Bezos Earth Fund Avoidable Forest Conversion Map, Version 1 (AFC v1)

Estimating avoidable emissions from anticipated forest conversion

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Changes since version 1.0 (Feb 6, 2022) of this README

- Found error in production of the ***Zero-forest-future emissions*** layer. The layer wasn't capturing the complete forest footprint. Corrected Geotiff layer is named AFC_woodyC_alb_v1p1_nd.tif and prior version AFC_woodyC_alb_v1.tif was deleted
- Due to user feedback, saved Geotiffs as 32bit instead of original 64bit and set NoData value to -999999. In prior version, NoData wasn't behaving as expected in GIS software likely because of how Google Earth Engine handles NoData.
  Updated Geotiff file names:
  Exponential forest conversion rate: AFC_conv_rate_v1_nd.tif
  Avoidable forest conversion: AFC_emis_alb_v1_nd.tif
  Zero-forest-future emissions: AFC_woodyC_alb_v1p1_nd.tif
- The prior 64bit versions of ***Exponential forest conversion rate*** (AFC_conv_rate_v1.tif) and ***Avoidable forest conversion*** (AFC_woodyC_alb_v1p1_nd.tif) were moved to the "Archived" folder. The data values in these archived versions are the same as the data values in the re-exported version.

Data access and permission to use

AFC v1 is not yet peer-reviewed and will be updated and improved substantially before public release. This release is meant primarily for **internal TNC review, and feedback only**. Thus, any sharing outside of TNC must pass through Nick Wolff. Before granting access, we ask that all internal users first submit a request using our online form. Soon after receiving the form, users will be granted access to a Google Earth Engine (GEE) visualization script and assets. In addition, users will be added to a restricted Box folder with Geotiff versions of the GEE assets.

Synopsis

Our goal with AFC v1 was to produce conservative, additional, defensible, and transparent estimates of avoidable emissions from persistent forest conversion. We accomplished this using three broad analytical stages, relying primarily on publicly available data: 1) *Estimate historical rate of persistent, anthropogenic deforestation, per pixel; 2) Estimate biomass loss / emissions from projected deforestation, per pixel*; 3) *Estimate albedo forcing (CO_2eq) from forest conversion and apply as an emissions offset.* We see this release as an important first step and are already busy making improvements. We expect to release version 2 during the fall of 2022 and version 3 during the fall of 2023.

Overview (see figure 1 for a visualization of our analytical steps)

1) *Estimate historical deforestation rate per pixel*: Hansen et al (2013) global forest cover data was aggregated to 1km pixel resolution for two time points, 2000 and 2018. At each time point, the pixel area with forest was estimated. From Puyravaud (2003), we adopted the equation, $r = (1/(t_2 - t_1)) \times \ln(A_2/A_1)$, to estimate annual rate of deforestation (r) using years 2000 (t_1) and 2018 (t_2) and the forest area during each of those years (A_1 , A_2, respectively).
    a. Before aggregating to 1km, 30m Hansen forest cover data from 2000 was classified as forest if cover was >=25%. All non-forest pixels were masked out. For 2018, all forest losses between 2000 – 2018 were captured. Thus, for each year, 1km pixels simply represent a sum of the cell area (30m) that were classified as forest.
    b. Curtis et al (2018) provides 10km resolution data on primary drivers of forest loss. Only persistent forest conversion (commodity-driven conversion and urbanization) was considered with all other drivers masked out (fire, forestry, shifting agriculture).
2) *Estimate projected biomass/emissions loss from deforestation per pixel*: Santoro and Cartus (2021) forest above-ground biomass was used as an estimate of above ground woody biomass (AGB) in 2018 for each 1km pixel. We assumed annual rate of deforestation (r) would not change and thus calculated above ground woody biomass in 2030 using the exponential decay function, $AGB_{2030} = AGB_{2018} \times e^{r(2030\text{-}2018)}$. The difference between AGB in 2018 and 2030 represents the avoidable forest biomass loss. To express as annual biomass loss, the mean annual biomass loss between 2018 and 2030 was estimated. To express as emissions, the C fraction of biomass was calculated and converted to CO_2eq.
    a. Mokany et al (2006) root to shoot ratios were used to estimate belowground woody biomass. Because root to shoot ratios vary by forest type, we used Hengl et al.'s (2018) maps of vegetation types to crosswalk root to shoot ratios with appropriate forest type. Our final layers capture emissions associated with total (aboveground and belowground) avoidable biomass loss. We use a 'committed emissions' assumption for both aboveground and belowground components based on Zarin et al (2016) and papers cited therein (Ramankutty et al 2007 and Houghton et al 2012)
3) *Estimate albedo forcing (CO_2e) from forest conversion and apply as an offset*: Land cover change affects surface albedo which in turn affects radiative forcing. With forest conversion, albedo magnitude and direction (increase/decrease) depend on latitude (solar radiation), the type of forest and what the forest is being converted to (e.g. urban, crop), modeled future snow cover and top of atmosphere radiative forcing. An example of a strong albedo effect is the conversion of boreal forest to crop or pasture. Dark conifer forests have relatively low albedo (absorb more solar energy) year-round, while crop or pasture has relatively high albedo (reflects more solar energy) during the growing season, and even higher albedo during the winter, when snow is not concealed under conifer forest canopy. In some locations, the cooling effect of albedo change can be stronger than the warming effect of carbon emissions from forest loss. This does not imply that we advocate for deforestation as a mitigation approach! Forests are important for a plethora of services and values beyond just mitigation potential. However, albedo effects should be considered when estimating the climate forcing of avoidable forest conversion.

