GEO-Google Earth Engine (GEE) Programme: Tackling deforestation and forest degradation in Costa Rica using Google Earth Engine

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Executive Summary

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5° C (IPCC, 2019) encourages countries to significantly increase the ambition of their action plans to reduce greenhouse gas emissions and global warming and to initiate these actions immediately. Otherwise, global temperatures could rise by 3º C by 2100, far from the goal of the Paris Agreement to keep it below 2º C.

The IPCC estimated that 24% of all greenhouse gases in 2010 were caused by the agriculture, forests and other land use sector (AFOLU). However, this sector also has a high mitigation potential through forest conservation, restoration, sustainable management, and effective crop management, among others. Thus, the AFOLU sector is strategic for increasing global ambition. Implementing actions in this sector also contributes to safeguarding ecosystems and takes advantage of nature's ability to reduce emissions and improve the resilience of human populations to climate change. These Nature-Based Solutions (NBS) strengthen the implementation of the Aichi Biodiversity Targets for 2020, established to reduce the loss of biodiversity and improve services provided by nature to human populations.

Costa Rica’s National REDD+ (Reducing Emissions from Deforestation and Forest Degradation) Strategy, a key nature-based solution, involves five forest-related actions: reducing deforestation, reducing forest degradation, increasing carbon stocks through forest restoration, sustainable forest management, and conserving carbon stocks. Through the REDD+ framework, developing countries can access results-based payments by reducing emissions by implementing the proposed actions. The emissions reductions are measured against historical forest reference emission levels (FREL). Costa Rica developed the National Land Use, Land Cover and Ecosystems Monitoring System (SIMOCUTE) to measure the emission reductions and support various other decision-making processes.

SIMOCUTE is a comprehensive, integrated system of three primary monitoring subsystems, specifically: sample-based area estimation for monitoring land use and land cover, a national forest inventory, and a mapping system. The three elements use common land use, land cover, and/or ecosystem classification systems and integrate both field and remote sensing data. The primary objective of SIMOCUTE is to provide consistent and coherent information at a national scale on the state of and changes in the county’s land use, land cover, and ecosystems for REDD+ and other national and international reporting needs and decision making.

Sample-based area estimation relies on visually interpreting land use (LU) and land cover (LC) from a systematic grid of 10,600 plots using high-resolution imagery. By interpreting these data for multiple years, areas of each type of LU and LC can be estimated along with changes in them. The change data can be used by the REDD+ program to estimate carbon emissions from deforestation and forest degradation along with carbon sequestration from reforestation and forest conservation. However, in countries such as Costa Rica where deforestation rates are low, few samples fall in areas of change, resulting in high uncertainty of the area estimates, which can have a negative impact on the ability to qualify for and receive results-based payments.

One way to address this problem is to create a change map spanning the reporting interval, which serves as a source of stratification for the existing samples. More importantly, additional plots added into the change strata can reduce the error or uncertainty of the change estimates. However, if the map has errors such that areas of true change are incorrectly mapped and included as part of the forest or non-forest strata, and are detected by the sample plots, the error of the estimate of change will experience a large increase that can offset the benefit of stratification.

Due to the sampling issues caused by map error, it is imperative to create highly accurate maps for stratification to achieve more precise estimates of change and carbon emissions. Costa Rica tested the Continuous Degradation Detection (CODED) and Breaks for Additive Seasonal and Trend (BFAST)

algorithms to create change maps with some success. Nevertheless, it is believed that considerable improvements can be made by fine-tuning these and/or other algorithms.

In addition to uncertainty caused by map error, other sources of error must also be accounted for. One of these is the error associated with the emission factors that are multiplied by the areas of deforestation or reforestation to estimate carbon emissions or sequestration. Although IPCC guidelines permit the use of emission factors of varying degrees of refinement, they should ideally be as precise as possible. Costa Rica has opted to apply unique emission factors to account for varied amounts of biomass contained in different types and ages of forests. Taking advantage of the benefits offered by applying emission factors adapted to forest age requires an accurate map of forest by age class, but this has proved challenging to be challenging. Similarly, Costa Rica needs to accurately detect forest degradation to achieve precise estimates of carbon emissions resulting from this activity.

On a different, but related topic, Costa Rica seeks to combat illegal activities such as drug trafficking and the accompanied illegal logging. These activities threaten the country's security and safety, as well as the environment and biodiversity. Therefore, the country is interested in developing a remote sensing–based early warning system to detect deforestation, in near real time, such that law enforcement agencies can respond rapidly and intercept criminals.

