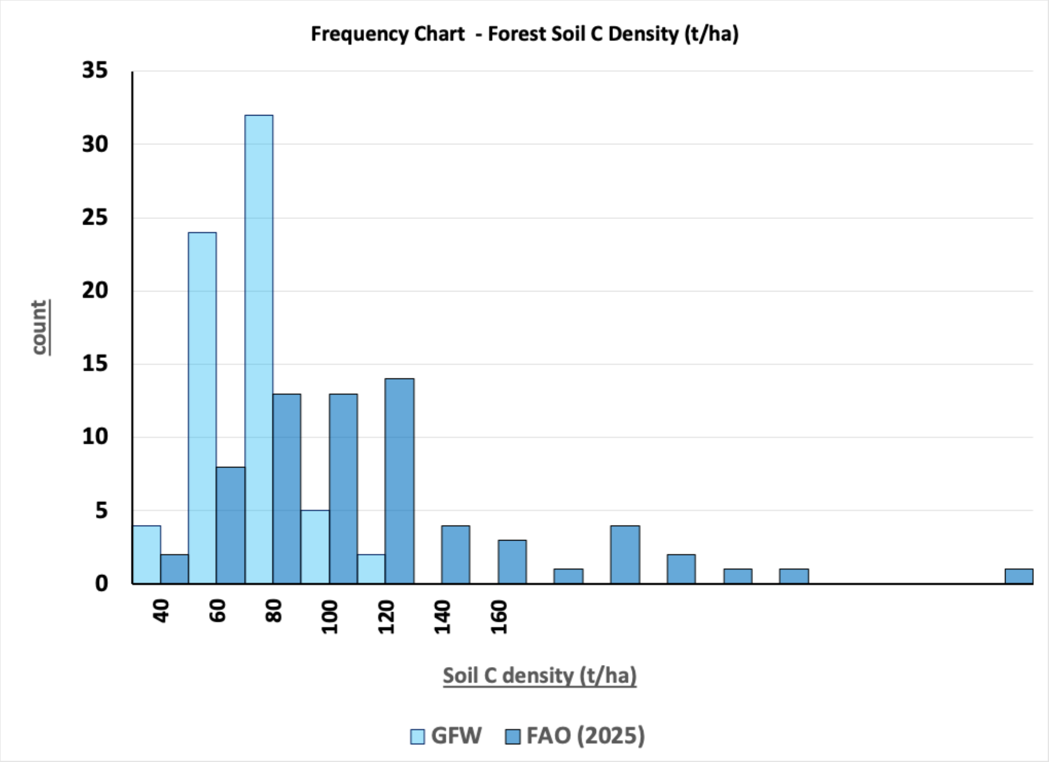


Figure 10: Frequency plot of country-level forest Soil C density data for GFW (2024) and FAO (2025)

Table 7 shows the descriptive statistics for both datasets. Given they are near-normally distributed, the mean, Standard deviation, and coefficient of variation are relevant.

	Above Ground Biomass C (n=192)		**Below Ground Biomass C (n=192)**		**Soil C (n=67)**	
	GFW	**FAO (2025)**	**GFW**	**FAO (2025)**	**GFW**	**FAO (2025)**
Mean (t/ha)	71	61	21	16	63	88
1st Quartile (t/ha)	49	34	15	9	54	52
Median (t/ha)	64	54	20	14	63	74
3rd Quartile (t/ha)	89	85	25	20	71	100
Standard deviation (t/ha)	30	37	8	9	16	55
Coefficient of Variation (%)	42%	60%	38%	58%	25%	63%

Table 7: Descriptive statistics across GFW (2024) and FRA (FAO, 2025)

The correlation plots below also demonstrated that the two datasets give correlated estimates for AGB (Figure 11), BGB Carbon (n=192) (Figure 12) and Soil Carbon (n=67) (Figure 13).