    In a collaboration led by Prof Chris Williams and Natalie Hasler from Clark University's Biogeosciences Research Group, we estimated spatially explicit albedo effects, expressed in emissions equivalent, from avoidable forest conversion. Albedo-induced global radiative forcing of forest conversion was calculated in two broad steps: 1) land cover change in surface albedo and 2) the radiative forcing due to that surface albedo change.

To calculate changes in surface albedo, we use the albedo atlas developed by Gao et al. (2014). The atlas defines albedo values for each month, each MODIS-CMG grid pixel and for each possible IGBP biome (see Table 3 from link) for snow-covered and snow-free, white and black sky conditions. Forest type was defined by IGBP biome, conversion type (urban, pasture, croplands) was defined by Curtis et al (2018) and then cross-walked to the atlas to find appropriate albedo value. We calculated monthly top of atmosphere (TOA) radiative forcing (RF) locally within areas undergoing a land conversion with the grid-cell specific albedo radiative kernels (Km) generated by seven different global climate models (we used the median value from the GCMs). We averaged monthly TOA RF to the annual scale accounting for each month's fraction of the year. We converted TOA RF to the global scale by multiplying by the grid cell area ratio to global earth surface area. Next, we convert radiative forcing into CO_2e, by adopting the global annual mean radiative forcing caused by carbon emissions per square meter of global surface area from the IPCC [2001, p. 358]. Finally, the albedo effect is applied as an offset to projected, avoidable emissions.

Please note, this work is being prepared for publication and is not publicly available. However, more detailed albedo methods are available upon request from Nick Wolff.

Input data

- Historic (2000 to 2018) rates of forest conversion were estimated using the Hansen et al. global forest cover data
- Aboveground emissions are estimated from aboveground woody biomass (i.e. not accounting for soil C, leaf litter, woody debris) using SAR data (v3 of the ESA CCI aboveground biomass dataset produced by Santoro et al.)
- Belowground emissions are estimated from belowground woody biomass (roots) using Mokany et al 2006 root to shoot ratios cross-walked with forest type using Hengl et al 2018 potential natural vegetation maps
- Emissions estimates were constrained to 'permanent, anthropogenic' forest conversion (i.e. commodity-driven deforestation and urbanization; thus we exclude wildfire, forestry, and shifting cultivation), based on the Curtis et al 2018 map of global drivers of deforestation

Output data layers

We produced three primary layers: 1) *Exponential forest conversion rate*; 2) *Avoidable forest conversion emissions*; 3) *Zero forest future emissions*.

