Protecting and Enhancing Natural Carbon Sinks

Natural Climate and Community Solutions

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1   Introduction

A healthy biosphere is critical to a stable climate system. For much of the Holocene, Earth's natural systems have maintained their essential role in the carbon cycle. However, recently global natural systems have become severely degraded and their capacity to serve as major carbon sinks is in grave danger.[1] Deforestation and forest degradation in the Amazon, Central Africa, and South-East Asia are reducing their natural carbon capture capacity and altering their critical ecological functions.[2] This project aims to protect tropical forests, a key component of the carbon sink capacity of the biosphere, through an integration of targeted technology breakthroughs, deep community engagement, and innovative bioeconomic opportunities.

Stopping deforestation and forest degradation is critical to keeping the global temperature increase below 1.5 °C. Tropical forests capture approximately half of all CO_2 emissions by terrestrial systems,[3] representing 14.5% of the global carbon sink, amongst terrestrial, atmospheric, and oceanic carbon sinks.[4] Mature forests in the Amazon alone store about half of all aboveground carbon across terrestrial ecosystems globally (150-200 Pg C[5,6]). In addition, while tropical forests account for approximately 6% of the Earth's surface, they contain between 50-90% of the world's species,[7] sheltering more tree species in a single hectare than in all of the continental US and Canada.[8] The Amazon is fundamental for the South American hydrological cycle[9] and provides numerous other ecosystem services to more than 30 million people.[7]

Deforestation and forest degradation are considered a 'wicked problem' with multi-faceted and evolving causes that cannot be resolved along single dimensions.[10] Whereas direct drivers of deforestation involve natural and anthropogenic activities that cause land cover change, indirect drivers involve large-scale global dynamics difficult to delineate.[11] Popular conservation methods (e.g., protected areas) have not slowed the continued pace of deforestation[12] and forest degradation. Carbon losses from forest degradation (e.g., selective logging) are three times greater than deforestation in the "arc of deforestation" in the south eastern regions of the Brazilian Amazon,[2,13,14] altering its ecological functions, increasing its vulnerability to ecosystem change,[15] and resulting in large portions of the eastern Amazon becoming net carbon emitters.[16] Indeed, tropical forests face "tipping points"—triggering feedback cycles that degrade their ecological structures and functions, reducing their carbon sequestration abilities,[17] and in the case of the Amazon, resulting in its "savannization."[6,18] See Appendix B for more on drivers and responses.

Natural climate solutions (NCS) deliver cost-effective mitigation and adaptation strategies that entail conservation, restoration, and improved land stewardship capable of increasing carbon storage, reducing biodiversity loss, and reducing global GHG emissions by a third[19] as well as pressures on other planetary boundaries (e.g., biochemical loading P and N).[20] While underrepresented in Nationally Determined Contributions (NDCs) to the Paris Agreement, they are essential strategies for meeting the agreement's objectives.[21] However, NCS strategies are in need of enhanced methods and technological tools, and deeper involvement of local communities.

Recent advances in remote sensing, unmanned aerial vehicles (UAVs), satellite data accuracy and availability, and processing capabilities through machine learning (ML) have created new

opportunities for the integration of high-resolution forest monitoring and management.[22] When combined with deep community engagement, particularly with indigenous and afro-descendant communities, this integrated approach promises to deliver substantially enhanced efficacy in conservation coupled to robust and sustainable local development.[12]

We therefore propose a Natural Climate and Community Solution (NCCS) comprised of the following three integrated pillars:

1.   Pillar 1: Community engagement and data collection framework to integrate in-situ (ground-based and airborne) and ex-situ (remote/satellite-based) monitoring systems of drivers of deforestation and degradation, carbon, biodiversity, and bioeconomy indicators;

2.   Pillar 2: Data processing, forecasting, and visualization decision-support platform utilizing machine learning to improve detection of early indicators and prioritize in-situ data collection, to empower local communities with actionable data; and

3.   Pillar 3: Bioeconomy business model co-creation incubator that identifies bioeconomy opportunities, strengthens local entrepreneurship and innovation capacity, incentivizes sustainable forest management practices and monitoring, and generates local income.

