Carbon emissions due to deforestation and land use change represent nearly one-fifth of global greenhouse gas emissions, second only to the energy sector. This sector has been cited as a potentially cost-efficient means of reducing emissions when compared to other sectors. One approach is the implementation of individual REDD (Reducing Emissions from Deforestation and Forest Degradation) projects, where a specific parcel of land is protected, and the change in deforestation and carbon emissions due to this protection is quantified. This approach is accessible in TerrSet on the REDD Project tab of the Land Change Modeler (LCM).

The GeOSIRIS model takes a different approach. Instead of protecting a specific parcel of land from deforestation, GeOSIRIS projects work on the regional or national scale, where a specific price is set to each ton of carbon dioxide emitted ($/tCO2e). The GeOSIRIS model assumes forest users face a trade-off between the agricultural revenue obtained from deforesting land, and the carbon revenue obtained by protecting it. Given a proposed carbon price, and maps of previous deforestation and other variables, the model predicts how deforestation, carbon emissions, and agricultural and carbon revenue would change if such a carbon-trading policy were implemented.

The GeOSIRIS model was originally developed as OSIRIS by Jonah Busch at Conservation International, as a transparent decision support tool for REDD+ policy makers. OSIRIS stands for Open Source Impacts of REDD+ Incentives Spreadsheet, and the original versions of these tools are Excel spreadsheets available at Conservational International’s website. As the OSIRIS tool was designed to be transparent and open-source, all calculations can be seen within this spreadsheet. The implementation of OSIRIS in TerrSet allows you to see the OSIRIS results in a spatial context, thus the name: GeOSIRIS.

This chapter goes into detail of how to use the GeOSIRIS module in TerrSet, as well as, the mathematical underpinnings of different aspects of the model. You may find it useful to review the REDD project tab in the Land Change Modeler (LCM), to see a different approach to reducing carbon emissions related to deforestation.

Outline of GeOSIRIS Panels

The GeOSIRIS model follows a sequence of seven panels.

---


GeOSIRIS Project Parameters

In this panel you can create, load, and save your GeOSIRIS project. You can also choose to overlay a vector file on the result images or use a custom palette for images.

External Factors

In this panel you specify (i) the carbon price for emission reductions or increases, and (ii) the country national reference level of emissions. The country national reference level of emissions specifies the baseline against which emission increases or decreases are measured.

Decision on National REDD+ Rules and Incentives

This panel determines how carbon revenue and penalties are shared between the national government and other administrative levels, such as districts or provinces that are specified in the Input Image Files panel. The GeOSIRIS model allows for a portion of carbon revenues and penalties to be shared, which can increase participation and emission reductions in the GeOSIRIS project. The diagrams below show examples of how carbon revenue and penalties would be shared between the national government and the district level.

Model Parameters

The model parameters are economic and affect the price of agriculture. The price elasticity is a measure of how sensitive the domestic production price of agriculture is to the change in deforestation. The exogenous increase in agricultural price is one portion of the final change in agricultural price (see the Equilibrium Step section below).

Input Image Files

This panel contains the input maps for the project area, the forest area, carbon (above/below ground, soil, and peat) and the administrative levels, like province or district on which GeOSIRIS is administered (see the Geographic Approach section). Maps can be Boolean or Fractional, which determines the regression type that can be run in the Effective Opportunity Cost panel (see the section Boolean vs. Fractional Maps and Logistic vs. Poisson Regression).
Effective Opportunity Cost

This panel calculates a regression between deforestation and agricultural revenue and other independent variables. There are two main outputs of this panel: (1) the regression coefficient relating agricultural revenue to deforestation, and (2) the effective opportunity cost image, which displays the relative probability of a pixel being deforested, based on a linear combination of the regression coefficients for all independent variables. (See the sections Boolean vs. Fractional Maps and Logistic vs. Poisson Regression, Regression Coefficient Stratification, and Effective Opportunity Cost sections for more information).

Output Parameters

The output parameters panel calculates the final change in the domestic agriculture price, based on an iterative process. The process ends when the proportional change in the agriculture price for two successive iterations is less than the model precision input.

Important GeOSIRIS Calculations

Emission Factor

The emission factor map is used to calculate how many tons CO₂ will be emitted per hectare of deforestation. There are three components for the emission factor in the GeOSIRIS model: above and below-ground carbon, soil carbon, and peat.