1. ***Exponential forest conversion rate (unitless)***
   Methods explained in Overview stage 1

   a. Layer name in Google Earth Engine (GEE) visualization script:
      exponential conversion rate (unitless)
   b. Layer name of GEE asset:
      `AFC_v1.conv_rate (first AFC_v1 band)`
   c. Geotiff filename:
      ~~AFC_conv_rate_v1.tif~~ (moved to Archive folder)

AFC_conv_rate_v1_nd.tif (same as above, but NoData now = -999999 and saved as 32bit instead of 64bit)

2. *Avoidable forest conversion (Mg CO_2e yr^{-1})*

This map layer is the core product of this research and its production is explained above in the Overview (stages 1 - 3).

a. Layer name in Google Earth Engine (GEE) visualization script:
avoidable emissions (Mg CO2eq/yr)

b. Layer name of GEE asset:
`AFC_v1.emis_alb (second AFC_v1 band)`
`Geotiff filename:`
~~AFC_emis_alb_v1.tif~~ (moved to Archive folder)
AFC_emis_alb_v1_nd.tif (same as above, but NoData now = -999999 and saved as 32bit instead of 64bit)

This layer can be used to estimate spatially explicit mitigation potential of avoiding future forest conversion and can assist TNC with prioritization. For example, to determine which global areas would provide the largest emission mitigation returns if forest conversion were slowed or halted.

Units are megagrams (Mg) of CO2e per year. A megagram is equivalent to a metric ton (mt), also called tonne, which equals 1,000 kilograms. For context, a typical passenger vehicle emits about 4.6 metric tons of carbon dioxide per year. Positive values are emissions. Negative values are thus equivalent to sequestration (i.e. negative emissions). Some pixels with forest conversion have negative emissions. These are places where albedo increases substantially when forest is removed, generating a cooling effect on the global climate system that more than offsets warming caused by radiative forcing from CO2 emissions.

3. ***Zero-forest-future emissions (Mg CO_2e yr^{-1})***

This layer uses forest woody carbon stocks (above and belowground) and answers, "what would be the emissions if global forests were all converted?"

a. Layer name in Google Earth Engine (GEE) visualization script:
max potential emissions (Mg CO2eq)

b. Layer name of GEE asset:
`AFC_v1. woodyC_alb (third AFC_v1 band)`

c. `Geotiff filename:`
~~AFC_woodyC_alb_v1.tif~~ (this file has been deleted due to error in production)
AFC_woodyC_alb_v1p1_nd.tif (error corrected version. Also, NoData now = -999999 and saved as 32bit instead of 64bit)

We offer the *zero forest future emissions map* with trepidation. We provide this layer because it is so often requested by our TNC colleagues. However, **we urge extreme caution with any application of this layer, because it does not account for additionality**. AFC climate mitigation claims are inherently flawed without a corresponding assessment of conversion risk! It is never appropriate to claim mitigation without a solid foundation of additionality. Evidence of additionality is a core principle of any natural climate solution, including AFC, as well as all conservation interventions that claim mitigation of ecosystem service loss.

Here, we estimated aboveground and belowground carbon stocks using the methods described above (aboveground biomass from Santoro et al, belowground biomass from Mokany et al cross walked with Hengl et al). Albedo correction was estimated by assuming forests were converted to crops. For conversion rate, we assume all forests are converted by 2030. In summary, this layer shows the maximum mitigation potential IF forests were to be converted in the coming decade.

In addition to the three primary layers, we also provide a fourth layer in GEE for visualization purposes. This layer is just a version of # 2 above, *Avoidable forest conversion emissions, masked by forest IGBP biomes.* It is available within the GEE visualization script only. This was created in response to a pre-release review of the *Avoidable forest conversion emissions* layer. Some pixels with very little remaining forest and low conversion rates, and thus low avoidable emissions, are difficult to distinguish visually from standing forests that have experienced no conversion and thus have no expected emissions. Often, these pixels with low forest, low avoidable emissions are found within patches experiencing high conversion, high avoidable emissions, adding to the visual confusion. As a simple visual fix, we have used the 2016 IGBP forest biomes as a mask. Many of these 'problem' pixels were masked out because they are classified by IGBP as non-forest (e.g. crop).

- Layer name in Google Earth Engine (GEE) visualization script:
  avoidable emissions (Mg CO2eq/yr) (FRAGMENTS MASKED)
- Layer name of GEE asset:
  `Not available`
- `Geotiff filename:`
  Not available

Assumptions, caveats, and limitations

We view this product as a starting point upon which we will build future versions. Our goal was to produce conservative, defensible, and transparent estimates of emissions that we expect will occur (i.e, emissions that could be avoided), thus operationalizing additionality at a pixel scale. To qualify as a carbon mitigation benefit, any reduction in emissions from avoiding forest conversion needs to be 'additional' to what would have happened if things continued as is (i.e., 'business-as-usual'). In other words, if a particular area of forest was never targeted for deforestation, then claiming its protection as a carbon benefit is invalid because the forest was never in any real danger of conversion, and thus was being protected from nothing.