In an effort to achieve more precise estimates of deforestation, forest degradation, and forest restoration and the associated carbon emissions and sequestration, in addition to reducing deforestation through early detection of illegal activities, through the "GEO-Google Earth Engine (GEE) Program," we propose to:

- Develop and implement an efficient pipeline for processing time series data (both optical and radar) in GEE to create maps of change
- Operationalize existing and/or new time series–based change detection algorithms to produce highly accurate change maps to complement sample-based area estimation
- Implement algorithms in GEE to generate forest age maps and detect forest degradation
- Create an early warning system in GEE, building from the previous points, to provide near real-time alerts of deforestation
- Share strategies, tools, results, and lessons learned with other countries in the region

It is anticipated that these activities will:

- Increase the efficiency and quality of map production, while reducing costs, by taking advantage of Google's powerful computing environment and code repository.
- Enable Costa Rica's sample-based area-estimation monitoring system to generate more precise estimates of change using fewer sample plots, yielding more precise estimates of greenhouse gas emissions, which translates to higher results-based payments.
- Enable Costa Rica to further increase the precision of the estimates of greenhouse gas emissions by developing highly accurate forest age and degradation maps, which can translate directly to an increase in the REDD+ results-based payments to the country.
- Enable law enforcement agencies to detect and rapidly respond to illegal logging associated with drug trafficking and other illegal activities by developing an early warning system, which will lead to increased security and safety in the country. Illegal deforestation should also slow.
- Facilitate knowledge sharing with other countries. Many countries are facing similar challenges to Costa Rica in regard to precisely estimating rates of deforestation using sample-based area-estimation. The advancements in knowledge, algorithms, and protocols achieved through this project will be shared with other countries regionally through the AmeriGEO and SICA organizations, which could improve their greenhouse gas reporting using the methods and codes developed for Costa Rica.

Project Plan

Background and Motivation

Climate Change

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 ° C (IPCC, 2019), encourages countries to significantly increase the ambition of their action plans to reduce greenhouse gas emissions and global warming by 2020, as well as to initiate these actions immediately. Otherwise, the global temperature could rise by as much as 3 degrees Celsius by 2100, far from the goal of the Paris Agreement to keep it below 2 degrees Celsius.

In this scenario, the IPCC estimated that 24% of all greenhouse gases in 2010 were caused by the agriculture, forests and other land use sector (AFOLU) (IPCC, 2015). However, this sector also has a high mitigation potential and can yield very high benefits for adaptation to climate change, as it plays a central role in sustainable development and food security.

For these reasons, the AFOLU sector is strategic for increasing global ambition and countries should plan cost-effective actions in forest conservation, reforestation, landscape restoration, sustainable forest management, and effective management of crops and grasslands, as well as soil conservation. The implementation of actions in this sector also contributes to safeguarding the balance of ecosystems, by taking advantage of nature's ability to reduce emissions and improve the resilience of human populations to potential phenomena caused by climate change. This approach is what has been called Nature-Based Solutions (NBS), a concept that strengthens the implementation of the Aichi Biodiversity Targets for 2020, established to reduce the loss of biological diversity and improve the services provided by nature to human populations.

The National REDD + (Reducing Emissions from Deforestation and Forest Degradation) Strategy of Costa Rica (MINAE, 2017) is one of the nature-based solutions developed by the country, which involves the development of 5 fundamental actions related to forests: reducing deforestation, reducing degradation of forests, increasing carbon stocks by restoring forest ecosystems, sustainable forest management, and conservation of carbon stocks. The preparatory steps for the implementation of REDD + strategies were discussed and adopted in the Warsaw Framework of REDD+, during the United Nations Framework Convention on Climate Change (UNFCCC) COP19 in 2013.

In this framework, developing countries can access results-based payments by demonstrating emissions reductions by implementing the proposed actions. The emissions reductions are measured against historical forest reference emission levels (FREL). A monitoring system evaluates the emissions reductions against the FREL for the established actions that must be carried out.

To monitor the emission reduction commitments related to the National REDD + Strategy, Costa Rica developed the National Land Use, Land Cover and Ecosystems Monitoring System (SIMOCUTE) (https://simocute.go.cr/), which has grown to become a comprehensive, multipurpose and multi-disciplinary monitoring system that supports various decision-making processes (Figure 1).

The National Land Use, Land Cover and Ecosystems Monitoring System (SIMOCUTE)

SIMOCUTE is one of the main initiatives of the Government of Costa Rica to promote the generation and use of high-quality data and reliable information for decision making in the public and private sectors, in particular regarding land use monitoring and planning for climate change and various other reporting purposes.

Figure 1: Official logo of SIMOCUTE

Costa Rica formally initiated the design of SIMOCUTE in 2015 under the coordination of the National Center for Geo-environmental Information (CENIGA) of the Ministry of Environment and Energy (MINAE) through a ministerial directive issued by the former Minister of the Environment. The construction of SIMOCUTE has been participatory and includes key stakeholders from public and private institutions from the agriculture and environmental sectors, as well as international agencies. A key to the success of SIMOCUTE has been the high level of coordination and integration among these stakeholders.

The primary objective of SIMOCUTE is to provide consistent and coherent information at a national scale on the state of and changes in the county's land use, land cover, and ecosystems. It includes several coordinated subsystems that will integrate field-based data with remote sensing-based information to provide comprehensive data that can improve land use decision-making and satisfy a variety of national and international reporting requirements.

