Map-based Projections of GHG emissions and removals using FLINT

v1.0.0

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Background:

The Full Lands Integration Tool (FLINT), is a MRV tool that countries can build on to implement and operate their emissions estimation systems for the land sector. FLINT integrates remote sensing and ground data to estimate fluxes and stocks of greenhouse gasses in different pools in line with the guidance from the IPCC.

moja global is an open source collaboration under the Linux Foundation that allows users of the FLINT to work together to continuously improve the tool in line with the needs of the users. Moja global was set up and continues to be run by the users of FLINT. All FLINT users can request a seat on the Strategy Board of moja global.

Users have indicated that the ability to make projections is an essential feature for FLINT. While it is already possible to run projections with the FLINT as it is a model based system, the approaches to make projections can be further improved to make it easier to make complex projections.

This document demonstrates how the current FLINT system can be used to make projections. This mainly manual process to generate maps, is providing useful insights into the automated processes necessary to develop more complex projections.

Basic Principle of Projections based on Models

Projections are always possible with a model based system like FLINT. Since reality is modeled by the software, the model does not know whether the inputs it receives are from the past or are a prediction of the future. Hence it is already possible to generate projections if one can map out the events and activities that will happen in the future.

Below some simple projections are generated to demonstrate the method one could follow. The examples are based on a historical land-cover timeseries from 2004 to 2018 of a small plot of forest. The following simple projections have been implemented:

Projection of a Baseline

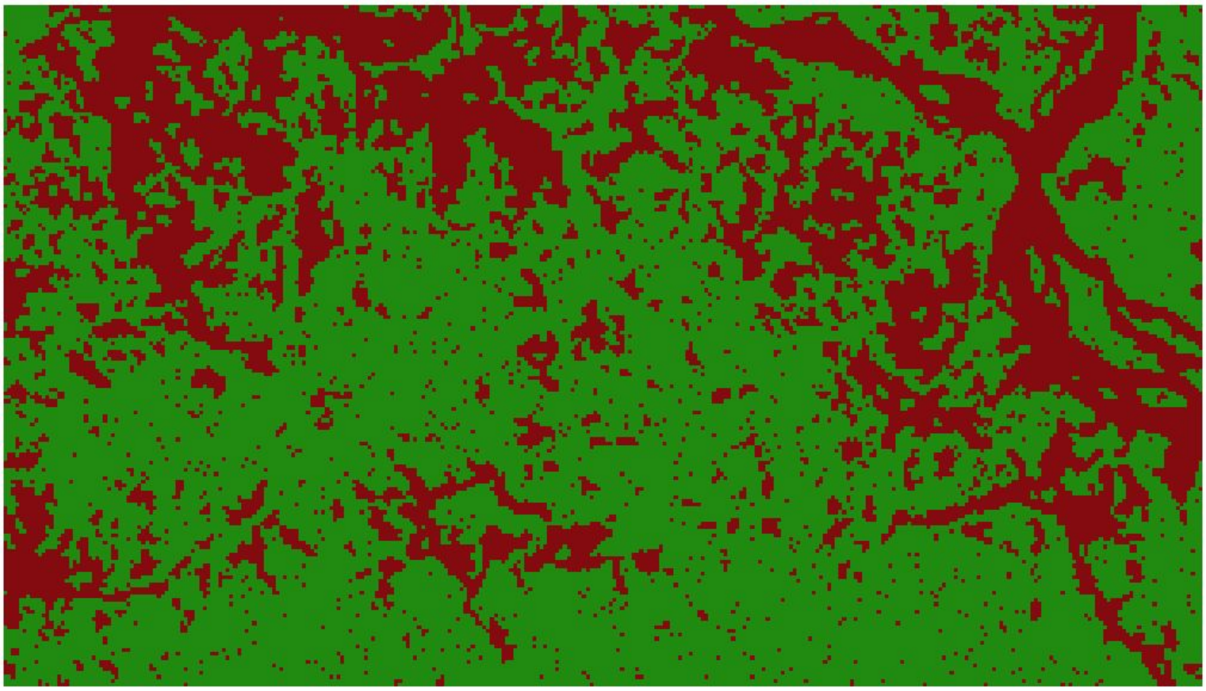
To project a baseline the historical information is analysed. Depending on the rules concerned, various methods can be used to determine the baseline. All methods are however based on the same concept: i.e. a trend from the past is continued into the future.

In this example the annual average deforestation between 2005 and 2012 is considered the rate at which forest would have been lost under a business as usual (BAU) scenario. Hence, the projection of the baseline, requires to reduce the forest in the selected area with the same annual rate as the observed deforestation between 2005 and 2012. The real observed deforestation is of course different every year, but from the last observation forward the same amount of forest will be removed to predict the baseline.

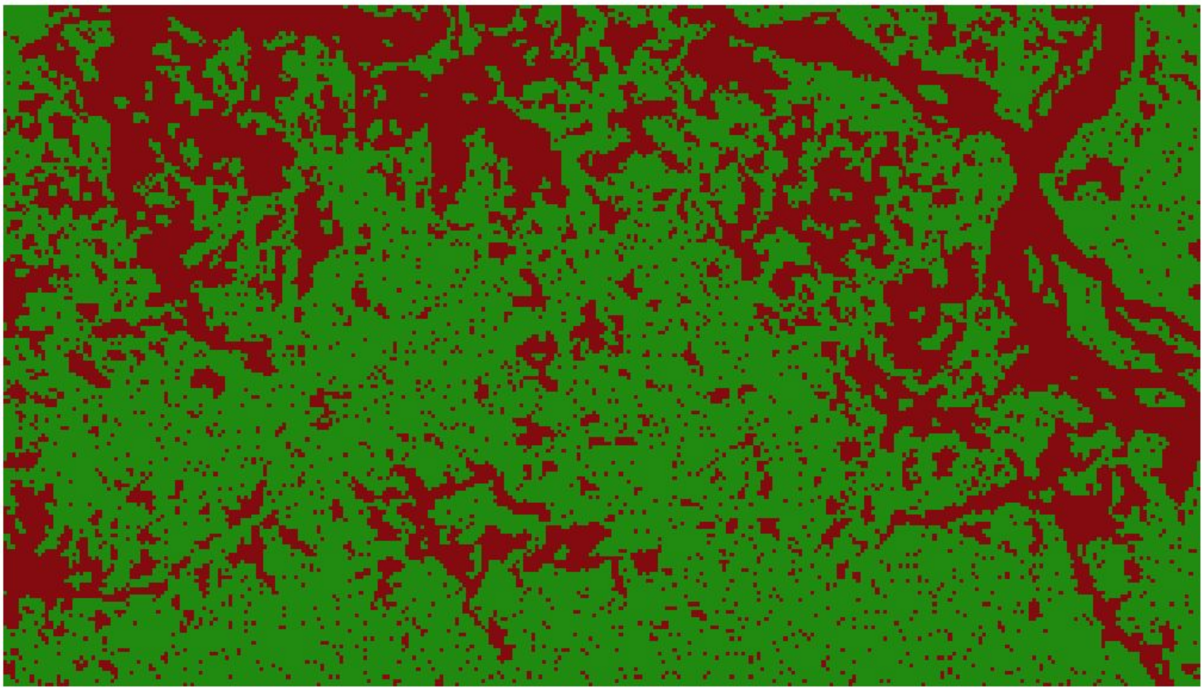
Any other time period or scenario can be used as input into the method below. Even non-linear projections are possible as long as the annual rate of deforestation can be calculated.

Practically the following steps can be taken to develop the maps and to estimate the emissions for such a BAU baseline:

1. Establish the annual rate of deforestation and express it in a number of pixels: e.g. 1220 pixels per year for the small project area under consideration (The size of the pixels can be chosen by the user. Let’s use the pixel size for rasters derived from LandSat imagery, i.e. 25 by 25 meters.) Calculations can be found in this file.
2. The annual rate of deforestation is applied to the most recent observation in the time series: In our example, the most recent observation is from 2018. From the total number of pixels that are still forested in 2018, 1220 pixels are selected randomly. These randomly selected pixels are marked as deforested. This new situation is saved as the map of 2019.

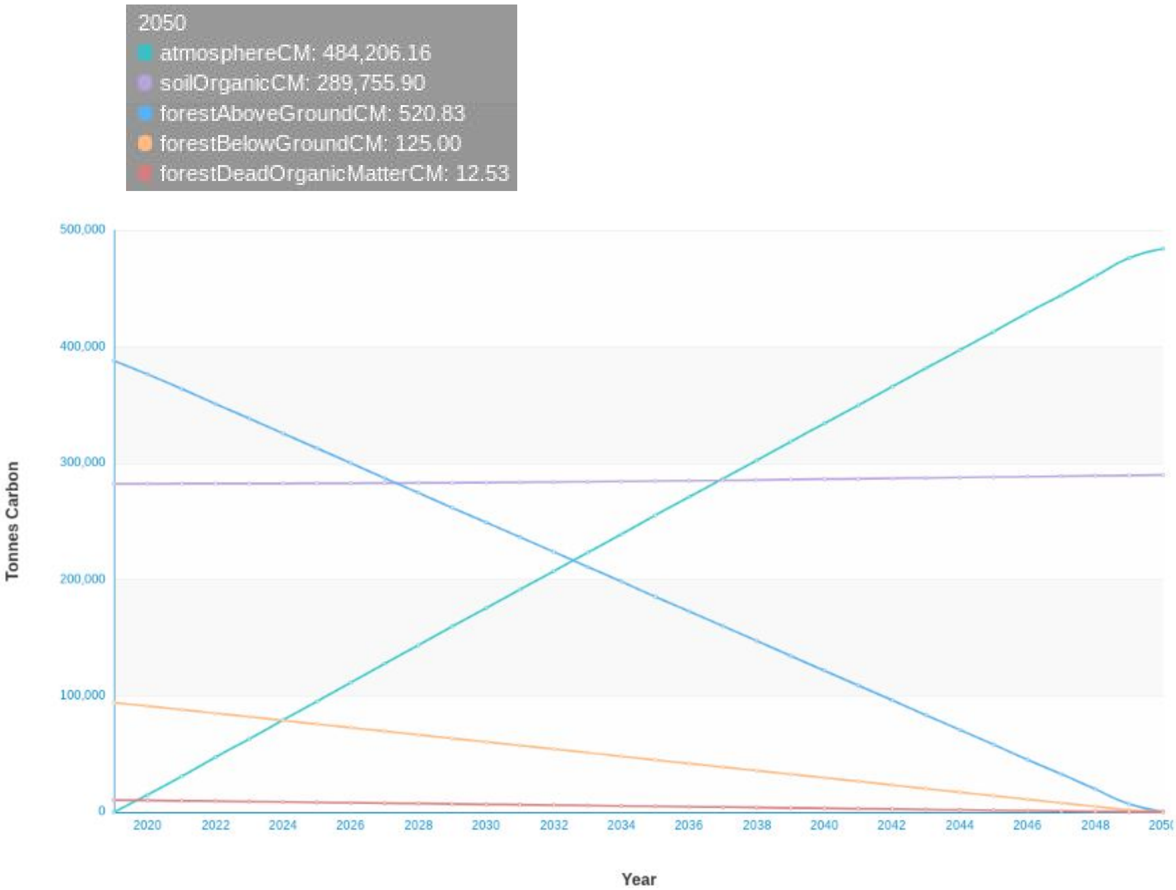


3. The new map is used to apply the same deforestation rate: On the map of 2019, 1220 pixels are randomly selected and deforested. The new situation is saved as the map of 2020.