1.1   Pillar 1: Community Engagement and Data Collections Framework

Community-based planning processes and capacity building will be centered around the specific needs and priorities of local communities to initiate and substantially enhance local efforts to monitor forest carbon dynamics, biodiversity, drivers of deforestation and forest degradation, and species of interest for bioeconomic opportunities. Guaranteeing collective land rights to local communities has been shown to conserve forests just as effectively as nationally protected areas,[23] and allows sustainable use of forest resources and local socio-economic development.[24] Yet, current data collection frameworks often are not co-designed with local communities who tend to be digitally disconnected[25] and do not provide the level of detail necessary for community conservation systems leading to slower and more dangerous interventions.[26] An effective solution transforms the current conservation paradigm by combining traditional knowledge with new forestry monitoring technologies, facilitating local communities' access to the digital economy and offering an incentive for monitoring and protecting their forests.[11]

Pillar one is a foundational element of the program's holistic, integrated approach that combines in-situ and ex-situ sensing technologies and platforms, in partnership with Indigenous Peoples and Local Communities, NGOs, and government agencies to provide breakthrough capacity to monitor and protect tropical forests. The in-situ sensing and networking strategy will enable more rapid, automated verification and truthing of remote/satellite data, to inform faster, better satellite products, and an improved early warning system that incorporates AI/ML for deforestation prediction, discussed in Pillar 2. This predictive capability will inform smart sensor placement, such as EO/IR/PIR intrusion sensors, cameras, and acoustic and seismic sensors, in forest regions that are identified to be at risk of imminent harm, improving the ability of local communities to monitor their territories, and alert local and national authorities.

 All aspects of the monitoring system will be co-created, tested and deployed with local communities, including co-ownership and secure data protocols. The composition of the in-situ technological toolkit will be continually refined through a collaborative process with local experts, communities and on-the-ground partners, including capacity building workshops in data collection, processing, and analysis as well as the operation and maintenance of the systems. The novelty of this integrated model resides in working with local communities to develop and smartly deploy in-situ sensing and networking packages enabling while strengthening local communities capacities to monitor and protect tropical forests.

1.2   Pillar 2: Data Processing, Forecasting, and Visualization Platform

The second pillar involves the development of algorithms and models for integrating and processing the large amounts of data needed for forecasting deforestation and forest degradation patterns, and developing a decision-support platform for information communication, visualization, and uptake. Current platforms display deforestation and disturbances (e.g. WRI GFW[27]), but they lack timely forecast and information about degradation from selected logging,[28] and tend to rely on optical data which is sensitive to weather conditions.[29] The success of the decision-support platform depends on making information accessible and relevant to communities on the ground,[30] which can be complemented by integration of localized bioeconomy indicators and data provided by neighboring communities. This pillar addresses the challenge of integrating a combination of different data types with diverse levels of detail and data collection frequency in ex-situ and in-situ approaches into user-friendly format that provides actionable information.

Integration of in-situ and ex-situ monitoring systems will extrapolate data in an iterative process to offer real-time monitoring information across the Amazon biome. Identification of strategic ground sampling sites via satellite data is an established practice in deforestation monitoring,[25] which can be expanded to other monitoring goals such as forest degradation[30] and biodiversity assessments.[31] Strategic in-situ monitoring and data collection informed by ex-situ data sources and ML processing will provide the necessary training datasets and models for ground-truthing[32] that will allow to scale and forecast[33] forest dynamics. In-situ data processing can be accomplished via on-the-edge computing on smartphones[34] or novel approaches using cloud processing,[35] which can further improve integration of in-situ and ex-situ technologies.[36]

Integrated data will be visualized in a decision-support platform in the form of a website and smartphone application according to the needs and communication technologies' limitations of local communities. By offering real-time and high-resolution data to communities, local authorities, and NGOs in order to identify deforestation and forest degradation early warning signs and likelihood of drivers' occurence in at risk areas, intervention resources allocations and pre-placement of assets can be improved. Through bioeconomy species identification (Pillar 3), alternative development pathways can be identified to support regional planning processes and local communities' decision-making around the sustainable use of the forest. Finally, the platform will serve as a social arena to empower and connect communities across the Amazon biome, hence promoting knowledge sharing and sustainable development for the region.

1.3   Pillar 3: Bioeconomy Business Model Co-creation Incubator

The third pillar includes the co-design, research, and incubation of bioeconomy business models with local communities in order to transform the current economic development paradigm, incentivize forest conservation and monitoring, and develop and refine bioeconomy indicators. The identification of bioeconomy business opportunities, combining scientific advances with ancestral knowledge, will be followed by a training in entrepreneurship, business model creation, and will be coupled with the monitoring systems and scenario planning through the decision support platform to serve as an arena for raising awareness of sustainable practices. Thus, communities will increase their understanding of where in the value chain they operate, and with the technological support, be able to connect with other actors in the bioeconomy.