SIMOCUTE is designed as a decentralized system in which the institutions generate their data and information according to their respective mandates and roles, based on previously established requirements. An important role of SIMOCUTE is to support the development of protocols, methodologies and tools to standardize and ensure the quality, comparability and compatibility of the information produced. The data from the various institutions are integrated into a common platform that allows users to analyze the data and generate periodic reports to respond to various needs both nationally and internationally.

In the case of data or indicators derived to satisfy international agreements for organizations of which the country is a party, the methodologies and information are generated in accordance with the guidelines established in the agreements or organizations (e.g., Forest Emission Reduction Program and REDD + Strategy, IPCC guidelines, Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development SGD's).

In 2020, Costa Rica is transitioning the system into an implementation stage, which will be marked by the signing of an executive decree to officially adopt it, the launch of new modules on its technology platform (www.simocute.go.cr) and the consolidation of the work of thematic technical work groups that have worked to design the system.

SIMOCUTE's Conceptual Framework

SIMOCUTE can be thought of as a comprehensive, integrated system of systems founded on three interrelated processes: classification (what?), mapping (where?), and inventory and related registries (how much?) (Figure 2). The inventory and mapping processes include monitoring subsystems that use common land use, land cover, and/or ecosystem classification systems.

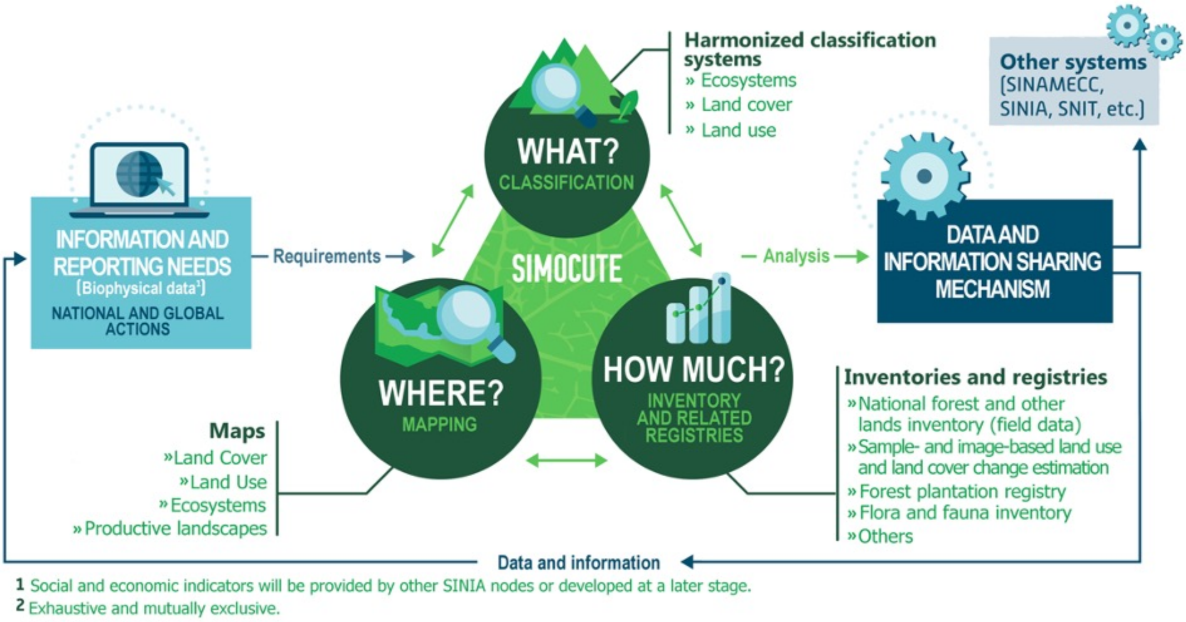

Figure 2: Conceptual framework of SIMOCUTE

Primary subsystems include: 1) a sample-based, area estimation monitoring system used to monitor the country's land use and land cover through visual interpretation of these attributes from a systematic grid of plots distributed across the country using high-resolution imagery, 2) a field-based national forest inventory, and 3) a mapping subsystem.

The information generated under SIMOCUTE will be accessible through different dissemination mechanisms directed to stakeholders and the general public. Data from different sources will be integrated into a common technological platform, where the institutions will process and analyze it to produce information that will provide solid support for the development and monitoring of policies related to the management of the land and its resources.

SIMOCUTE is also linked to several other existing monitoring systems developed for specific thematic areas, to ensure consistency, coherency and transparency in the data and the processes developed to generate them. This optimizes the human, technical and financial resources available in the country, and strengthens the governance and the adoption of different policies and methodologies.

SIMOCUTE Inter-institutional Coordination

A broad range of national and international institutions have supported the development of SIMOCUTE during its design stage, including more than 40 government, academic, international, and other institutions representing especially the environmental and agricultural sectors, but others are included as well.