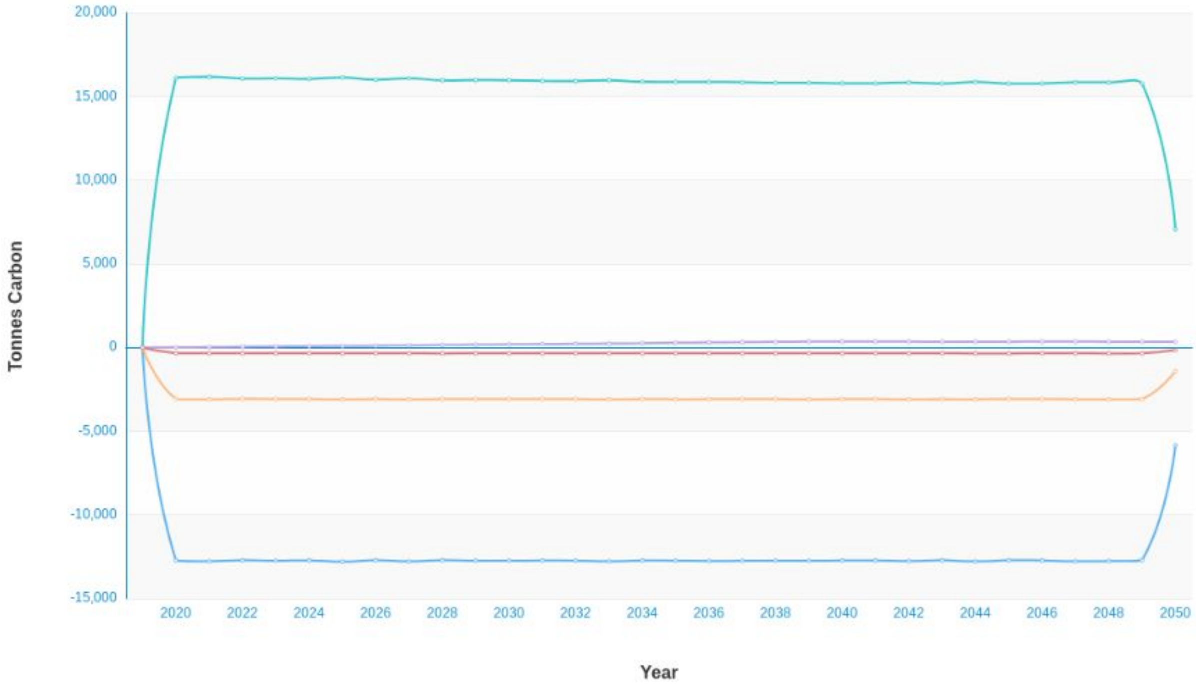
4. Repeat this process for the whole projection period: The example used, the projection period runs upto 2050. So the same process is repeated 31 times.
5. The maps that have been created are now entered into a FLINT-based system. For the example we have used FLINTpro and with Tier 1 emissions factors.

6. FLINT calculates the annual emissions and sinks from all the pools based on the supplied maps. The projections of carbon pools are provided below. The chart shows a constant reduction of the above ground biomass, below ground biomass and dead organic matter.[1] These reductions are translated into emissions to the atmosphere that constantly increase over time.



[1] The Soil Organic Matter pool would be more accurate if a Tier 3 model would be used. As the model will remember the soil pools across land uses. In the example accuracy is lost due to changes between land uses and the related default values in a Tier 1 system.

7. The annual emissions are constant over time (except in 2050 as there is no forest left). The losses in biomass in the AGB, BGB, DOM are also constant.



8. This simple baseline will be used as a reference for the scenarios developed below.

These are the step-by-step instructions to implement this approach in the open source QGIS software. The resulting maps can be downloaded.

Projection of Reforestation

To project the reforestation of an area, a reforestation plan needs to be developed. The real-life approach might take into account a wide range of terrain conditions (e.g. access) and map based approaches are really suited for such approaches.

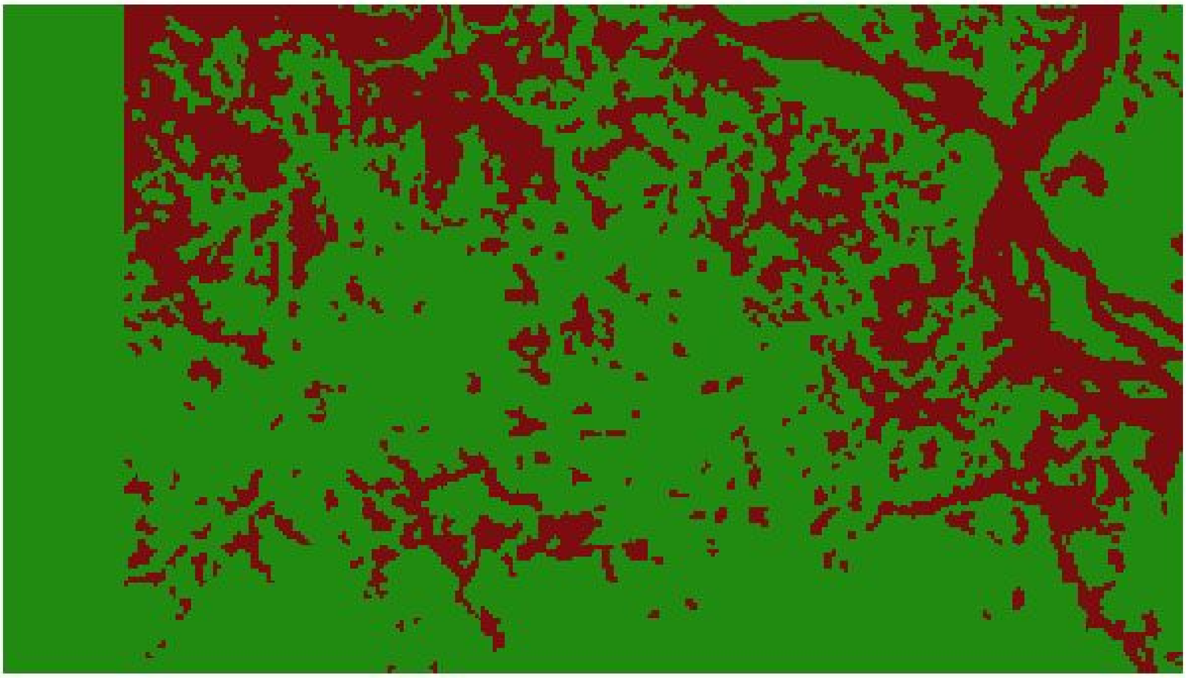
For our example we have divided the project area in 10 equal zones and are planning to reforest 1 zone each year. So in total the reforestation will be complete after 10 years. Calculations can be found in this file. Any other timeframe or reforestation approach can be applied using the same method.

Practically the following steps can be taken to develop the maps and to estimate the emissions for such a reforestation scenario:

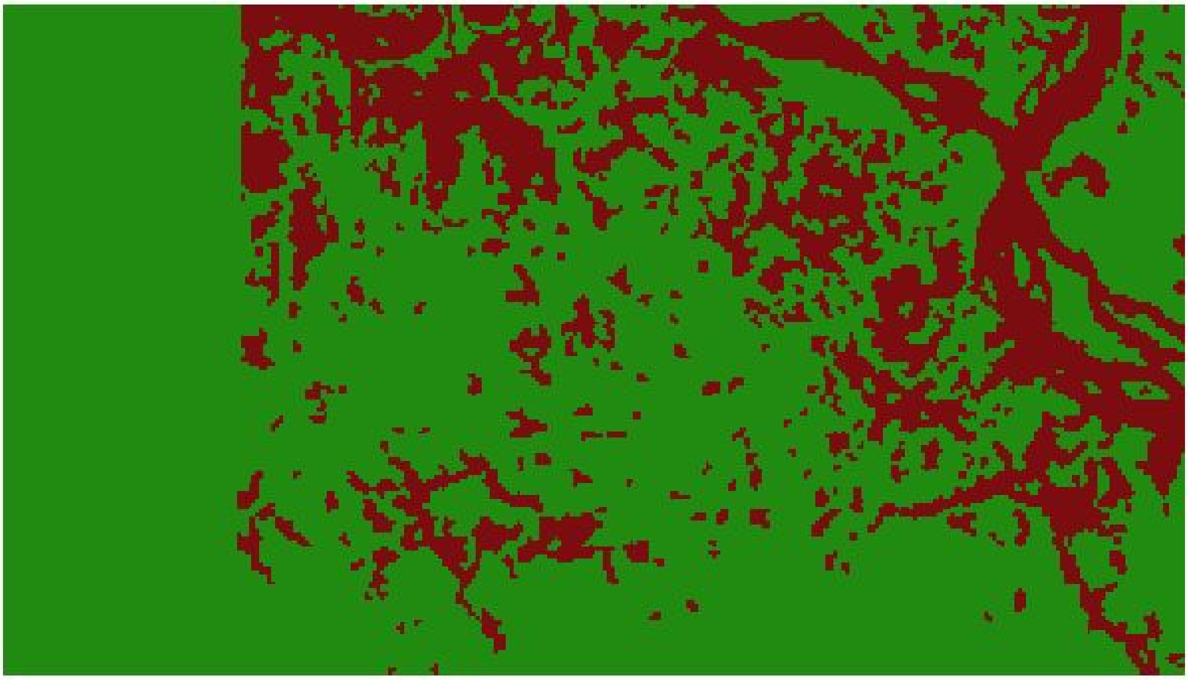
1. Establish the annual areas that will be reforested: in our example, a strip of 10% of the forest area will be added every year.
2. Turn all unforested pixels in to forest in the first strip of 10% of the project area. Select all pixels of the first 10% of all columns on the left hand side of the project

area (for simplicity reasons). Brown colour is no-forest, green colour is forest. (Any other reforestation shape can of course be selected.)

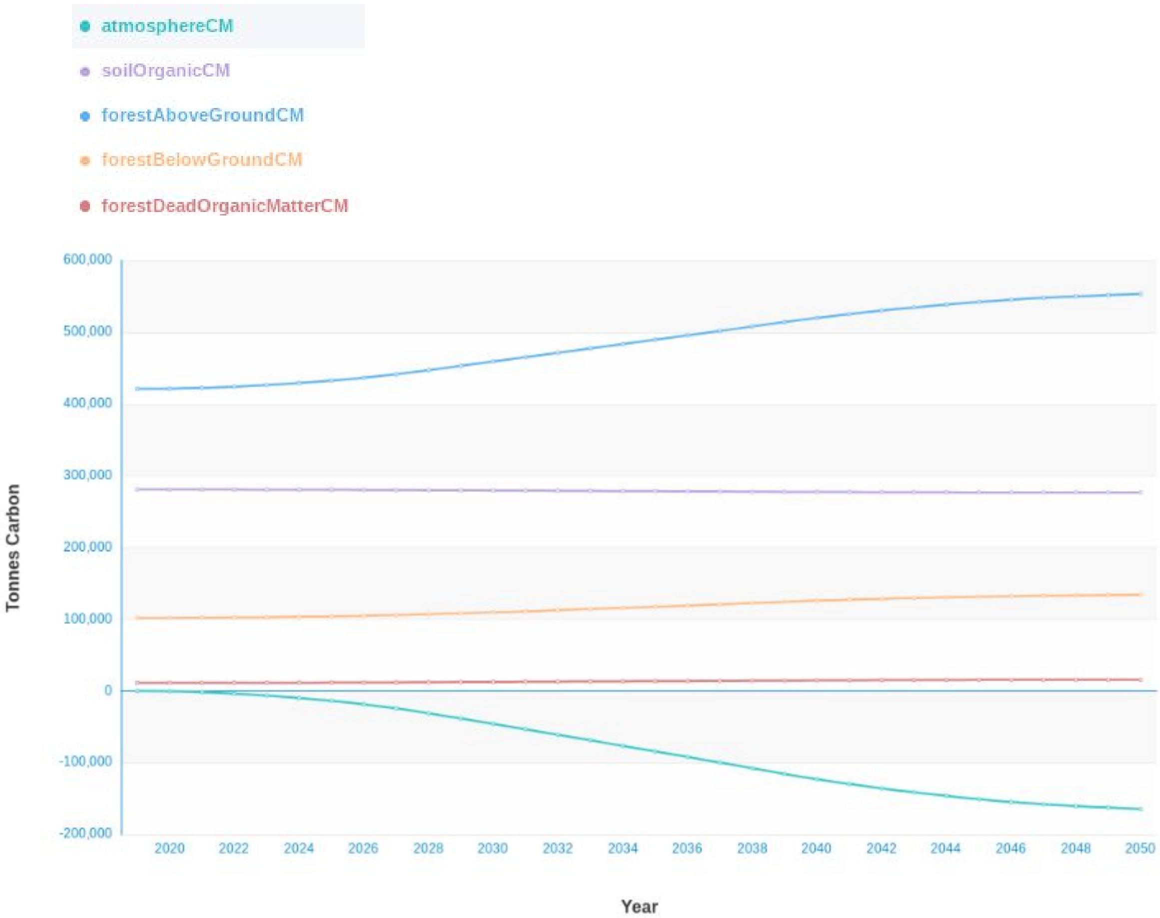
3. Combine this reforestation plan with the existing situation: Using the latest historical observation (in our example the observation from 2018), keep the existing forest and turn all non-forested pixels of the first strip of 10% into forest.