Combining traditional knowledge with scalable innovative business models has been implemented in the Amazon[11] with higher rates of economic return[6] than cattle ranching and monocultures,[18] entailing a wide range of value-added economic activities (e.g., biochemicals, bio-cosmetics, pharmaceuticals),[37,38,39] particularly the sustainable extraction of non-timber forest products[38,40,41] and aquaculture.[38,42,43] Yet, the Amazon bioeconomy falls short of its potential due to limited R&D, value chain and logistical challenges, and training support.[44] Circular business models,[45] together with an ecosystems approach[39] and the Canvas business model,[46] provide a foundation for a bioeconomy anchored to a strong sustainability paradigm[47] for implementing bioeconomy enterprises[48,49] detailing value creation, delivery, and capture. By developing innovative business models and incubation programs, local economic development will be dynamized, reducing the investment risk and attracting further investments, raising community GDP, and overcoming dependency on subsidies and PES systems.[50]

This approach is unique and stands apart from other current initiatives because of its biome-wide focus, its integration of community-driven monitoring with a full spectrum of data collection systems and forecasting, and its incorporation of bioeconomy development. Co-creation of bioeconomy models based on non-timber forest products and sustainable services such as tourism will incentivize monitoring and transform the underlying regional development paradigm to protect tropical forests. Community-driven monitoring can be incentivized by combining biodiversity assessment of species distribution with the monitoring species of interest to bioeconomy businesses while guaranteeing community ownership of such data.

2   Methodology & Scope

This focused white paper describes an approach for the development and implementation of a technologically-enhanced and community-driven toolkit to monitor and protect natural carbon sinks. It starts with an initial pilot project in the Colombian Amazon Basin, followed by others in the Amazon biome to develop the proof of concept needed to be replicated and scaled up in other tropical forest regions of the world, and ultimately other strategic ecosystems. In following through this progression, it attempts to empower local communities to protect and enhance their ecosystems; it engenders information that decreases the current significant

knowledge gap on ecosystems degradation; and it proposes co-creation of sustainable business models at various scales of planning, policy, and design that challenges contested practices of ownership, tenure, and production. It enters the MIT scope framework (Figure 1) through portal (4) "Carbon Capture, Removal, Utilization, and Sequestration", but encompasses a full range of issues that must be addressed to make significant climate progress.

	Human, community, and social impacts.	*Implementation and policy.*	*Climate science and technology.*
Carbon capture, removal, utilization, and sequestra-tion.	Strengthen local capacity for forest monitoring, restoration, and sustainable use of forests that improve carbon sequestration capacities of forests.	Provide evidence for cost-effectiveness of natural climate and community solutions as well as payment for environmental services programs that do not rely on carbon credits.	Develop and deploy an integrated monitoring system for forest monitoring and AI forecasting to assess forest degradation, carbon dynamics, and biodiversity.
GHG emissions reduction.	Support community-driven bioeconomy business models that strengthen cultural identity and equitable sharing of natural resources.	Develop partnerships with diverse stakeholders to improve pre-place- ment of resources for deforestation reduction programs that support NDCs.	Use ML to develop breakthrough capacity for real-time monitoring and forecasting of deforestation and forest degradation risk.
Climate change adaptation and resilience.	Foster participatory monitoring systems and data-driven bioeconomy practices and knowledge sharing networks at a biome-wide scale that adhere to ethical safeguards.	Develop a chain of socio-economic incentives at the local and global scale for monitoring, restoration, and conservation, through innovative bioeconomy models.	Develop a platform for scenario planning to optimize forest manage-ment and bioeconomy strategies for carbon capture, biodiversity, and local development enhancing socio-ecological resilience.

Figure 1. *Scope Framework*

The white paper was developed following a comprehensive literature review, and engagement with potential partners. The literature review was conducted using keywords and relevant phrases (e.g., natural carbon sinks, tropical forest conservation, forest monitoring technology) in the following databases and search engines: Web of Science, Scopus, Science Direct, Google Scholar, and Google, complemented by forward and backward citing.[51] Over ten workshops

were conducted with research institutes and government agencies, at the local, regional and national level in Colombia, Brazil and Peru, that provided inputs to identify critical technological needs in forest monitoring as well as capacity building needed to strengthen on-going efforts to reduce deforestation and effectively deliver on greenhouse gases emissions reductions and carbon storage related to Nationally Determined Contributions (NDCs). These workshops combined with field visits to the Colombian and Peruvian Amazon conducted in 2018 and 2019 sharpened the role of potential partners across the Amazon region in the adoption of new technologies, and the implementation of the proposed approach. See Appendix A for more on institutional partnerships.