The work of the various institutions is coordinated through thematic technical work groups. Figure 3 summarizes the work groups that are currently active (others will be activated in the future). These work groups have an advisory role and their main functions are to prepare, propose, review and adjust methodologies, indicators, protocols, standards and other tools for generating data and monitoring the landscape through time, while ensuring continuous improvement of SIMOCUTE's processes and products. The activities of these technical work groups are coordinated by the National Center for Geo-environmental Information (CENIGA) as Coordinating Unit of the process.

The Thematic Technical Work Groups have a decisive role in SIMOCUTE's structure, as they define the methodologies and processes governing the generation and use of the information. By integrating public institutions, academia, the private sector and international donors, these work groups become forums for discussion and joint networking between sectors to reach consensus while respecting institutional mandates and responsibilities, incorporating scientific and technological contributions, and considering the various information needs.

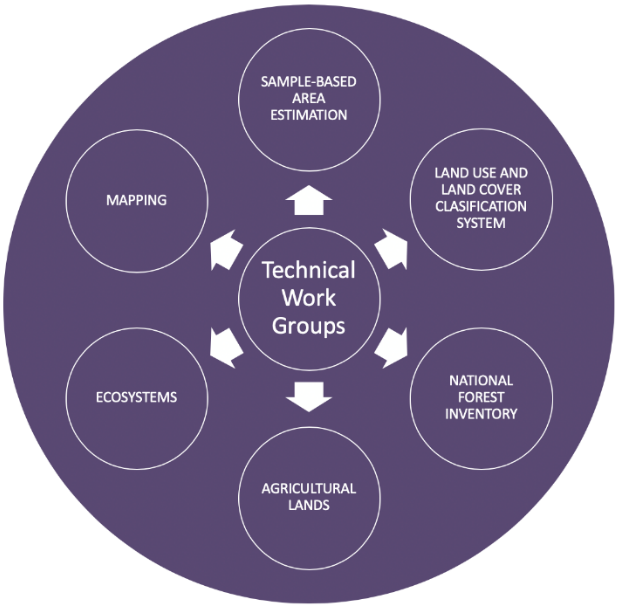

Figure 3: Technical Working Tables of SIMOCUTE

Specific responsibilities of SIMOCUTE's Technical Work Groups include the following:

Land Use and Land Cover Classification System: Propose and validate two classification systems: one for land cover and the other for land use. The classes in both systems must be hierarchical, exhaustive, mutually exclusive, applicable at a variety of scales, and with detailed definitions for each class.

Sample-based Area Estimation: Develop a monitoring system that provides institutions with knowledge of the current state and changes in land use and land cover through visual interpretation of these attributes from a systematic grid of plots using high-resolution images. This system provides statistically robust and frequently updated information for decision-making and to satisfy monitoring commitments such as for REDD+.

Mapping: Responsible for establishing standards and developing methods and protocols for generating maps of land use, land cover, ecosystems, and associated changes to support decision-making and complement the other technical components of SIMOCUTE.

Agricultural Lands: Defines methodologies and indicators for the Agricultural Sector in order to provide data on the current state and changes in the relevant land uses, land covers, and ecosystems. It also provides a space for technical dialogue between the agricultural, environmental and private sectors on issues of land use, land cover and ecosystems, including risks of climate change to the agricultural sector.

National Forest Inventory (INF): Analyze the various technical aspects of field inventory and make recommendations to the National System of Conservation Areas (SINAC) on methodological adjustments to the INF to transform it into a permanent and integrated monitoring component of SIMOCUTE.

Ecosystems: Analyze proposals and develop methods and protocols related to monitoring ecosystems.

Sample-Based Area Estimation Methodology and Work Group

The sample-based area estimation monitoring system developed by the technical work group of the same name will be essential for monitoring the emission reduction commitments related to deforestation and forest degradation for the National REDD + Strategy. This work group has been the most active group and has produced a series of relevant technical elements that are already being implemented by Costa Rican institutions.

Figure 4. Joint meeting of the Sample-based Area Estimation Work Group and the Mapping Work Group. November 27th, 2019.

The sample-based area estimation methodology aims to provide consistent and periodic information about the composition of the country's land use and/or land cover as well as changes in both properties through time, at both national and local scales. This methodology is presented as a complement and/or viable alternative to the traditional map-based approach of calculating the areas of different land uses, land covers, and changes in them. The design of the system has been overseen by a group of technicians and experts from different Costa Rican government and academic institutions, with the guidance of the United States Forest Service (USFS) and the SilvaCarbon program.

The sample-based area estimation methodology consists of sampling all lands through visual interpretation of images, to quantify the areas of each land use and land cover, along with the associated changes and the level of uncertainty of the estimate, without the effort required to develop a map (Webb, et al., 2012).

The sampling frame used to carry out this methodology is a systematic hexagonal grid of 10,600 plots, with a distance between the central points of approximately 2.4 km (Figure 5). The grid is an updated version of one constructed for the National Forest Inventory (INF) 2012-2015. The defined size of the plots is 2 ha (141.4 x 141.4 m). The methodology consists of placing another grid of 5 x 5 points (or more depending on the need) on the plots and viewing them on a remotely sensed image (Figure 6). An analyst reviews the points in the grid and interprets and records the land use and/or land cover of each one of them using tools such as Collect Earth (http://www.openforis.org/tools/collect-earth.html) or Collect Earth Online (https://collect.earth/).