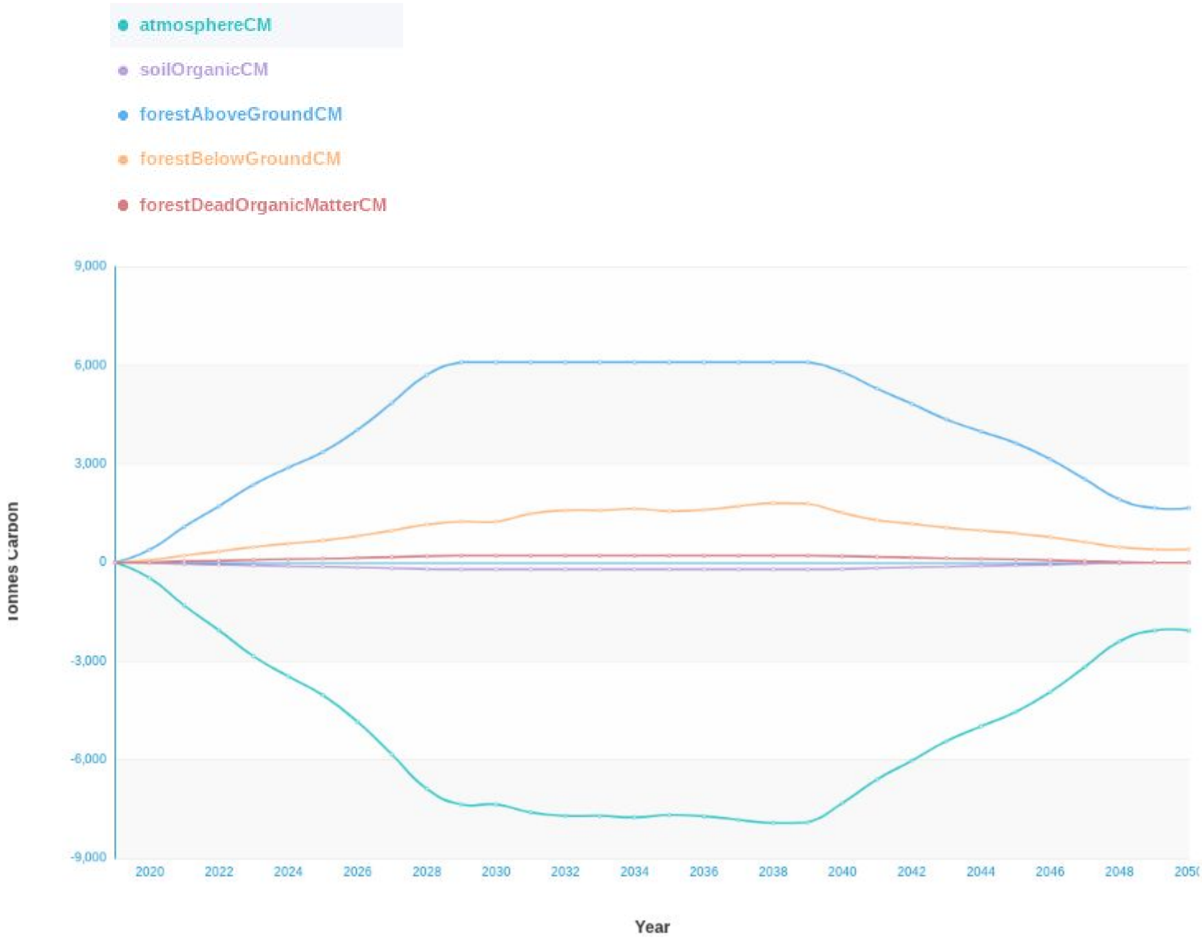
4. The map of the following year will include an additional strip of reforestation: Create a map with a strip of 20% of all columns on the left hand side of the project area. Combine this area with the existing forest from the latest historical observation (i.e. from 2018).



5. Repeat for each year until the whole reforestation plan for 10 years is complete. After that the area will be considered to remain completely forested so up to 2050 there will be no changes.
6. FLINT will calculate the annual emissions and sinks from all the pools based on the supplied maps.

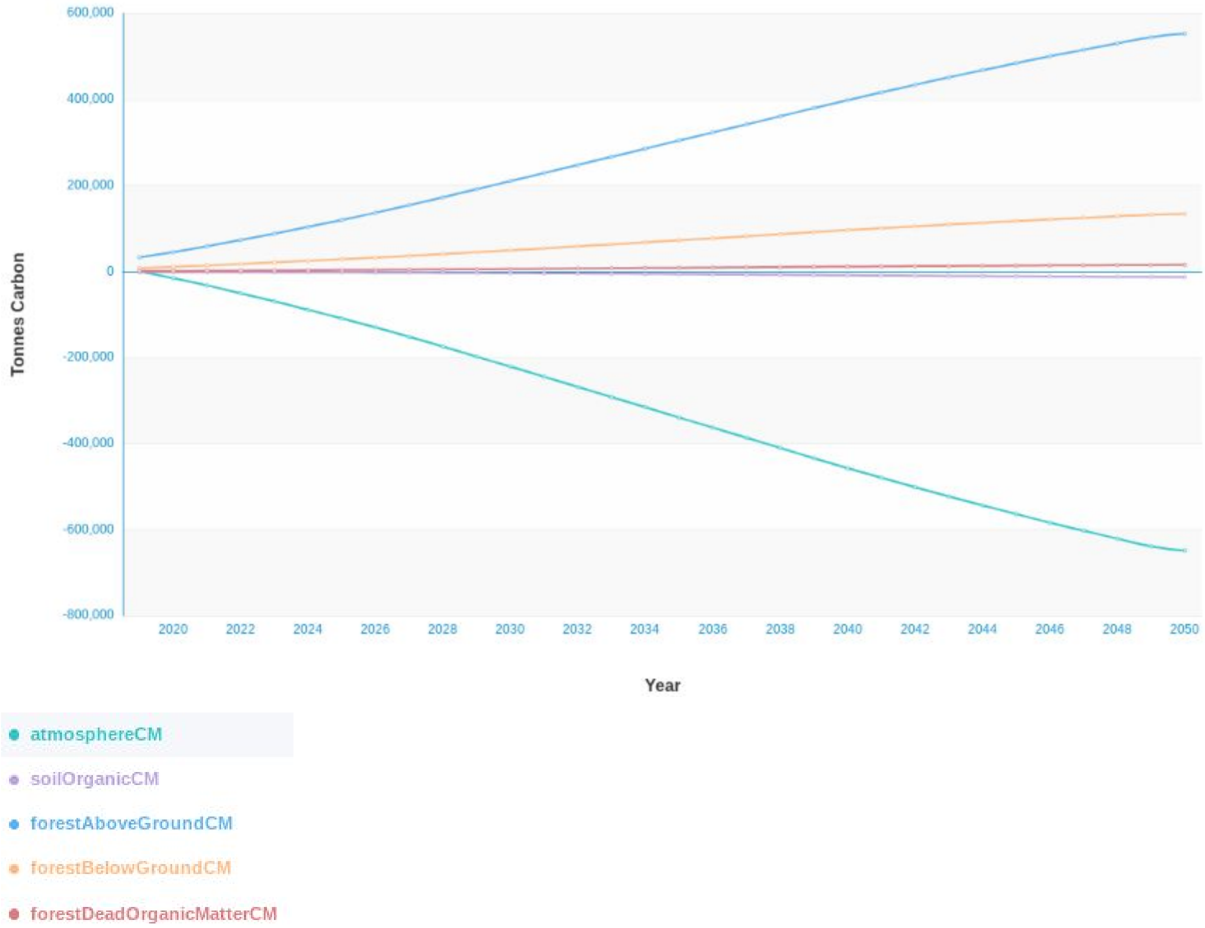


7. The chart above shows that there is an annual increase biomass in all pools. This translates into removals from the atmosphere. The increase tapers off towards the end of the projection period. This change can be better observed when annual fluxes of carbon are plotted in a chart as below. The removals from the atmosphere go up as a larger part of the project area is reforested over a period of 10 years. Then the removals are constant while the forest matures. When the forest matures, the removals slowly decrease again.

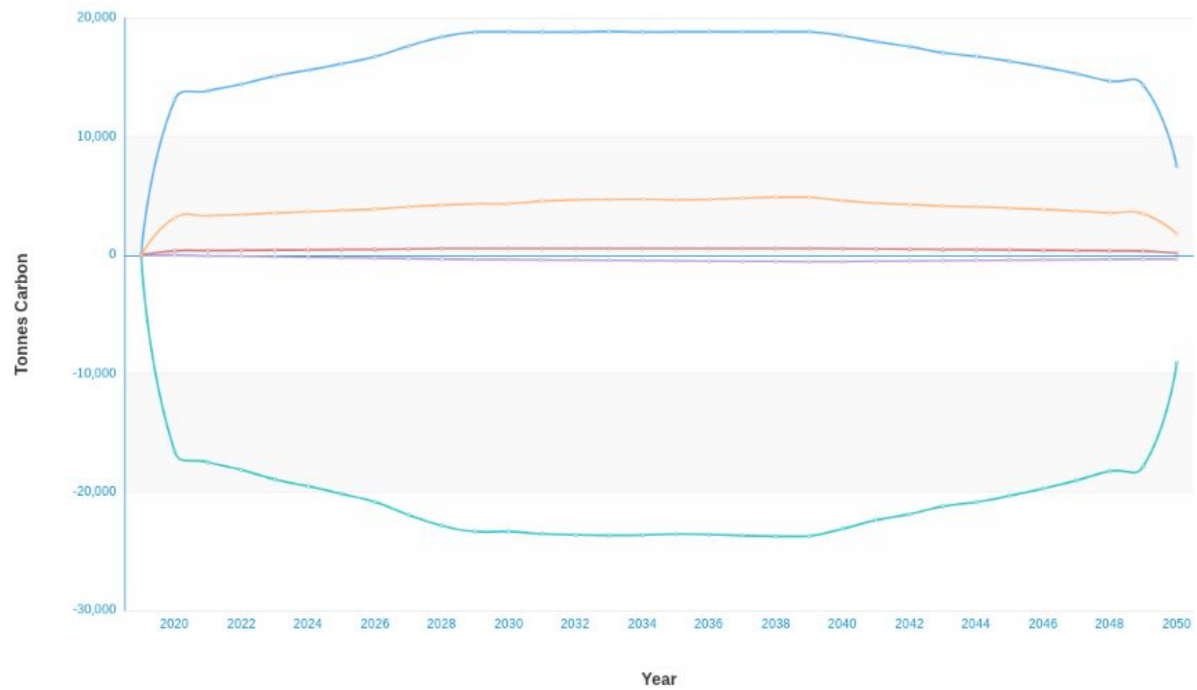


8. The change compared to BAU is calculated by subtracting the BAU scenario calculated in the example above from the results based on this reforestation scenario. The chart below shows a continuous increase of the removals from the atmosphere. The second chart shows the annual changes in carbon stocks. The chart clearly shows the effect of degradation (jump in the first year) and of the reforestation (same shape as above but less pronounced.)

Cumulative carbon stock for each pool



Annual Stock Change



These are the step-by-step instructions to implement this approach in the open source QGIS Software. The example uses a non-regular shape follow terrain features as an area to be reforested to demonstrate how this can be achieved. The resulting maps can be downloaded.