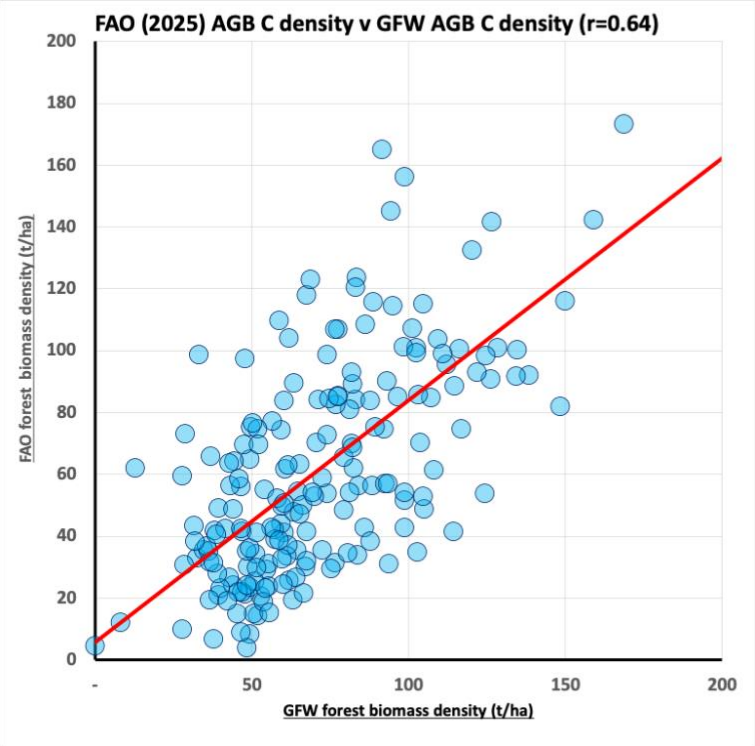


Figure 11: Correlation plot of Country-level forest AGB C emissions density from FAO (2025) against GFW (2024)

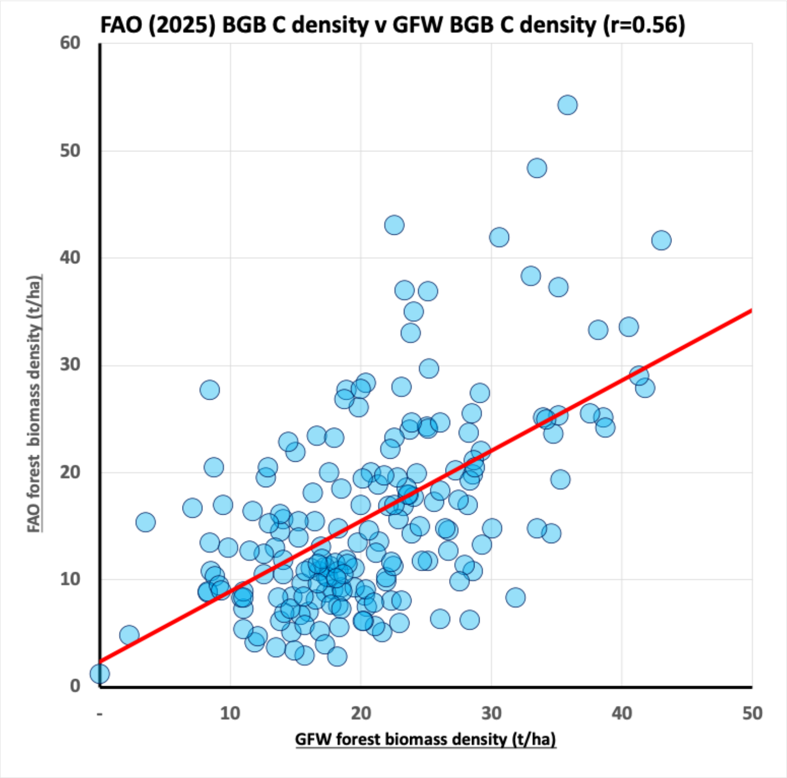


Figure 12: Correlation plot of Country-level forest BGB C emissions density from FAO (2025) against GFW (2024)