The equations for the emission factor at each pixel are:

\[
E = (AB + SC \times f_s) \times 3.67 \text{ where Peat } = 0
\]

\[
E = AB \times 3.67 + f_p \text{ where Peat } > 0
\]

\[
E = \text{emission factor } \left( \frac{tCO_2e}{ha} \right) \text{ (pixel level)}
\]

\[
AB = \text{above and below ground carbon (pixel level)}
\]

\[
SC = \text{soil carbon (pixel level)}
\]

\[
f_s = \text{soil carbon factor (input parameter)}
\]

\[
f_p = \text{emission factor for peat soil (input parameter)}
\]

Note that when the peat value of pixel is non-zero, the emission factor equation does not depend on the depth of the peat soil, only the peat emission factor \( f_p \).

Boolean vs. Fractional Land Cover Type

You may have noticed in the Input Image Files panel that you have the option of selecting Boolean or Fractional land cover type. This refers to the data type of the (1) reference area, (2) forest before REDD, and (3) deforested area maps. When the Boolean option is selected, these maps must be Boolean images where a value of 1 means a pixel is either (1) completely contained in the reference area, (2) has 100% forest cover, and (3) 100% deforestation, respective of the three maps listed above.
If the data type is fractional, then these images change in the following ways: (1) the Reference Area map is renamed Land Area, with values in hectares. Pixels can have an area value representing only a fraction of the pixel, which is often the case for pixels along the coastline. (2) the Forest Before REDD image has values in hectares. (3) The Deforested Area map has value in hectares.

The data type also affects whether the GeOSIRIS Modeler uses a logistic or Poisson regression in the Effective Opportunity cost panel. See the Logistic vs. Poisson Regression section for more details.

The following table lists the discrepancies between Boolean and Fractional Landcover Types.

<table>
<thead>
<tr>
<th>Boolean</th>
<th>Fractional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input maps that change (with units)</td>
<td></td>
</tr>
<tr>
<td>Reference Area (0 or 1)</td>
<td>Land Area (ha)</td>
</tr>
<tr>
<td>Forest Before REDD+ (0 or 1)</td>
<td>Forest Before REDD+ (ha)</td>
</tr>
<tr>
<td>Deforested Area (0 or 1)</td>
<td>Deforested Area (ha)</td>
</tr>
<tr>
<td>Input maps that do not change</td>
<td>Biomass Carbon (tC/ha)</td>
</tr>
<tr>
<td>Soil Carbon (tC/ha)</td>
<td>Soil Carbon (tC/ha)</td>
</tr>
<tr>
<td>Peat (tC/ha)</td>
<td>Peat (tC/ha)</td>
</tr>
<tr>
<td>Independent Variables</td>
<td>Independent Variables</td>
</tr>
<tr>
<td>Regression Type</td>
<td>Logistic or External Model</td>
</tr>
<tr>
<td></td>
<td>Poisson or External Model</td>
</tr>
</tbody>
</table>

**Logistic vs. Poisson Regression**

In the Effective Opportunity Cost panel, a regression is used to calculate the regression coefficient relating agricultural revenue (and other variables) to deforestation. The regression type can be logistic (for Boolean data) or Poisson (for fractional data). This section briefly describes the difference between these two regression types. Please note that while the regression coefficient displayed in GeOSIRIS modeler is for the agricultural revenue variable, all coefficients are used in calculating the Effective Opportunity Cost image (described in the Effective Opportunity Cost section).

**Logistic Regression**

A logistic regression analysis in TerrSet uses the LOGISTICREG module to perform a binomial logistic regression. In this regression, the dependent variable (deforestation) must only have values of 0 and 1. The logistic regression equation is:

\[
P(y = 1 | X) = \frac{\sum_{i=1}^{N} \beta_i x_i}{1 + \sum_{i=1}^{N} \beta_i x_i}
\]
where:

\[ P = \text{the probability of the dependent variable being 1} \]
\[ X_i = \text{independent variables \( (X_0 = 1 \text{ for the constant term}) \)} \]
\[ B_i = \text{variable coefficients (or parameters)} \]

For more information, please see the related TerrSet Help system.

**Poisson Regression**

A Poisson regression is generally used to model count data, such as the number of cases of diabetes occurring in a population within a given period of time. For the GeOSIRIS modeler, deforestation can be interpreted as count data by thinking of each pixel as composed of smaller subsections which may be individually deforested. For example, a 3 km by 3 km pixel will have an area of 900 ha, which can be thought of as 36 individual 25 ha sections, each of which can be individually deforested.