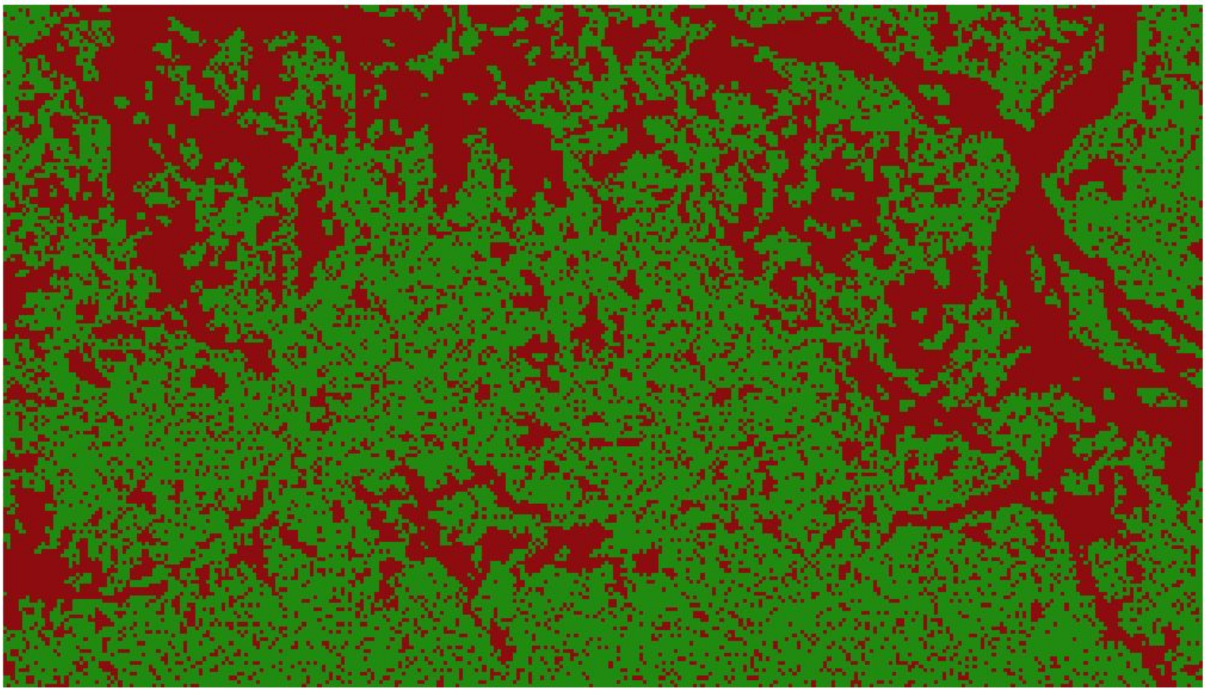
Projection of Delayed Reforestation

If the reforestation plan does not immediately start after the latest historical observation several years of deforestation might be observed under the BAU scenario before the reforestation plan starts.

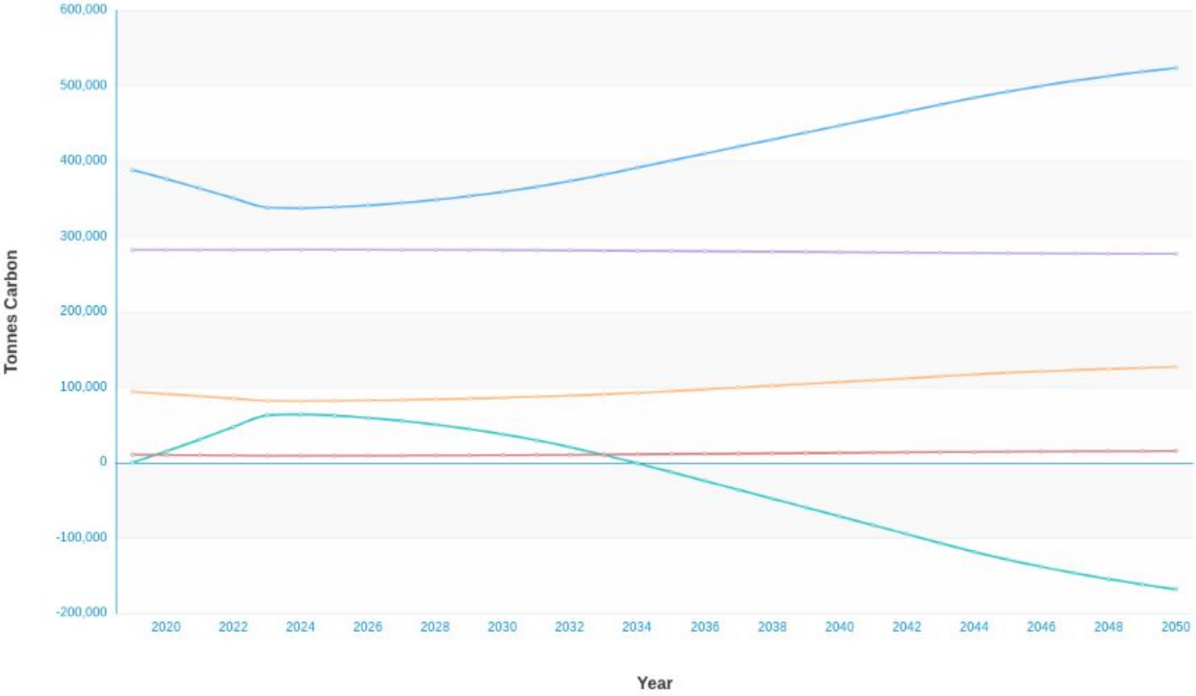
For example, reforestation only starts in 2024. Hence, deforestation continues at the BAU rate until 2023. The BAU does not need to be the same as the baseline scenario. It is possible the more recently deforestation has increased or actually decreased. The BAU rate or any other rate determined by rules and science can be applied as the rate does not change the method described.

Practically the following steps can be taken to develop the maps and to estimate the emissions for such (a) postponed reforestation scenario(s):

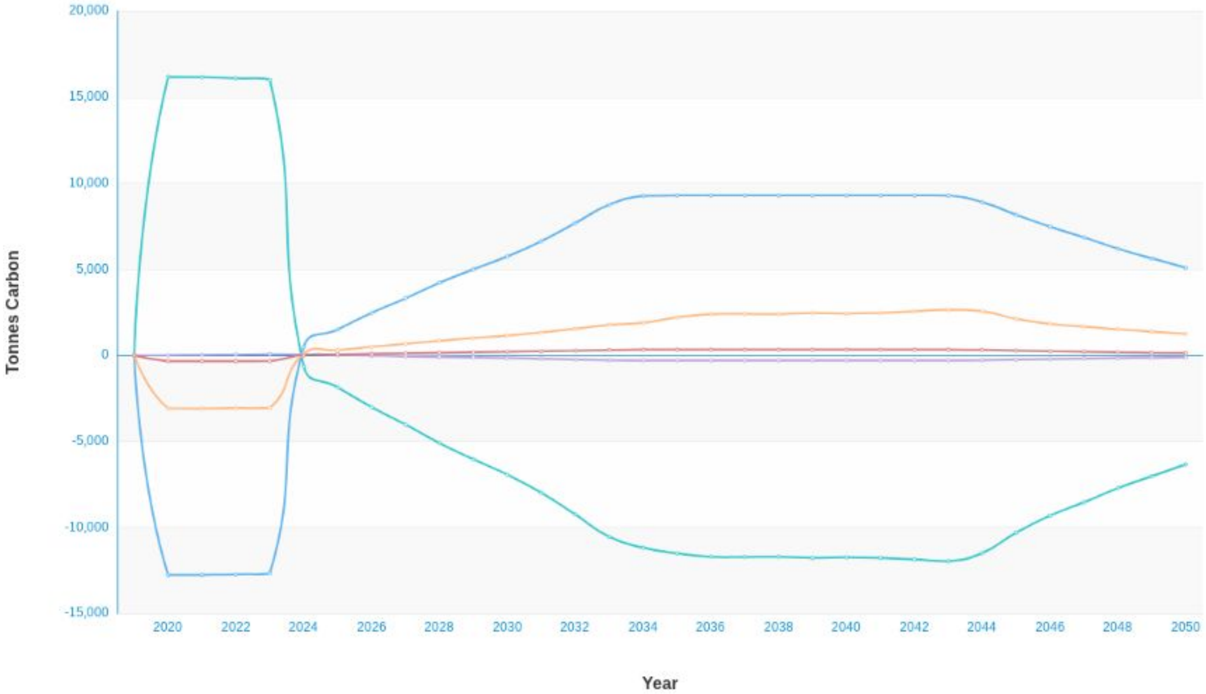
1. Establish which year the reforestation process will start, e.g. 5 years after the latest historical observation.
2. Establish the annual rate of deforestation and express it in a number of pixels. As explained, this rate can be different from the baseline. It can for example be calculated on the basis of the deforestation of the last 2 years. For simplicity our example uses the same deforestation as the baseline: i.e. 1220 pixels per year.
3. Establish the annual areas that will be reforested once the reforestation starts: We will use the same reforestation plan as above: i.e. a strip of 10% of the forest area will be added every year.
4. Generate 5 maps using the approach explained under Projection of a Baseline. This was already done under the BAU scenario.



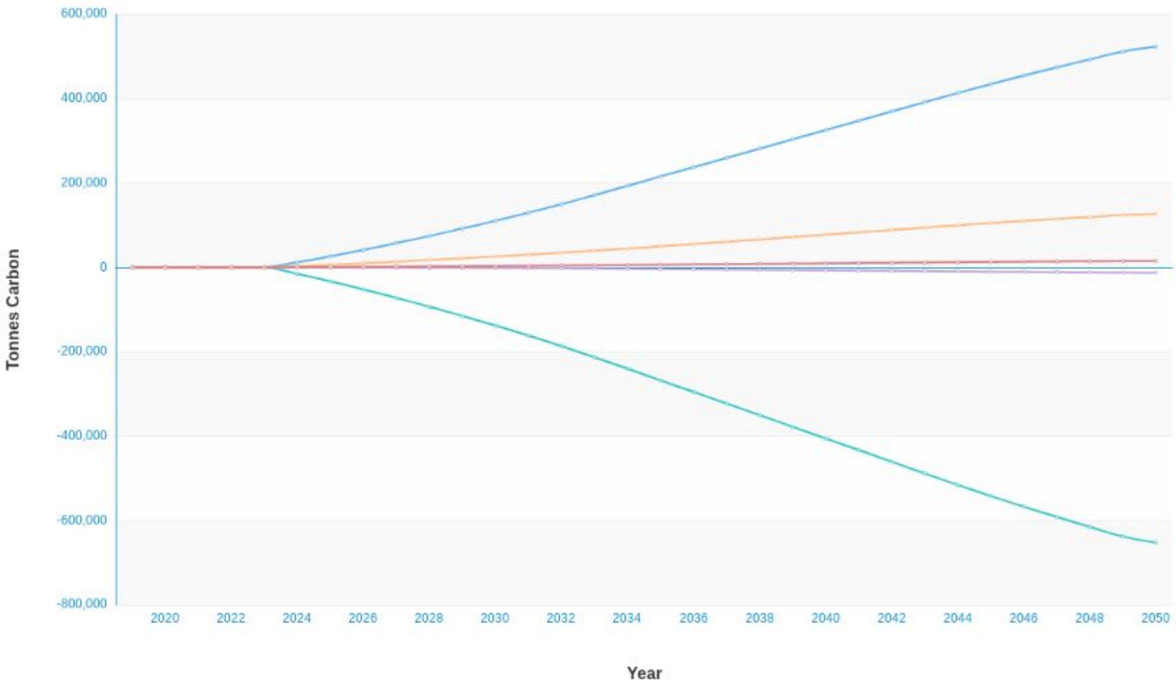
5. Using the latest map of the Baseline time series of 5 years, i.e. the map for 2023, apply the approach explained under [Projection of Reforestation](#) for 10 years, i.e. until 2033.
6. For the years 2034 to 2050, the map from 2033 will be used as the project area will be considered as completely forested for that period.
7. FLINT will calculate the annual emissions and sinks from all the pools based on the supplied maps. The chart clearly shows emissions to the atmosphere for the first 5 years equal to those under the BAU. It takes until 2034 for the landscape to remove these emissions from the atmosphere again despite the reforestation over the same period.