When aggregated to country level or globally and compared to previous estimates of avoided forest conversion mitigation potential (e.g., Griscom et al. 2017, Roe et al. 2021), our map yields very conservative estimates. This results from methodological design decisions we made because of inherent analytical constraints. Our goal was to develop a product that captures spatial patterns of persistent, anthropogenic forest conversion (to aid spatial prioritization decisions), but that does not make unwarranted spatial predictions of the expansion of forest conversion activity (to avoid overestimation of emissions at certain pixels that could appear to justify unduly elevated project-level baselines). The net effect of balancing those two concerns is a product that is purposefully conservative, but that is certainly an underestimate of the total emissions that would occur if forest conversion continues to increase and expand.

We conducted an initial sensitivity analysis to provide a very rough estimate of the influence of our methodological decisions on our results. We include a multiplier factor that demonstrates how much our AFC emission results would increase if this methodological constraint were removed. When we remove the set of methodological constraints that most differentiates our product from previous ones, (i.e., include all forest loss, irrespective of likely driver; omit belowground carbon; omit albedo correction; estimate linear rather than exponential rates of loss; and exclude most boreal land area), our results (~1.9 Gt CO_2 yr^{-1}) are only slightly more conservative than previously published estimates (2.165 Gt CO_2 yr^{-1} in Tyukavina et al. 2015; 2.270 Gt CO_2 yr^{-1} in Zarin et al. 2015; 2.45 Gt CO_2 yr^{-1} in Griscom et al. 2017). Masking out non-persistent forest conversion has by far the biggest downward-bias influence on our results. Given that the Curtis et al. (2018) drivers map that we use here was not available when previously published analyses were conducted, but that persistent conversion is more likely to misclassified as non-persistent that vice versa in the regions of greatest importance, we believe that the true mitigation potential from avoided forest conversion is likely to lie somewhere between our estimates here and those previously released. Future work to improve global mapping of forest conversion drivers at much higher spatial resolution (in progress at WRI) is likely to help resolve and better constrain the true mitigation potential.

Sources of uncertainty that contribute to our estimates being conservative

1. **Assigning drivers of forest conversion**:
   The map of forest conversion drivers (Curtis et al 2018), which we used to identify areas of 'persistent anthropogenic' conversion (i.e., conversion due to commodity agriculture and urbanization) , is coarse (10km resolution) and only captures the primary regional drivers. We are therefore likely missing spatial heterogeneity in drivers. Further, we did a quick summary of the confusion matrix from the Curtis et al Supplemental Information which demonstrated a systematic bias in the categorization of drivers in our regions of greatest emissions. Globally, misclassification of persistent drivers as non-persistent (e.g., shifting agriculture) was 5.8 times more likely than the inverse misclassification. Removing drivers completely in the sensitivity analysis (assumed all conversion was persistent, which is clearly false) led to a ~4.7 x increase in AFC emissions.

2. **Future forest conversion excludes expansion:**
   Future forest conversion is assumed to remain spatially constrained, with no expansion. Only pixels that experienced historical conversion will experience future conversion. This biases our estimates downward, both in pixels where remaining forest cover is less than the total future loss implied by recent rates, and in neighboring pixels to which the surplus of that future loss is likely to spread. We performed a simple neighborhood analysis which estimated mean forest conversion rates and AFC emissions for each 1km pixel within 10km circular neighborhoods. We have no expectation that this neighborhood approach is a reasonable proxy for future expansion. Still, replacing our spatially constrained AFC method with this neighborhood approach in our sensitivity analysis resulted in a ~2.2 x increase in AFC emissions.

3. **Forest conversion rate is assumed to be exponential:**
   As explained above, we used an exponential decay function (based on Puyravaud (2003)) to estimate forest conversion rate. A consequence of exponential decay is that loss has a long tail that gradually approaches zero. This could underestimate loss/emissions, particularly in pixels that have already experienced some loss and are approaching the tail portion of the function. However, we have not assessed whether or not an exponential function is appropriate.

Replacing the exponential loss with linear loss in our sensitivity analysis resulted in a ~1.8 x increase in AFC emissions.

4. **Including albedo forcing from forest conversion**
   We see the inclusion of albedo effects on emissions potential from AFC as an important, previously overlooked, advance. Nonetheless, in most cases, persistent forest conversion leads to an increase in albedo and thus a cooling effect. Removing albedo in our sensitivity analysis resulted in a ~1.2 x increase in AFC emissions.