The Poisson regression equation is

\[
E(Y | X) = e^{\sum_{i=0}^{N} B_i X_i}
\]

where:

\[ E(Y | X) = \text{the expected "count" of deforestation} \ (Y) \ \text{given certain input conditions} \ (X) \]
\[ X_i = \text{independent variables \( (X_0 = 1 \text{ for the constant term}) \)} \]
\[ B_i = \text{variable coefficients (or parameters)} \]

There is technically no upper bound for the response variable \( Y \) in a Poisson regression. If any pixels are predicted to have a greater area of deforestation than their currently forested area, then the predicted deforestation area is scaled down to equal the amount of currently forested area.

**Regression Coefficient Stratification**

The regression step of the GeOSIRIS modeler calculates the relationship between deforestation and several independent variables, including agricultural revenue. There are several options to stratify this regression, where GeOSIRIS will run a separate regression for several different classes. These classes can be based on either the amount of preexisting forest cover (for quantile or user-defined classification), or geographic regions, such as provinces or districts (for geographic stratification). What follows is a brief overview of each stratification option.

**Single Forest Cover Class – No stratification**

All pixels with preexisting forest cover are included (i.e., where Forest Before REDD+ is non-zero.)

**Multiple Forest Cover Classes**

**Quantile Classification** – The study area is divided into (approximately) equally sized areas based on forest cover. As an example, a quantile classification with 4 classes may be divided into regions of 0-40% forest cover, 40-80% forest cover, 80-95% forest cover, and 95-100% forest cover. (Note: these regions do not overlap, and the first region does not contain areas with exactly 0% forest cover. More precise boundary values are 0.001%-40% for the first class, 40.001%-80% for the second class, etc.)
**User-Defined Classification** – The study area is divided into forest cover classes defined by the user. The user specifies the upper bounds for the classes. For example, if there are 3 classes, and the user defines upper bounds as 35%, 90%, and 100% forest cover, then the forest cover classes will be regions of 0-35% forest cover, 35.001% - 90% forest cover, and 90.001% - 100% forest cover.

**Geographic Stratification** – The study area is divided by geographic region, such as districts or provinces.

<table>
<thead>
<tr>
<th>Model</th>
<th>Boolean</th>
<th>Fractional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logistic – Single Coefficient</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Logistic – Geographic Stratification</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Poisson – Single Coefficient</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Poisson – Quantile Classification</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Poisson – User-Defined Classification</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Poisson – Geographic Stratification</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>External Model – Single Coefficient</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>External Model – Quantile Classification</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>External Model – User-Defined Classification</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>External Model – Geographic Stratification</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Effective Opportunity Cost Score**

The Effective Opportunity Cost Score image is produced during the regression step of the Effective Opportunity Cost panel. There are no units for the image – it displays the relative probability of deforestation at each pixel. The score is a combination of the independent variable coefficients. The equation for the score is:

\[
OC = \frac{B_0 + B_1X_1 + B_2X_2 + \ldots + B_NX_N}{B_1}
\]

where:

- \(OC = \text{Effective Opportunity Cost Score}\)
- \(B_0 = \text{Constant term}\)
- \(B_1 = \text{Agricultural revenue coefficient}\)
- \(B_i = \text{Variable coefficients}\)
- \(X_1 = \text{Agricultural revenue variable}\)
In other words, the effective opportunity cost score at a pixel is a linear combination of the constant term and the values of the independent variables at that pixel multiplied by their respective regression coefficients, all divided by the regression coefficient for agricultural revenue. The score is used to calculate the fraction of a pixel which will be deforested.

**Geographic Approach**

The GeGeOSIRIS model can be administered at different sub-national levels, such as the district or provincial level. You can enter image files in the Administrative Levels table of the Input Image Files panel.

This section outlines how the geographic approach works, including the Province and District-Level decision maps in GeOSIRIS.

**Calculating the Proportional Change in Agricultural Price**

This section details how the final proportional change in agricultural price is calculated in the Output Parameters panel. This calculation uses an iterative loop and two input parameters, the Model Precision and the Maximum Number of Iterations.

The proportional change is calculated as the sum of endogenous change and exogenous change.

\[
\text{Change in Agricultural Price} = \text{Endogenous Change} + \text{Exogenous Change}
\]

The exogenous change is entered as an input parameter in the Model Parameters panel. For each iteration of the model, the endogenous change is calculated based on the amount of deforestation with and without REDD, and the price elasticity.

\[
\text{Endogenous Change} = \left( \frac{\text{Deforestation without REDD}}{\text{Deforestation with REDD}} \right)^e
\]

where the exponent \( e = \text{price elasticity} \).

The model compares two successive values in the change in agricultural price to see if they are within the model precision value. If they are, then the most recent iteration’s value is used for the final calculations. The model will continue to run until two successive values meet the Model Precision criteria, or the maximum number of Iterations is exceeded, in which case the model terminates without performing any final calculations.