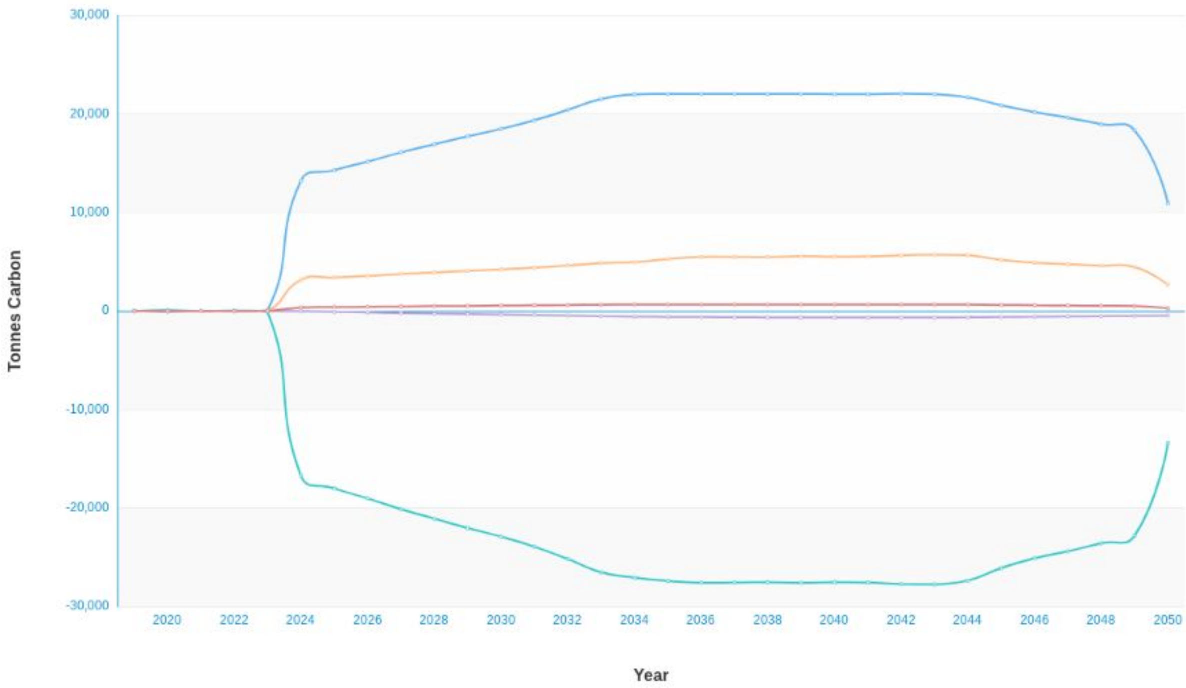
The annual carbon stock change, shows a similar pattern as the BAU scenario for 5 years followed by the Reforestation scenario above. Interesting observation is that the annual BAU emissions (i.e. about 2% forest loss/year) are bigger than capacity of the landscape to remove these emissions again from the atmosphere even at the maximum change (i.e. after full reforestation and maximum forest growth.) More info is available under the sustainable harvest scenario below.



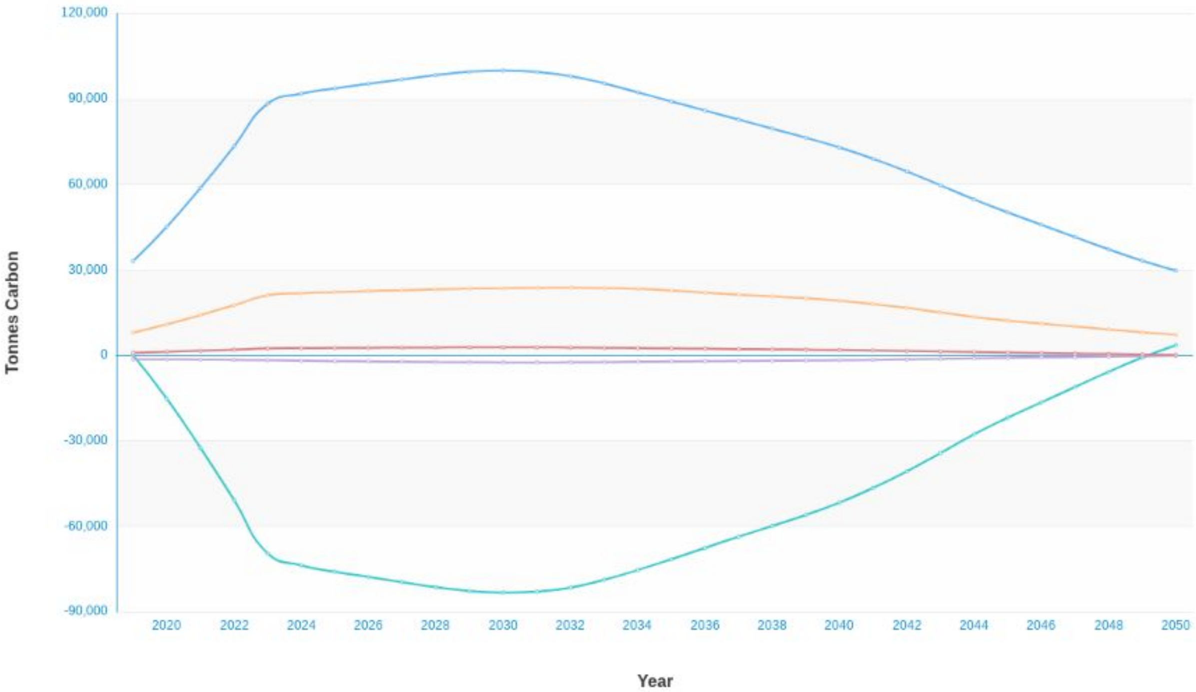
8. The change compared to BAU is calculated by subtracting the BAU scenario calculated in the example above from the results based on this reforestation scenario. The emissions are the same as BAU in the first 5 years. After that the cumulative removals from the atmosphere go up continuously.

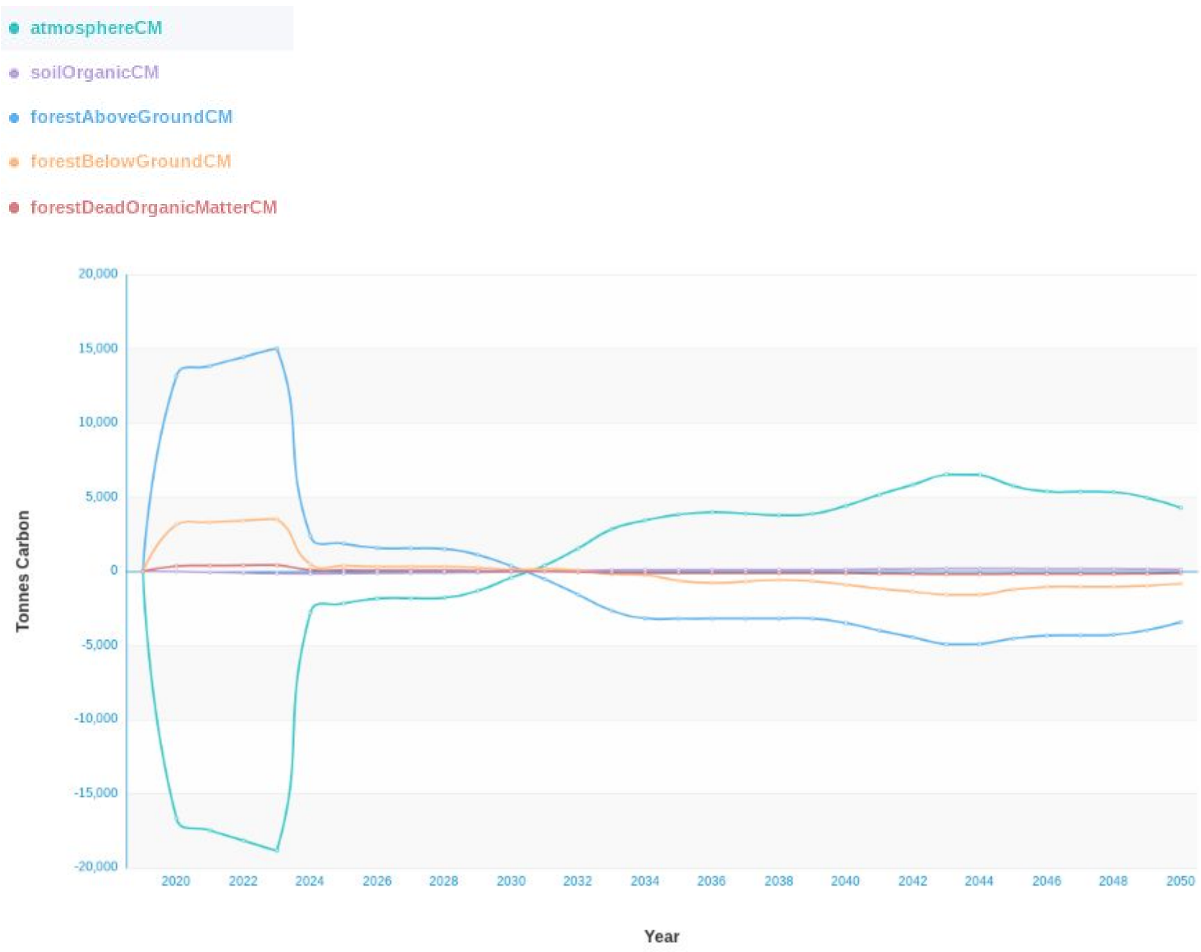


The annual stock changes against the BAU are similar to the reforestation scenario above but delayed with 5 years.



9. It might be useful to compare scenarios with different starting dates of reforestation. The difference in carbon stocks between immediately starting the reforestation and delaying reforestation by 5 years is shown below. Immediate reforestation provides an advantage in terms of carbon stocks that cannot be undone. However, postponed reforestation, catches up as the forest matures.





These are the step-by-step instructions to implement this approach in the open source QGIS Software. The resulting maps can be downloaded.

Projection of Unsustainable Forest Harvest

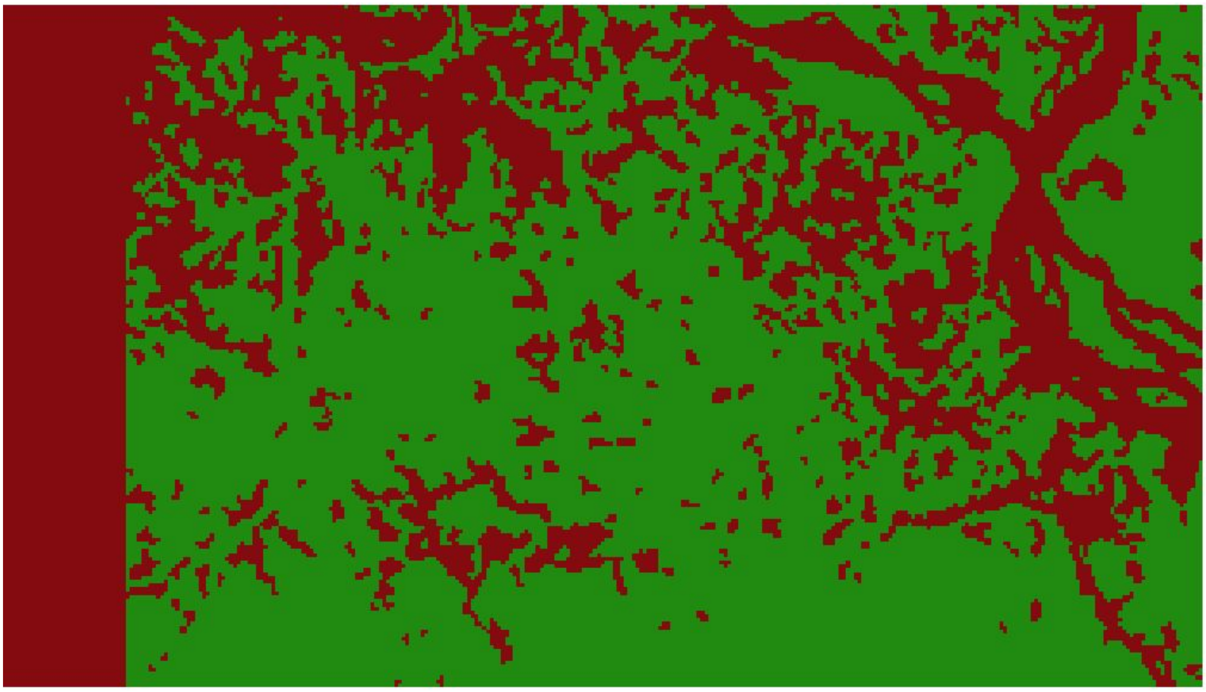
Developing maps for harvest plan is similar to the process of reforestation but instead of turning pixels into forests, they are turned into no-forest. There is an important difference: the year after the forest has been harvested, the forest will regrow (or will be reforested). So the pixels that were no-forest, will be turned back to forest.

For example, if the same harvest plan is used as the reforestation plan above, i.e. the forest will be harvested over a period of 10 years but after harvest the area is replanted. This will result in an average deforestation of 3490 pixels per year and an average reforestation of 5571 pixels every year. The difference between harvest and reforestation is caused by the deforestation that has happened in the past and that will be reforested as part of this harvest and reforestation cycle of 10 years. Calculations can be found in this file. On the map, these rates will differ slightly as in the past some areas are more deforested than others and the harvest is not based on total forested pixels but on 10% of the project area. (Of course, one could easily select number of pixels and use the same method as below.) After 10 years of harvesting and replanting, the forest is left untouched and so the maps the same (i.e. fully forested) up to 2050.