After interpreting all the plots, the average proportions of each land use/land cover class are calculated. With data from two periods or years, the average proportions of change of each class and the associated variances can be calculated. By multiplying these proportions by the area of the study area, area estimates are obtained for each category. The variances allow the sampling error to be estimated. In this way, Costa Rica can estimate the areas of deforestation and reforestation for REDD+ reporting. Interpreting both land use and land cover provides more complete data on the composition of the landscape, such as the area or number of trees within pastures and/or crops.

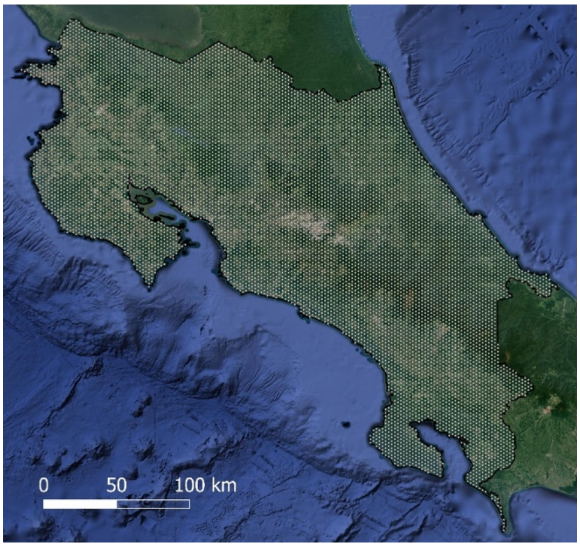

Figure 5: Base Grid (Level 1) with 10.600 plots for Costa Rica.

Although the grid provides a sample large enough to make accurate area estimates at the national level, 10,600 points may be insufficient to make reliable estimates in some sub-national areas of interest, as well as for small, rare classes such as change. Therefore, to estimate land use and land cover accurately for these areas, two additional equidistant hexagonal grids were elaborated, resulting from an intensification of the original grid. These new grids are nested within the original one. In this way, depending on the level of precision required, a different level of the grid may be used. In this way, the three levels of grids can complement each other to obtain better results.

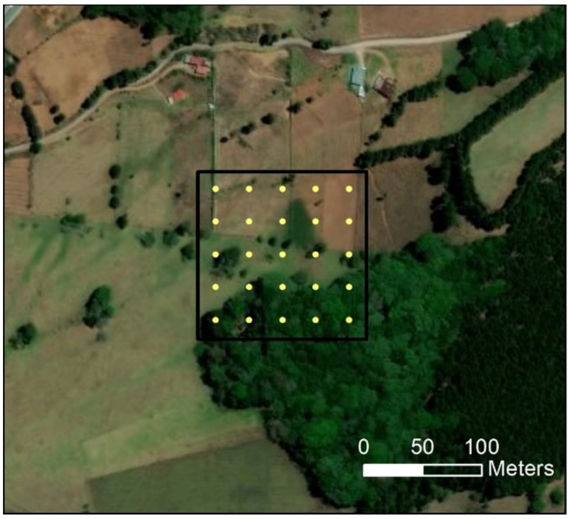

Figure 6: Example of a 2-ha plot, with a 5x5 points grid

Reporting and Information Needs for SIMOCUTE

One of the most important technical outputs of the design stage was identifying and achieving common agreement on the reporting and information needs of the country, which can be met through SIMOCUTE. This was accomplished by analyzing the policies and initiatives, both national and global, for which SIMOCUTE can provide information to monitor the status of and compliance with the goals and related commitments (Appendix 1).

Google Earth Engine Experience and Capacity Development

Costa Rican institutions have some experience using Google Earth Engine as related to SIMOCUTE. This tool has complemented the generation of the REDD + reports developed by the National REDD + Secretariat and it is anticipated that GEE will become an increasingly important part of REDD+ reporting and discussed below. Also, SINAC plans to use this tool to develop a new forest type map in conjunction with the next cycle of the National Forest Inventory, which will start in 2020.

As part of the capacity development strategy for SIMOCUTE, a series of trainings focused on the use of GEE were carried out for professionals from public, private and academic institutions. These trainings were carried out with the support of the SilvaCarbon program of the United States Government. The first training of this type was held in July 2018, and was taught by Noel Gorelick, software engineer and co-founder of Google Earth Engine (Figure 7). Gorelick showed the participants the image collections available in the tool and the analysis and mapping possibilities offered by the platform. Additionally, he taught participants how to use the GEE code editor to create cloud-free mosaics.

Figure 7. Instructor Noel Gorelick during the July 2018 Google Earth Engine training.

In May 2019, a follow-up workshop was held, this time with the participation of instructor Pablo Arévalo, an expert from Boston University (Figure 8). This training provided a more in-depth focus on developing capacities to detect deforestation and forest degradation using the CODED algorithm. Participants completed practical exercises to implement and adjust the degradation detection algorithm available in the GEE platform.