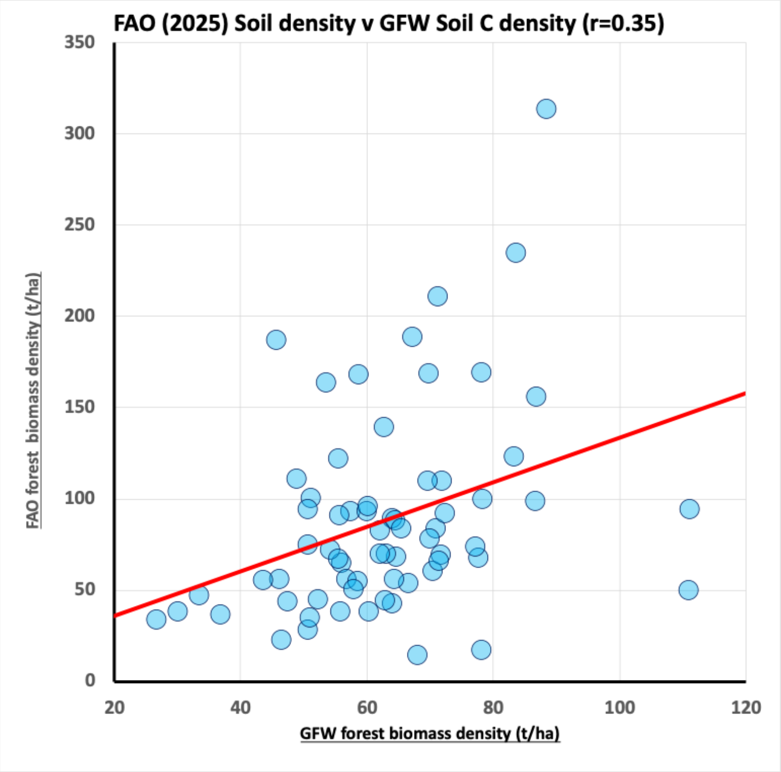


Figure 13: Correlation plot of Country-level forest Soil C emissions density from FAO (2025) against GFW (2024)

The GFW dataset had broader global coverage, and gave slightly higher estimates for biomass Carbon with less dispersion, making it a preferred choice for forest biomass Carbon emissions calculation. Soil Carbon in FRA did not have global coverage, and the chosen soil depth seems to vary by country (FAO, 2025a), unlike the GFW dataset from Sanderman et al. (2018) which had a consistent depth across geographies, making it the preferred data choice for this tool.

Future work should expand on the validation of biomass estimates used, leveraging geospatial datasets, and taking into account trends in forest Carbon over time, as supported by the FRA.

3.6. Forest disturbance

For a given block of forest that will be developed for fossil fuel extraction, we assume a portion of the land of the block will be cleared to build infrastructure linking the wells/ mines to refineries and export terminals (direct disturbance). Over time, road construction leads to settlement and colonization by migrant fossil fuel industry workers and their families who may engage in small farmer agriculture (indirect disturbance) (Robertson, 2021).

Data on the relationship between extraction rates/ reserves and deforested area is sparse, but we leveraged an Amazon Watch report (Robertson, 2021, Fig. 1) to estimate a range of values for the plausible deforestation consequences of fossil fuel extraction (% area of the block that is deforested), and converted the observations to a qualitative scale to help the analyst reason about the level of disturbance for a given block.

Ideally, we would've linked deforested area (in hectares) to extraction rates/ total extraction over a number of years to control for forest blocks of different sizes, and to capture the effect of project size on deforestation magnitude. However, the data available was only for oil extraction (so could not be linked to m^3 or tons for gas and coal) and was based on blocks in a single country case - Ecuador (n=11), so the utility of formulating a relationship between extraction and % deforestation would've posed conceptual challenges.