Practically the following steps can be taken to develop the maps and to estimate the emissions for such (a) postponed reforestation scenario(s):

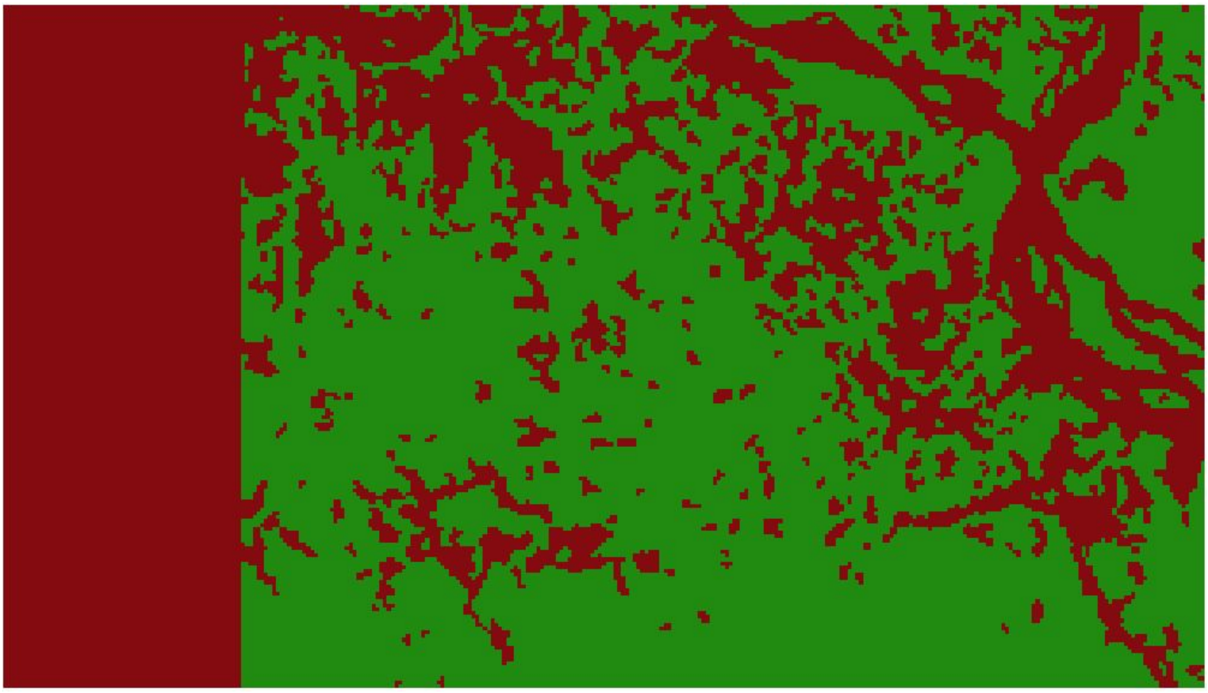
1. Establish the annual harvest rate, in our example, a strip of 10% of the forest area or a total of 5572 pixels of which an average of 3490 will actually be forested, others will have been deforested in the past.
2. Turn all forested pixels into no-forest in the first strip of 10% of the project area. Select all pixels of the first 10% of all columns on the left hand side of the project area (for simplicity reasons). Brown colour is no-forest, green colour is forest. (Any other harvest pattern can of course be selected.)

3. Combine this harvest plan with the existing situation: Using the latest historical observation (in our example the observation from 2018), keep the existing no-forest and turn all forested pixels of the first strip of 10% into no-forest.

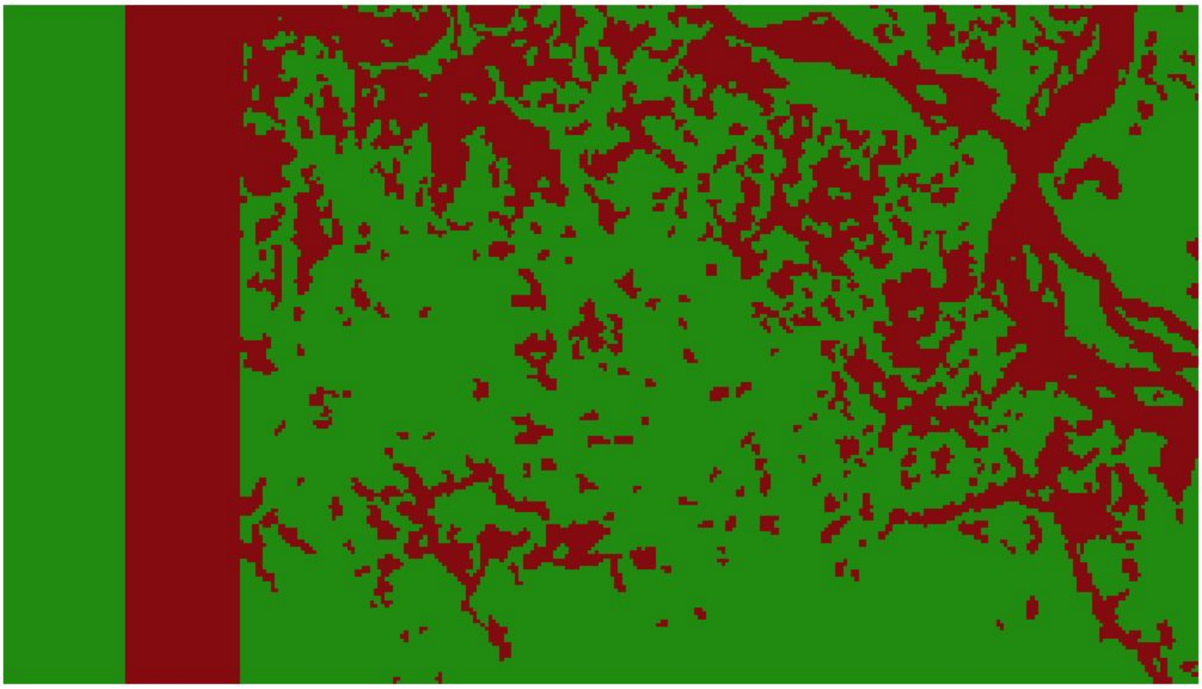


4. The map of the following year will shift the 10% strip of harvest to the right and reforest the first strip: Create a map with a strip of an additional 10% of all columns on the right from the previous harvest area.

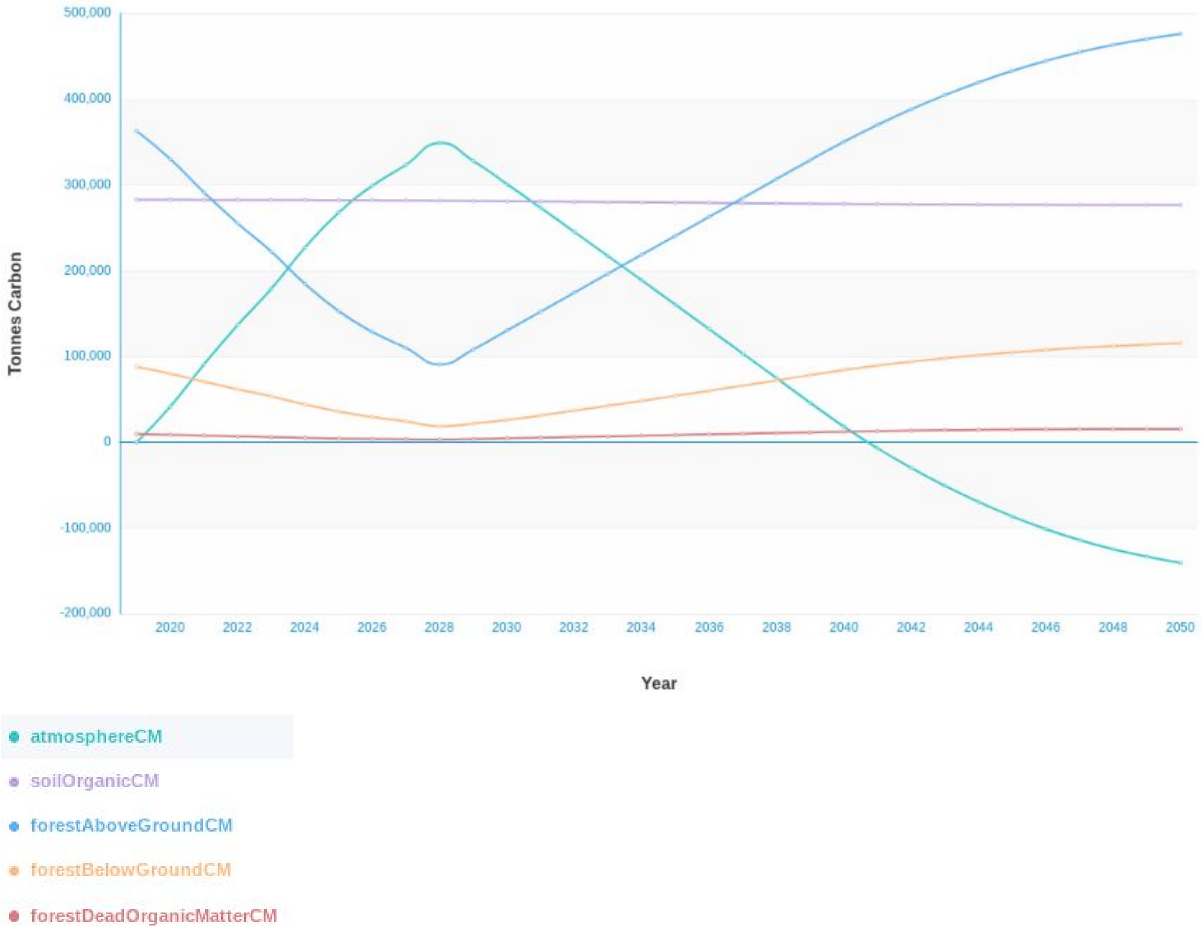
5. Combine with the previous map



6. Turn the previous strip into regrowing forest.



7. Repeat for each year until the whole harvest plan for 10 years is complete. After that the area will be considered to remain completely reforested so up to 2050 there will be no changes.
8. FLINT will calculate the annual emissions and sinks from all the pools based on the supplied maps. The chart shows rapid loss of carbon stock while deforestation takes place over 10 years. After that the landscape recovers but it takes until 2041 before the emitted CO2 has been removed from the atmosphere again.



These are [step-by-step instructions to implement this approach in open source QGIS software](). The [resulting maps]() can be downloaded.

Projection of Sustainable Forest Harvest

Projections can also be used to determine sustainable harvest rates. The aim of this section is to demonstrate map building and avoid scientific discussions about the definition of sustainable harvest. Therefore the following assumptions will be applied. Since we are in a tropical environment, the forest is assumed to grow back over a period of 65 years (based on a study focusing on the Brazilian Atlantic forest).

The carbon sequestration potential of our afforestation/reforestation example might be higher or lower than the grow back rate. Hence the grow back rate will be applied to the project area and the FLINT results will be used to determine whether carbon stocks are constant too or whether they go up or down.

For example, let's assume that we can reforest the whole area in 1 year. From then onwards, blocks of 1/65 part of the project area will be harvested every year, i.e. 857 pixels per year. This will be applied to a different part of the project area for the 31 years upto 2050. Calculations can be found in this file. The results of the FLINT estimates will determine whether this harvest rate results in constant levels of carbon stocks.