Figure 8: group photo of the participants to the workshop: "Detection of Forest Degradation Using Remote Sensing". May 22nd, 2019.

Proposal Motivation in the Context of SIMOCUTE, REDD+, Climate Change, and Law Enforcement

As previously mentioned, SIMOCUTE was developed in large part to monitor the emission reduction commitments related to the National REDD+ Strategy. In particular, the REDD+ strategy requires that carbon emissions caused by deforestation and forest degradation, as well as carbon sequestration from forest restoration activities be quantified and reported every two years. Costa Rica, like many countries, intends to use sample-based area estimation to quantify the number of hectares of deforested, degraded, or reforested land on a two-year cycle. These data are referred to as activity data. The areas are converted to tons of carbon emitted or sequestered by multiplying by conversion factors (known as emission factors). If the net emissions are lower than the baseline emissions (from the FREL), the country qualifies for results-based payments. There is a caveat, however. Under the Forest Carbon Partnership (FCPF) Carbon Fund Methodological Framework for REDD+, of which Costa Rica is a party, the country will be penalized for imprecise estimates (i.e., high error). Specifically, for every 15% of error of the estimate of carbon emissions, the country's payment will be reduced by 4%, up a total of 15% (FCPF, 2016). Currently, Costa Rica's reported error rate is between 15 and 30%, resulting in a penalty of approximately $140,000 per year (MINAE, 2019).

In Costa Rica, the amount of deforestation, forest degradation, and restoration that occurs on an annual basis is small (less than 1% of the country per year) (MINAE, 2016). As such, very few of the sample plots from the systematic grid fall in areas of change. Unfortunately, the low number of samples yields high sampling errors for the estimates of change. One way to address this problem is to create a change map spanning the reporting interval, which serves as a source of stratification for the existing samples. More importantly, additional plots can be added into the change strata (i.e., the map classes corresponding to change) to reduce the error of the change estimates. However, if the map has errors such that areas of true change are incorrectly mapped and included as part of the large forest or non-forest strata, and are detected by the sample plots, the error of the estimate of change (e.g., deforestation) will experience a large increase that can offset the benefit achieved through stratification.

Due to the statistical complications caused by map error, it is imperative to create highly accurate maps for stratification. Costa Rica worked with the Continuous Degradation Detection (CODED) algorithm (https://github.com/bullocke/coded) (implemented in GEE) with the assistance of an expert from Boston University for a short time to develop a change map for deforestation and forest degradation. While helpful, it did not achieve the level of accuracy desired. Similarly, the country worked with the Breaks for Additive Seasonal and Trend (BFAST) algorithm (http://bfast.r-forge.r-project.org/) implemented in the SEPAL platform (https://sepal.io/). Again, the map was helpful, but not as accurate as desired. Although Costa Rica's tropical environment, fragmented landscape, and small and disperse deforestation, degradation and reforestation activities pose significant challenges, it is believed that considerable improvements can be made by fine-tuning these and/or other algorithms. Developing highly accurate change maps is critically important to Costa Rica because it directly translates into higher results-based payments and reduces the cost of implementing sample-based area-estimation by reducing the number of sample plots that need to be interpreted.

In addition to the aforementioned sampling issues that can affect the precision of the final estimates of change and carbon emissions, other sources of error must also be accounted for in the final estimates. One of these is the error associated with the emission factors. Although IPCC guidelines allow countries to use emission factors of varying degrees of refinement (depending on national capacity and circumstances), the emission factors should ideally be as precise as possible to contribute the least possible amount of error to the final estimates. For example, some countries may opt to apply the same, generic emission factor to all types of deforestation, including deforestation of primary, old growth forests and of relatively young, secondary forests. The problem is that the amount of biomass and associated carbon emissions released by these two types of forests is vastly different, leading to uncertainty in the estimates. Other countries, such as Costa Rica, have opted to apply unique emission factors to account for different types and ages of forests.

To date, it has been challenging for Costa Rica to generate accurate maps depicting forest age. However, published approaches have been implemented in other tropical countries in Latin America and the Caribbean that have produced reliable maps (Feng et al., 2018; Montesano et al., 2016; Sexton et al., 2013, 2015). These approaches have also generated reliable estimates of forest degradation, which is a significant source of carbon emissions in Costa Rica that must be accounted for. Developing improved maps of forest age and better characterizing forest degradation is another way that Costa Rica can improve the precision of its emission estimates that could translate to increased results-based payments.

On a different, but related topic, Costa Rica seeks to combat illegal activities such as drug trafficking and the illegal logging that frequently accompanies it. These activities threaten the country's security and safety, as well as the natural environment and biodiversity. Therefore, the country is interested in developing a remote sensing–based early warning system to detect deforestation, in near real time, such that law enforcement agencies can respond rapidly and intercept criminals. While being an important tool for law enforcement, this type of early warning system is also important for REDD+ as it provides an important way to reduce deforestation and the associated carbon emissions, thus increasing carbon stocks and carbon removal due to forest growth. The reduction in deforestation can also translate to increased results-based payments that provide important financial resources to enable continued ability to monitor, protect and sustainably manage the lands of Costa Rica.