Thus, we first calculated the annual deforestation rate (% of the area of the block per year) by dividing the cumulative deforestation percentage by the duration of the study (2001-2019). Figure 14 shows the frequency chart of the observations, showing the positive-skew of the distribution (mean > median).

Table 8 shows the descriptive statistics of these observations (% deforestation per year).

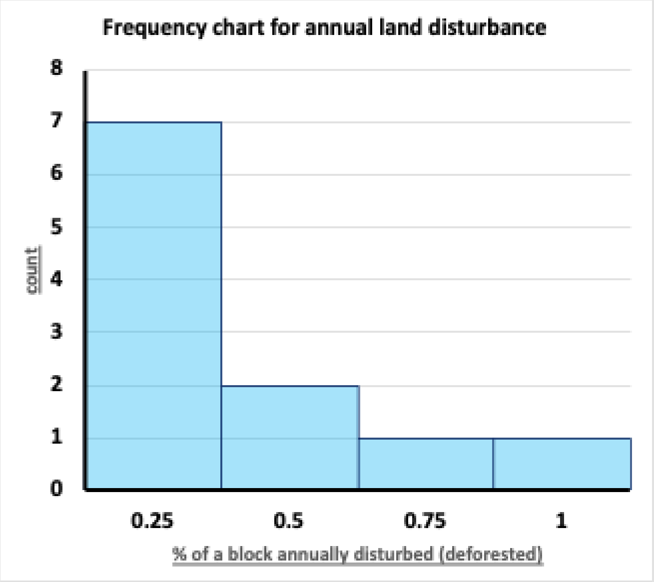


Figure 14: Frequency plot of block annual % disturbance (deforestation) from Robertson (2021)

Mean (%/ year)	0.27
Mean (excluding outlier) (%/ year)	0.19
Median (%/ year)	0.07
1st Quartile (%/ year)	0.04
3rd Quartile (%/ year)	0.39
Max	1.00

Table 8: Descriptive statistics of block annual % disturbance (deforestation) from Robertson (2021)

To err on the side of caution, and given our objective to generalize these observations on two levels: universality in terms of global forests and in terms of other fossil fuels, we converted the figures to a qualitative scale the analyst can choose from, as shown in Table 9.

1st Quartile (%/ year)	0.04	Low disturbance
Mean (excluding outlier) (%/ year)	0.19	Medium disturbance
3rd Quartile (%/ year)	0.39	High disturbance

Table 9: The % annual disturbance (deforestation) corresponding to the 3-scale qualitative scale given to the analyst

The low and high disturbance fractions were straightforward (1st and 3rd quartiles) to estimate. For the medium disturbance, we treated the highest observation as an outlier (using the 1.5 x IQR method) and recalculated the mean for (n=9), yielding 0.19, which is slightly higher than half the value of the mean, but is more than double the median, of the full dataset (n=11).

We also used the maximum observation 1.0 as the maximum possible custom value to be entered by the analyst into the tool. Table 10 shows the impacts of the analyst's choice of low/ medium/ high/ max degradation on the estimated deforestation % of a given block by two cutoff scenario analysis years.

	2050		**2100**	
	Low estimate	High estimate	Low estimate	High estimate
Cumulative % of land disturbed (Low disturbance)	1%	1%	1%	3%
Cumulative % of land disturbed (Medium disturbance)	4%	5%	4%	15%
Cumulative % of land disturbed (High disturbance)	7%	10%	7%	30%
Cumulative % of land disturbed (Max disturbance)	18%	25%	18%	75%

Table 10: The cumulative % disturbance (deforestation) lower and upper limits under a 2050, and 2100 scenarios

One thing to consider is that if the block is large or the project size (in terms of fossil fuel production) is small, the analyst can choose “Low disturbance” to represent the assumption that only a small portion of the block will have to be allocated for infrastructure and/ or colonized by the industry workers.

The opposite is true, where a small block or a large project would indicate going for the “high disturbance” option.

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