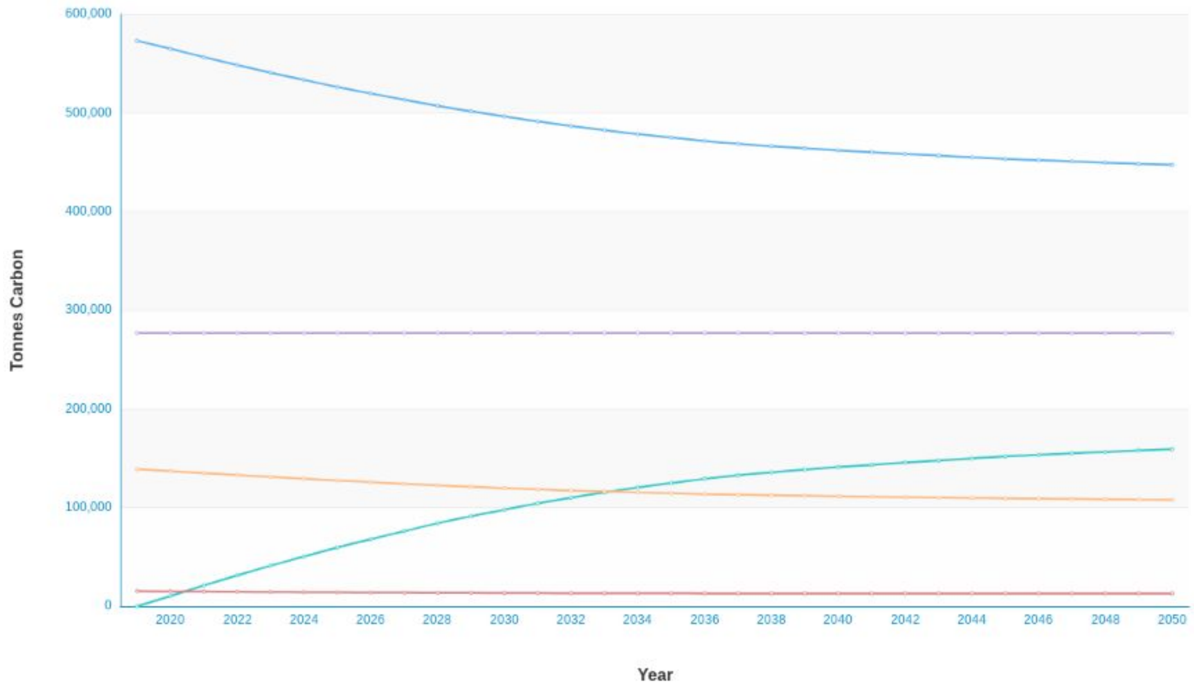
Practically the following steps can be taken to develop the maps and to estimate the emissions for this sustainable harvest rate:

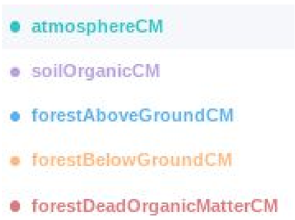
1. Reforest the whole area in the year after the latest historical observation, i.e. 2019. All pixels will be turned into forested.

2. Harvest the first 857 pixels in the next year, i.e. 2020. The pattern is not essential for this example. There will be some variation depending on the age of the pixels harvested. This example is limited to harvesting the pixels from left to right but of course the same approach can be used for any other harvesting plans.

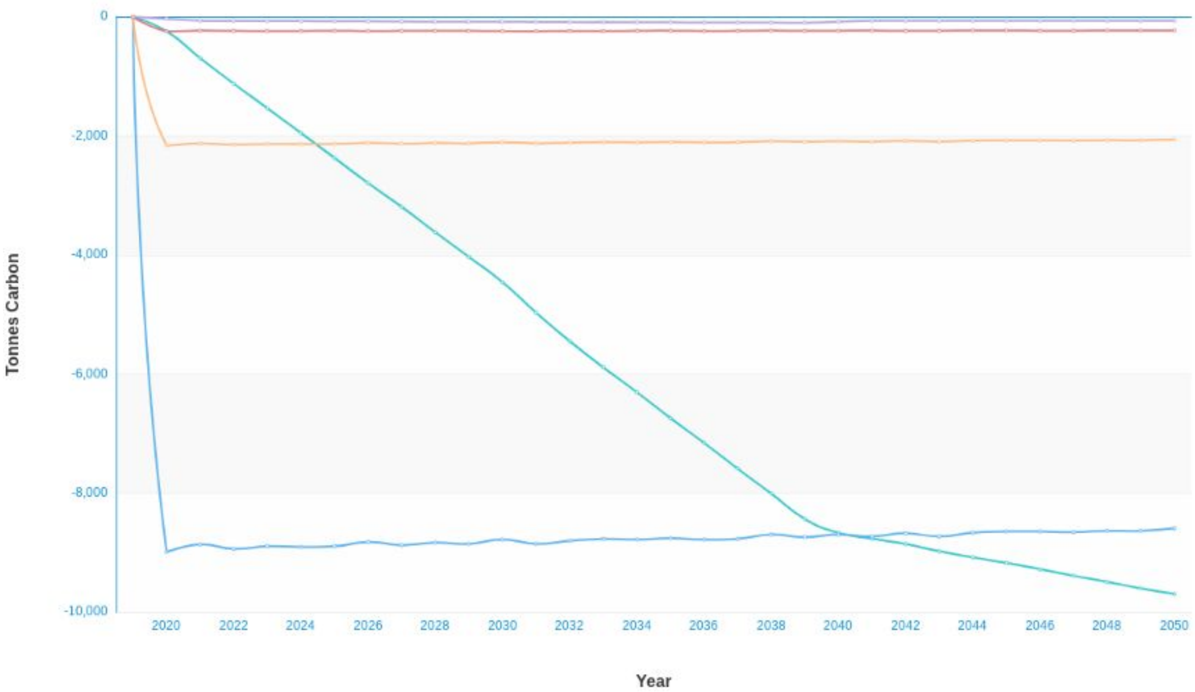
3. Harvest the next 857 pixels in the next year, i.e. 2021 and return the first 857 pixels back to forest as the forest will regrow on this area. This forest regrowth will restart at age zero.

4. Continue to the same steps for the next 857 pixels for the next 30 years.
5. FLINT will calculate the annual emissions and sinks from all the pools based on the supplied maps.
6. If total carbon remains constant, the renewal rate is sustainable from a carbon perspective. However, as can been seen from the chart below, the carbon stock go down when a renewal rate of 65 years is used.

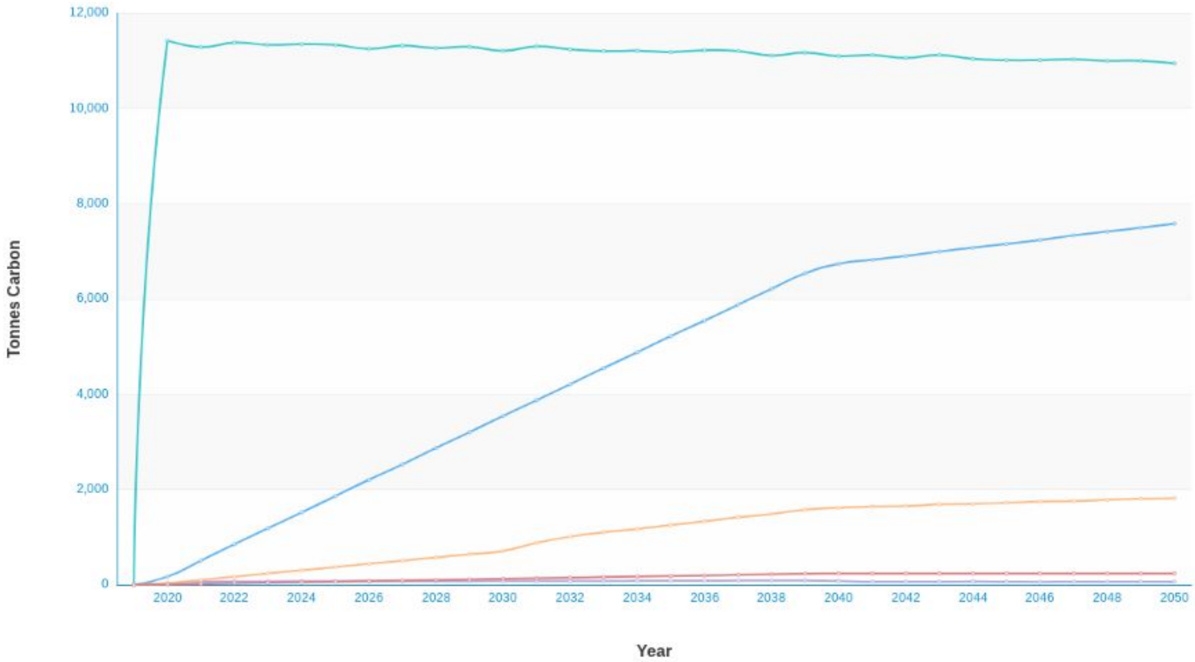




A more sustainable rate can be derived from the annual loss and annual gain charts. First annual just under 9000 Tons of carbon per year are lost when the harvest rate is 857 pixels. So about 10 Tons per year per pixel. This can be derived from the carbon loss chart below. (Careful, these are not nett fluxes as shown in the charts above.)



On the other hand, the recovering landscape can absorb about 7000 Ton of carbon per year as shown in the carbon gain chart below.



So a sustainable rate would be closer to 700 pixel per year, or a renewal rate of 80 years instead of the 65 years as reported for Brazilian Atlantic forest

These are the step-by-step instructions to implement this approach in the open source QGIS Software. The resulting maps can be downloaded from the DropBox.

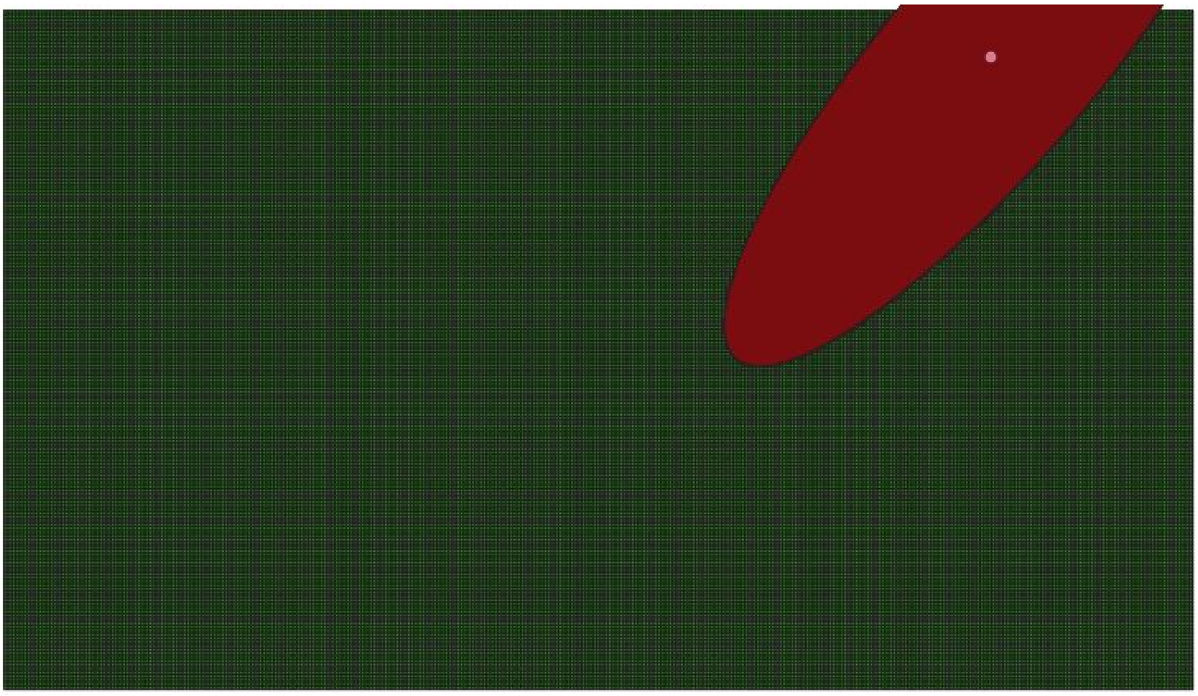
Projection of Fire Events

In view of the recent events in Australia, Brazil, USA and Canada, the projection of the carbon impacts of wildfires is moving up the agenda. As explained this document is not about the science of how the frequency or size of fires will change as a result of climate change. The purpose is to map a random fire annually and let the forest regrow after the fire.