Proposal Objectives

The purpose of this proposal is to address, in an efficient, effective, and cost-effective manner, the aforementioned challenges and strengthen the national capacities of the Costa Rican institutions linked to SIMOCUTE to develop and implement processes that allow better detection of deforestation, forest degradation, and forest restoration, and allow the country to develop more reliable change maps and implement an early warning system. Strategies, tools, and lessons learned will be shared with other countries in the region.

Project Proposal

In the context of the "GEO-Google Earth Engine (GEE) Program," we propose to:

1. Develop and implement an efficient pipeline for processing time series data (both optical and radar) in GEE to create maps of change
2. Operationalize existing and/or new time series–based change detection algorithms to produce highly accurate change maps to complement sample-based area estimation
3. Implement algorithms in GEE to generate forest age and forest degradation maps
4. Create an early warning system, building from the previous points, to provide near real-time alerts of deforestation
5. Coordinate with AmeriGEO and SICA to develop strategies to share results, tools developed, and lessons learned with other countries in the region.

GEE Pipeline for Processing Time Series Data

Costa Rica seeks to develop an operational production pipeline using Google Earth Engine to process both optical and radar time series data to generate change maps to support sample-based area estimation for the REDD+ program and to generate near real-time alerts of deforestation for law enforcement. This pipeline would become a new subsystem of SIMOCUTE within the mapping process.

SIMOCUTE's Mapping technical work group dedicated several sessions to analyzing and discussing the optimal infrastructure and processing environments to enable the country to process image time series stacks and other large data sets. Data cube technology along with GEE, in particular, were investigated in depth. In the end, the group concluded that given the characteristics and limitations of our country, and the advantages offered by GEE, GEE was best option to incorporate into SIMOCUTE. In particular, GEE offers access to Google's powerful, state-of-the-art computing environment; vast archives of pre-processed imagery and radar data; lightning-fast processing; existing, free and open code developed by renowned remote sensing specialists; a highly collaborative environment that facilitates knowledge sharing; and the ability to do rapid prototyping. It would be impossible for a country such as Costa Rica to develop and maintain this type of system.

It is hoped that through the "GEO-Google Earth Engine (GEE) Program" that an efficient, yet flexible pipeline can be developed that will produce the desired products. Flexibility is an important aspect of the pipeline. Since processing algorithms will change and improve through time, we want the processing pipeline to accommodate updates to the algorithms or even the integration of new algorithms without requiring extensive restructuring of the processing code.

Operationalize Existing or New Change Detection Algorithms

As previously mentioned, Costa Rica has attempted to create change maps using the CODED and BFAST algorithms, but wishes to improve upon those results. As part of the support from the "GEO-

Google Earth Engine (GEE) Program," we propose to work with the GEE developers to fine-tune these or other algorithms to produce highly accurate forest change maps to identify deforestation, forest degradation, and reforestation. Target accuracy for these maps would be above 90%. It will be particularly important to minimize deforestation omission errors (i.e., areas of true deforestation that are incorrectly mapped as part of the stable forest or non-forest map classes) to avoid large increases in sampling error that occur when these errors are detected by the sample plots. It is proposed that one or more effective algorithms will be integrated into the GEE processing pipeline to allow the country to generate these maps as needed to complement sample-based area estimation.

Operationalize Forest Age and Degradation Mapping

In order to minimize errors associated with the application of emission factors, Costa Rica needs to develop highly accurate maps that show forest age. Algorithms have been developed that generate maps in which the probability of each pixel being a forest pixel (at a given percent canopy cover threshold) is characterized (Feng et al., 2018; Montesano et al., 2016; Sexton et al., 2013, 2015). When the probabilities change or become unstable through time, it is assumed that a change (to or from forest, or degradation) has occurred. When evaluated across many dates, the age of the forests can be determined and areas of forest degradation detected. Note that forests that have remained forest since the beginning of the Landsat time series are assumed to be primary, old-growth forests with similar biomass for estimation purposes. The algorithms mentioned have been successfully implemented in other Latin American and Caribbean countries to produce forest age maps and detect forest degradation. As part of the "GEO-Google Earth Engine (GEE) Program," it is proposed to work with the GEE developers to operationalize these algorithms in GEE, as part of the GEE pipeline, to produce accurate forest age maps and identify areas of forest degradation.

Operationalize an Early Warning System

In order to combat drug trafficking and related deforestation activities, Costa Rica proposes to develop a near real-time early warning system to generate alerts of possible deforestation activities. This system would form another integral part of the GEE image processing pipeline that would complement the other mapping products and benefit both law enforcement and the REDD+ program.