The chart below shows the steps in this calculation.
Overall process

The overall GeGeOSIRIS model has two main steps, a regression step, where the regression coefficient(s) and Effective Opportunity Cost image are calculated, and the final output step, where the proportional national change in agricultural price and output images are calculated and the summary Excel spreadsheet is produced. You can see a flowchart of these steps in the diagram below. It is possible to revise model parameters after the regression or final output steps if you would like to vary the model.
List of GeGeOSIRIS Parameters and Images

The following is a list of all GeOSIRIS parameters and images.

Input Images

**Reference Area**: a Boolean image of the REDD+ project area, for Boolean image type. (units: Boolean)

**Land Area**: a continuous image of the land area per pixel, for Fractional image type. (units: hectares)

**Forest Area Before REDD+**: depicts where forest area existed at most recent time point, before the proposed REDD+ project. This is a Boolean map for the Boolean image type, and a continuous map for the Fractional image type. (units: Boolean for Boolean image type, hectares for Fractional image type)

**Biomass Carbon**: above and below ground biomass. (units: tons carbon per hectare)

**Soil Carbon**: carbon content in soil. (units: tons carbon per hectare)

**Peat**: carbon content in peat soil. (units: Boolean, 1 = presence and 0 = absence.

**Deforested Area**: observed amount of deforestation within the previous 5 years. This is a Boolean map for the Boolean image type, and a continuous map for the Fractional image type. (units: Boolean for Boolean image type, hectares for Fractional image type)
Administrative Levels: Maps of sub-national administrative jurisdictions, such as districts or provinces. (units: jurisdictions should be numbered with positive integers. They do not need to be consecutive).

Agricultural Revenue: The agricultural revenue variable should represent the Net Present Value (NPV) of the agricultural revenue of land at that pixel for a specified time frame (e.g., 5 years), usually with a discount factor applied to represent reduced revenue in future years. (units: U.S. Dollars per hectare)

Other Independent Variables: Other potential driver variables for deforestation. Examples include elevation, slope, logarithmic distance to the nearest road or provincial capital, or the amount of area per pixel included in a national park, or a timber plantation. (units: varies based on driver variable)

Effective Opportunity Cost (External Model Only): displays the relative probability of deforestation at each pixel. This is a composite index of all driver variables affecting deforestation. (units: index units)

Input Parameters

World Carbon Price: Global carbon price for REDD+ project. (units: U.S. dollars)

Country national reference level as proportion of business-as-usual (BAU) emissions: Proportion of recent estimated emissions (based on observed deforestation). This parameter is used to create a baseline level of emissions which will determine carbon revenue and penalties.

Benefit Sharing: Proportion of carbon revenue shared by subnational entities with the national government.

Cost Sharing: Proportion of carbon penalties shared by subnational entities with the national government.

Price elasticity: This parameter represents how sensitive the domestic production price is to change in deforested area.

Exogenous increase in price of agriculture: This parameter represents how much the agricultural price on newly deforested land will increase due to factors outside of this particular project, such as the implementation of a global REDD+ mechanism.

Soil-carbon percent: percent of carbon contained in soil which will be emitted as carbon dioxide in the case of deforestation.

Emission value (peat soil): amount of carbon dioxide equivalent emitted from peat soil during deforestation. (units: tons CO₂ equivalent per hectare).

% of BAU: This parameter is used to calculate the reference level of emissions for each subnational jurisdiction, which is used to determine carbon payments/ penalties.

% of Emission Rate: the percent of the national emission rate to be used as the reference-level floor.

Proportion of potential agricultural revenue retained after production costs: the proportion of agricultural revenue retained after production costs are considered.

Regression sampling proportion: Proportion of pixels used in regression calculation.

Output Images and Parameters (Regression)

Effective Opportunity Cost: the relative probability of deforestation at each pixel. This is a composite index of all driver variables affecting deforestation. (units: index units)
The equation for the score is:

\[ OC = \frac{B_0 + B_1X_1 + B_2X_2 + \cdots + B_NX_N}{B_1} \]

where:

\[ OC = \text{Effective Opportunity Cost Score} \]
\[ B_0 = \text{Constant term} \]
\[ B_1 = \text{Agricultural revenue coefficient} \]
\[ B_i = \text{Variable coefficients} \]
\[ X_1 = \text{Agricultural revenue variable} \]
\[ X_i = \text{Other independent variables (for } i = 2 \ldots N) \]

**Regression Coefficients**: the regression coefficients relate the net present value (NPV) of agricultural revenue with deforestation.