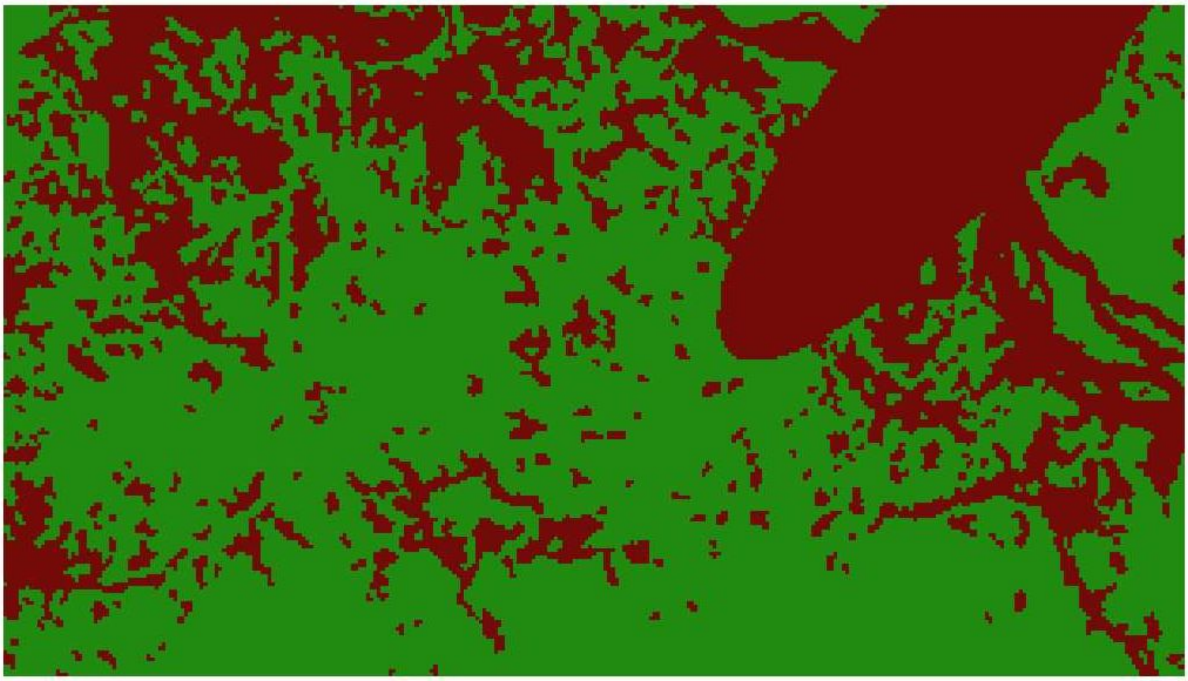
More complex fire management maps (e.g. including events like thinning, the creation of fire breaks, removal of dead organic matter, etc.) can be mapped similar to other events demonstrated in this document. However, such complex projections will quickly surpass the utility of the manual mapping process. More advanced mapping capabilities will be required. One of the projects described in the existing approaches to making FLINT-based projections describes an advanced approach to fire projections.

For example, let’s assume that there is a fire in our project area every 5 years at a random place in the project area. The deforestation that happened before the projection series, is considered permanent but there will be no deforestation added (for simplicity and comparability with the harvest scenario above). It is of course possible to combine both deforestation under BAU and forest fires in the same map. Here we will focus on the forest fire only:

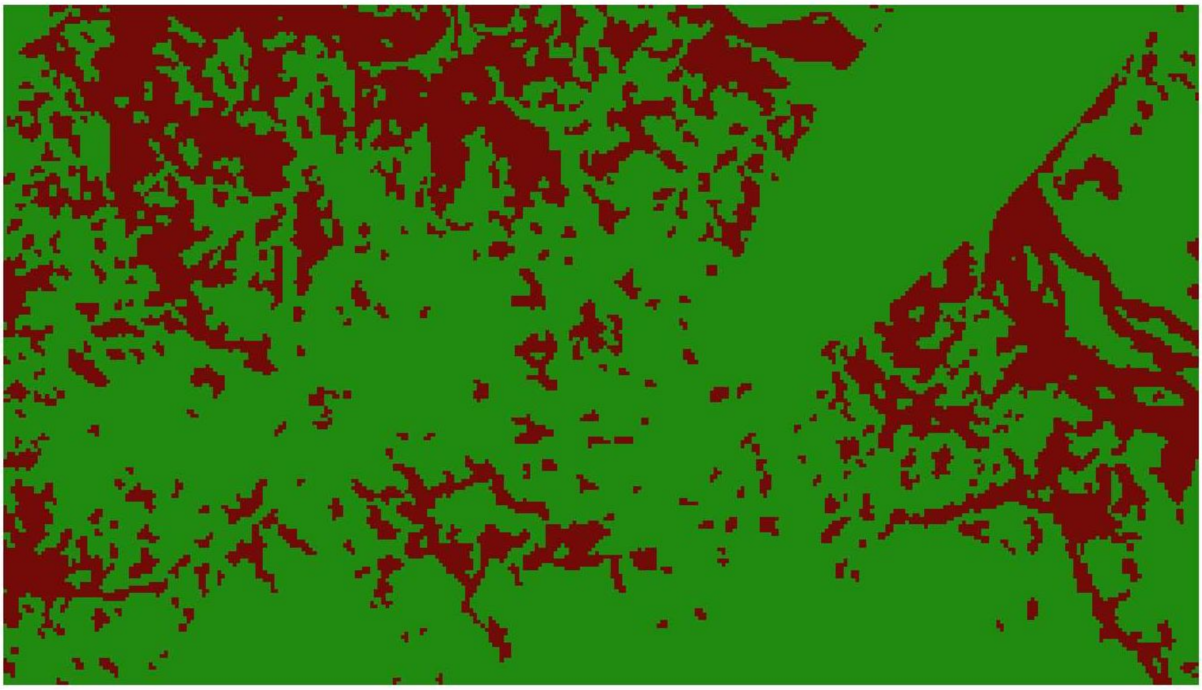
1. Establish the size of the area that burns down every 5 years: in our example, a 10% of the project area will be burned every 5 years. So comparable to the harvest scenario above, the area burned is 10% but due to the historic deforestation, not every pixel in that area will be forested, only an average of 3490 pixels will be forested. Also similar to the harvest scenario, the whole area will recover after the fire, so the whole 10% or 5571 pixels will be turned back to forest the next year. The calculations can be found here.
2. Establish the location of the area that burns down every 5 years: in our example, a random point is selected in the project area (in the spreadsheet). Next a random angle for the ellipse of the burned area is generated in the spreadsheet. With these two points, an ellipse with about 5571 pixels in the project area is drawn. The ellipse can be largely outside the project area, so the size has to be increased until about 5571 pixels are inside the project area.



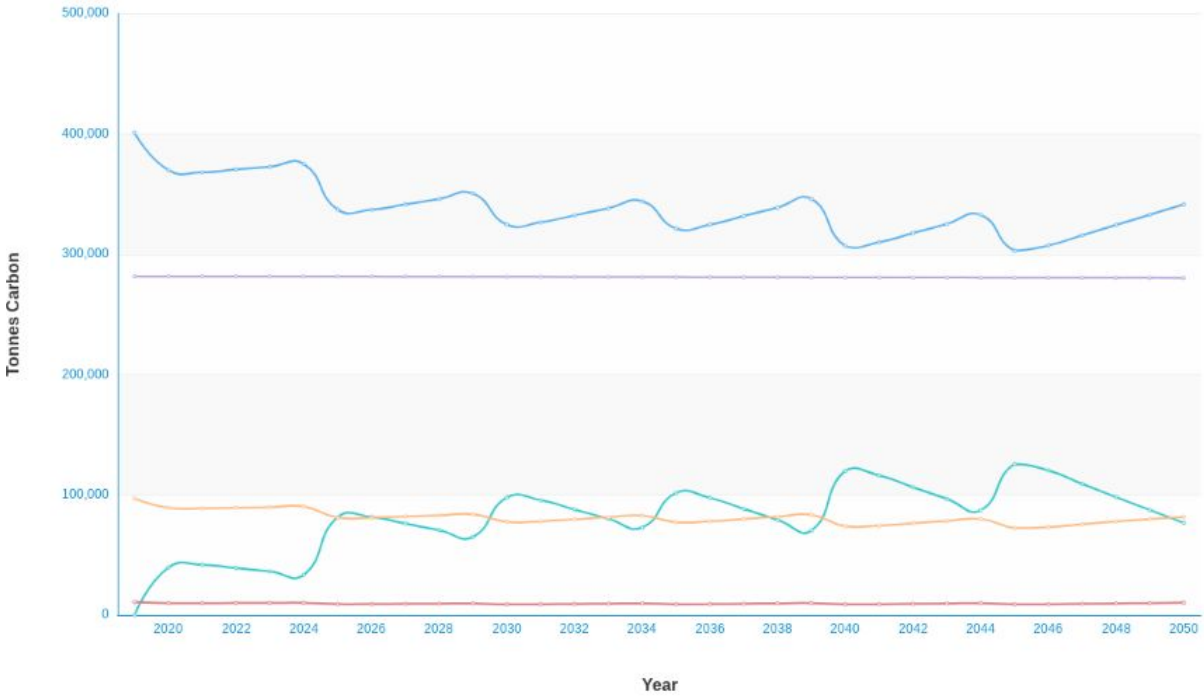
3. The burned area is combined with the existing deforestation.

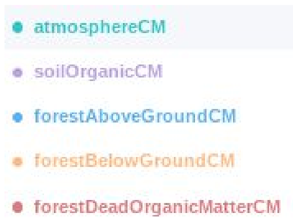


4. The next year, the burned area is regenerating. The existing deforestation is considered permanent. This might seem illogical in a real world scenario but it makes the scenario comparable to the approach taken under the harvest scenario.



5. This same map will be used for the next 4 years, i.e. 2021 until 2024.
6. In 2025, a new area of 10% will burn down so the same approach will be applied but using the 2021 map as the basis.
7. The maps for 2025 to 2050 are generated repeating the above process 5 times
8. FLINT will calculate the annual emissions and sinks from all the pools based on the supplied maps.





9. The chart shows a loss AGB which recovers over the next 4 years. Then another fire causes a similar loss of AGB. New vegetation will absorb more carbon so the recovery rate improves over time. However, the landscape cannot recover from a fire of about 10% of the area every 5 years. The losses in carbon to the atmosphere differ between fires even though the burned areas are the same. The carbon emitted is lower when areas that are still recovering from the previous fire (and have lower carbon stocks) are burned down again in the next fire.

These are the step-by-step instructions to implement this approach in the open source QGIS Software. The resulting maps can be downloaded from the DropBox.

Projection of Bark-Beetle Attacks

The changing average temperatures are causing more regular outbreaks of bark-beetle infestations. The impact of such infestations can be projected using FLINT if scientific research can provide information about the spread and about the impact. The spread will possibly be dependent on forests composition (i.e. species), winter temperatures, and drought. The impact will require models that take into account influence on tree mortality and changes in growth and changes in litter, etc. This document does not focus on these factors but will explore how the possible science answers can be mapped in a way that can be used by FLINT.

The infestation will spread geographically from a point of first year infestation to a high number of new infestations (the number depends on factors like winter temperature, drought, etc.) within e.g. a zone of 100 m and a lower number of new infestations within e.g. a zone of 1 km around last years infestation.

For example, let’s assume that the infestation starts in 2 random pixels. Then spreads annually to 30% of the pixels in a 100 m radius around the first 2 pixels and to 3% of the pixels in a 1km radius around the first 2 pixels.

1. Draw two circles around each of the 2 random pixels, 1 with a radius of 100m and 1 with a radius of 1 km.
2. The cells are 25 by 25 meter so the radius of 100 m has 50 cells, of which 15 pixels will be infected the next year.
3. The radius of 1km will contain 5026 cells of which 150 will be infected the next year.
4. So in year two, 165 new pixels for each random point so a total of 330 points will need to used as centers for 2 new circles each, i.e. 660 circles.
5. It is clear that this exponential increase in operations cannot be performed by a manual process. Hence this type of mapping cannot be achieve through simple manual processing.
6. It is possible to use approaches in R-language that have been developed and shared for those who have some experience with R but do not have the coding skills to develop a script from scratch.

Mapping these types of patterns requires the development of an advanced mapping tool.

Projection of Drought Impact

Drought impacts on various parts of the carbon cycle. As above, we will not try to delve into the science in this document. While drought maps are important, they will not affect land cover until large numbers of trees would die off and a whole pixel would be considered deforested. Hence drought maps are an input into weather sensitive models that are completely separate from the land-cover maps we are trying to manipulate in this exercise.

Projection of Combinations of Events

As already discussed above, it would be likely that projections involve several of the interventions listed above. For example, on the same landscape some areas will be harvested, some will be reforested and some will burn down, while the rest regenerates or grows.

The combinations are of course possible by applying each of the steps explained above on each of the annual maps. While the complexity does not increase, the number of steps go up very quickly and risk for errors will exponentially go up. Hence, an automated advanced mapping tool would be required if the project area or the number of interventions would increase.

Projection of Same Events in Different Climatological Zones

To demonstrate the influence of the climatological zone one could take any of the scenarios above and run it in a different climatological zone.

Practically, there are 3 ways of achieving this:

1. Move the rasters: By changing the geographic areas in which the raster is located, the climatological zone, FLINT would look up, would change automatically.
2. Change the map with the climatological zones: Rather than changing the location of all the rasters, it would be easier to just change the map FLINT uses to find the climatological zone.
3. Change to models or emissions factors: A further short-cut would be set-up the FLINT run with specific models or emissions factors rather than letting FLINT look up the models / EF by checking the climatological zone on a global map.