Regional Coordination

Costa Rica plans to coordinate with the Americas Group on Earth Observations (AmeriGEO) and the Central American Integration System (SICA) to promote the use of the knowledge, algorithms, and protocols developed through this project in other countries in the region. Costa Rica actively participates in these regional initiatives and will be in contact with the respective Secretariats to coordinate strategies to disseminate and promote this knowledge with other countries, through meetings, webinars, and web-based platforms.

Project Impact

It is anticipated that the four proposed elements of the current proposal provide significant benefit and impact for Costa Rica as well as for other developing countries that are also implementing a REDD+ program. In particular:

- Developing an efficient and flexible image processing pipeline in GEE should increase the efficiency and quality of map production for the country, while reducing costs, by taking advantage of Google's powerful cloud-based computing environment and freely-shared code repository.
- Developing highly accurate change maps will enable Costa Rica's sample-based area-estimation monitoring system to generate more precise estimates of change using fewer sample plots, both of which can directly translate to increased results-based payments under the country's REDD+ program. These additional resources will provide the country with

greater ability to conserve, restore, and sustainably manage its natural resources. Such efforts will ultimately contribute to the global effort to reduce greenhouse gas emissions and reduce global warming.

- Developing highly accurate forest age maps will enable Costa Rica to further increase the precision of the estimates of greenhouse gas emissions, which can translate directly to an increase in the REDD+ results-based payments to the country. Similarly, detecting and accurately characterizing forest degradation will also improve the precision of the greenhouse gas emissions.
- Developing an early warning system will enable law enforcement agencies to detect and rapidly respond to illegal logging activities associated with drug trafficking and other illegal activities, leading to increased security and safety in the country. Illegal deforestation should also slow, leading again to increased results-based payments.
- Many countries throughout the world are facing similar challenges to Costa Rica in regard to precisely estimating rates of deforestation using sample-based area-estimation. The advancements in knowledge, algorithms, and protocols achieved through this project could have a significant impact regionally and globally as other countries improve their greenhouse gas reporting using the methods and codes developed for Costa Rica.

Costa Rica, GEO and Google Earth Engine partnership

Through the GEO-Google Earth Engine (GEE) Program, the Costa Rican institutions in this partnership expect to scale up the development of these initiatives, through the following actions:

- Develop the capacities of Costa Rican experts to maximize the use of Google Earth Engine to meet the project objectives.
- Explore new sources of information for the development of the analyses available in GEOSS.
- Share in detail the experience of Costa Rica with other countries interested in developing these processes.
- Make the data and information generated by the project accessible for common use at national and global scales through spatial data management platforms, institutional websites and other communication platforms, and by sharing this experience in different initiatives and events, nationally and internationally.
- Receive technical support from EO Data Science to improve national capacities in the use of earth observations technology and data.
- Work with EO Data Science to improve change detection mapping methodologies and contribute new knowledge in this area of research related to Earth observation.
- Increase the level of participation of Costa Rican institutions in the GEO working groups and the regional activities of AmeriGEO.
- Encourage and support other countries in the Central America, Latin America and the Caribbean region to develop their capacities in earth observation.

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Appendix 1

Early on in the development of SIMOCUTE, reporting and information needs were identified by analyzing relevant policies and initiatives, both national and global, for which SIMOCUTE can provide information to monitor the status of and compliance with goals and related commitments (Table A1).

Table A1. Information and reporting requirements for SIMOCUTE

Scope of the requirement	Policies and initiatives identified
National initiatives and policies	National Development Plan National Forest Development Plan National Decarbonization Plan National Action Program to Fight Land Degradation in Costa Rica National REDD + Strategy National Biodiversity Strategy National Strategy for Climate Change State of the Environment Report National System of Environmental Accounts Territorial planning
Global initiatives and coordinated groups	2030 Agenda / Sustainable Development Goals Food and Agriculture Organization of the United Nations (FAO) FAO Forest Resources Assessment (FRA) Forest Carbon Partnership Facility (FCPF) Group on Earth Observations (GEO) Organization for Economic Co-operation and Development (OECD) United Nations Convention on Biological Diversity United Nations Convention to Combat Desertification United Nations Framework Convention on Climate Change

Among the national initiatives, there are various examples of specific key country goals that are being monitored by the institutions that form part of SIMOCUTE and that will be improved with the consolidation of the system. Among them are the following:

- National Decarbonization Plan (Government of Costa Rica, 2018)
  - Maintain forest coverage and increase it to 60 % of the country's territory.
- National Development Plan (Government of Costa Rica, 2020)
  - By 2022, reduce emissions by 4,000,000 tons of CO_2 equivalent.
  - Maintain 115,000,000 tons of CO_2 equivalent within the forests, under Payment for Environmental Services Programme contracts.
- National Biodiversity Strategy and Action Plan (MINAE, CONAGEBIO, SINAC, 2019).
  - By 2020, increase the country's ecological connectivity by 0.15%, through the creation of terrestrial biological corridors, considering climate scenarios (Goal 5).
  - By 2020, intervene 1,000,000 hectares of forest cover-landscapes, to avoid land degradation and favor biodiversity (Goal 9).