Other assumptions and sources of uncertainty:

1. Forest conversion rate (FCR) is estimated from just two time periods (2000, 2018). FCR is likely to vary through time and is therefore sensitive to the time periods used for estimation, as well as to intrinsic error in pixel classification as forest and in the estimated year of forest loss.
2. FCR is assumed to remain unchanged in the future.

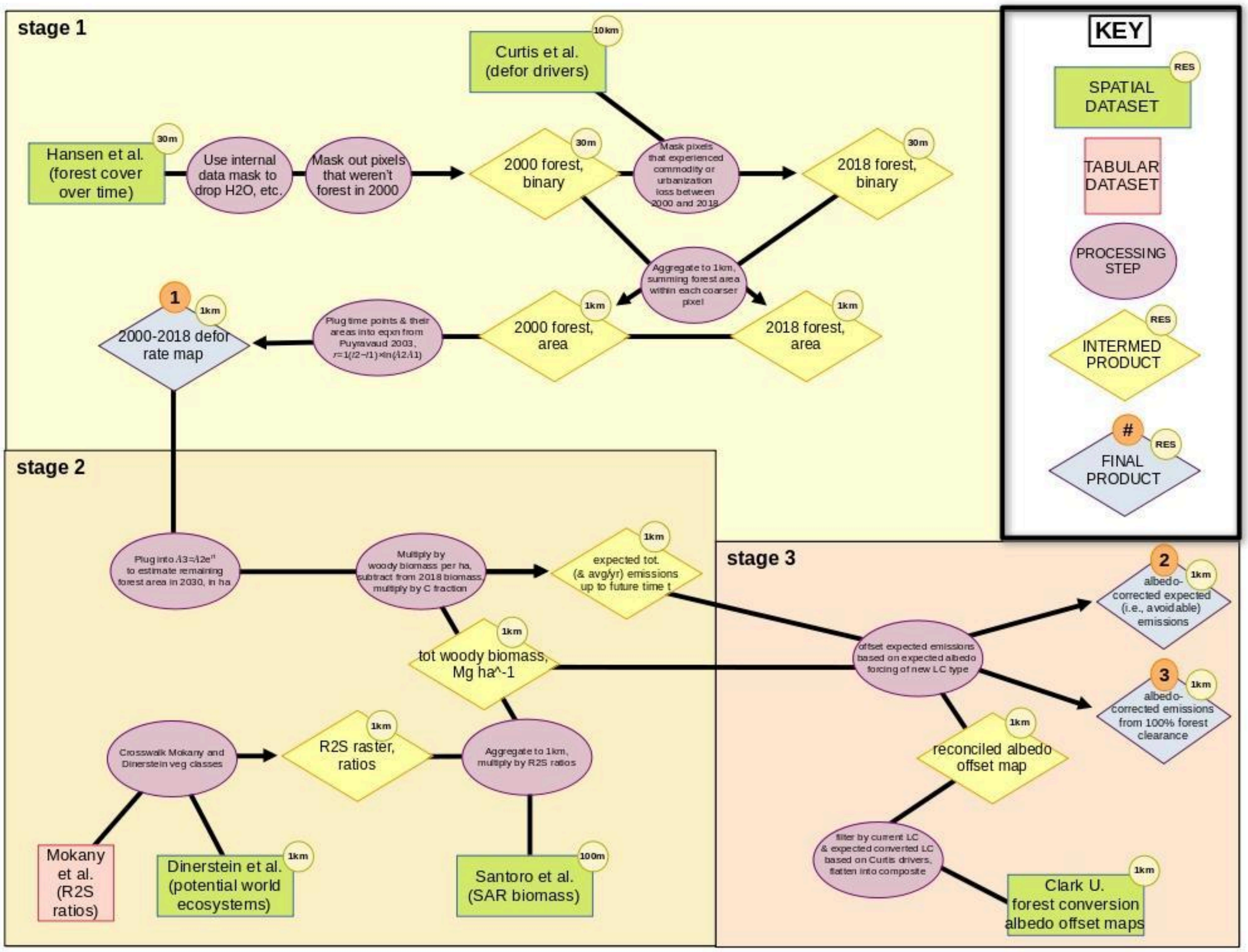

Figure 1. Analytical steps used to create AFC v1 (RES=nominal spatial resolution)