**Output Images and Parameters (Output Step)**

**Carbon emissions with REDD**: carbon emissions based on modeled deforestation over given period with REDD+ project in place. (units: tCO₂ / 5 years)

**Carbon emissions without REDD estimated**: estimated carbon emissions based on observed deforestation during a given time period. (units: tCO₂ / 5 years).

**Carbon emissions without REDD modeled**: carbon emissions based on modeled deforestation, without a REDD+ project in place. (units: tCO₂ / 5 years) (units: tCO₂ / 5 years).

**Change in emissions due to REDD**: change in emissions from modeled carbon emissions without REDD to modeled carbon emissions with REDD. (units: tCO₂ / 5 years).

**Deforestation with REDD**: modeled deforestation over given time period with REDD+ project in place. (units: ha / 5 years).

**Deforestation without REDD (modeled)**: modeled deforestation over given time period without a REDD+ project in place. (units: ha / 5 years).

**Effective opportunity cost score scaled for production costs**: this image represents the effective opportunity cost score created during the Regression step, scaled for agriculture production costs. (units: index units)

**Emission Factor**: The total potential carbon dioxide that can be emitted from all sources: above / below ground carbon, soil carbon, and/or peat. (units: tCO₂ emitted / ha)

The equations for the emission factor at each pixel are:

\[ E = (AB + SC \times f_p) \times 3.67 \text{ where } Peat = 0 \]

\[ E = AB \times 3.67 + f_p \text{ where } Peat > 0 \]

\[ E = \text{emission factor } \left( \frac{\text{tCO₂}}{\text{ha}} \right) \text{ (pixel level)} \]

\[ AB = \text{above and below ground carbon (pixel level)} \]
\[ SC = \text{soil carbon (pixel level)} \]
\[ f_s = \text{soil carbon factor (input parameter)} \]
\[ f_p = \text{emission factor for peat soil (input parameter)} \]

Emittable forest carbon in parcel before REDD: Atmospheric CO₂ equivalent of total above-ground, below-ground, and soil biomass, which is susceptible to release during deforestation. (units: tCO₂)

The equation for the emittable forest carbon is:

\[ FC = FA \times EF \]
\[ FC = \text{emittable forest carbon} \]
\[ FA = \text{Forest Area before REDD} \]
\[ EF = \text{Emission Factor} \]

Fraction deforested without REDD: fraction of forest area modeled to be deforested without a REDD+ project in place. (units: fractional units)

Raw agricultural revenue scaled for production costs: Net-present value (NPV) of agricultural revenue at a pixel, scaled to include production costs. (units: $/ha)

Site level baseline: The site-level (pixel-level) baseline of carbon emissions against which carbon increases or decreases are measured. Increases will result in carbon penalties while decreases will result in carbon revenue for the participating nation. (units: tCO₂ / 5 years).

The site-level baseline is calculated based on parameters for the particular administrative level applied (e.g., district). The baseline is the maximum of two values: the modeled business-as-usual emissions, (potentially multiplied by a scaling factor) and a baseline floor, which is calculated as a proportion of the total emittable forest carbon stock.

The equation for the site level baseline is:

\[ B = \max(CE_m \times BAU_a, \quad F \times E \times f_a) \]
\[ B = \text{site – level baseline (units: tCO₂ / 5 years)} \]
\[ CE_m = \text{carbon emissions without REDD (modeled) (units: tCO₂ / 5 years)} \]
\[ BAU_a = \% \text{ of BAU for the administrative level} \]
\[ F = \text{forest before REDD (units: ha)} \]
\[ E = \text{emission factor (units: tCO₂ / ha)} \]
\[ f_a = \text{administrative – level floor as proportion of total forest carbon stock} \]
Would be parcel deforestation if jurisdiction opts into REDD: amount of deforestation if jurisdiction opts into REDD. (units: ha / 5 years)

Would be parcel deforestation if jurisdiction opts out of REDD: amount of deforestation if jurisdiction opts out of REDD. (units: ha / 5 years)

Would be parcel emissions if jurisdiction opts into REDD: amount of carbon emissions if jurisdiction opts into REDD. (units: tCO₂ emitted / 5 years)

Would be parcel emissions if jurisdiction opts out of REDD: amount of carbon emissions if jurisdiction opts out of REDD. (units: tCO₂ emitted / 5 years)

Would be relative loss from foregone agriculture at parcel: opportunity cost of forest land that is not deforested and converted to agriculture due to a REDD+ project (units: $, net present value)

District/Province Level Decisions: Decision of a district or province to participate in a REDD+ project. (1 = opt-in, 0 = opt-out)

Proportional Change in Agricultural Price: proportional change in agricultural price if a REDD+ project is in place