3 Proposed Solution

With the leadership of the MIT Environmental Solution Initiative (ESI), each of the three pillars will be led by co-PIs from the following MIT groups and laboratories: Lincoln Laboratory will lead the design, testing and deployment of data collection systems (Pillar 1); the MIT Computer Science and Artificial Intelligence Lab (CSAIL), the Terrer Lab at CEE, and the Human Systems Lab in the Department of Aeronautics and Astronautics will focus on developing the data processing models as well as the decision support-platform (Pillar 2); co-PIs from the Sloan School of Management will focus on the creation of bioeconomy-business models incubator (Pillar 3); the Abdul Latif Jameel Poverty Action Lab (J-PAL) will i) support the development of evaluation metrics, ii) establish connections to J-PAL affiliated researchers to explore evaluating different pieces of the solution, iii) generate evidence on longer-term impacts, and iv) support bringing the model on-the-ground in other countries with large primary forests through their extensive network of policy and research partners. Across each pillar and at all stages of the project, local communities and partners will be engaged through comprehensive community-based planning processes and participatory research workshops in the early stages of the project to tailor the project to community needs and generate local ownership.
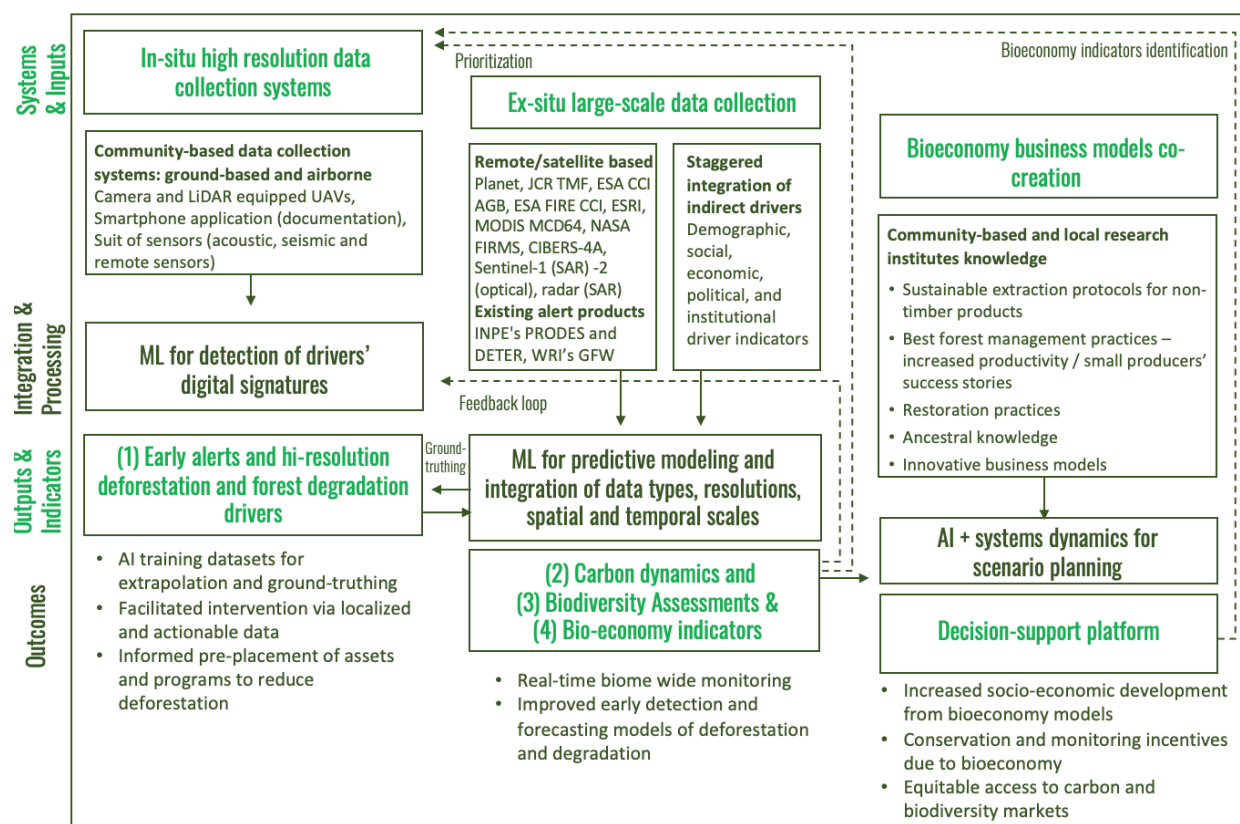
Figure 2. *Schematic Architecture of Monitoring Systems*

The architecture of the overall solution diagram is presented in Figure 2. First, both in-situ and ex-situ monitoring systems provide the necessary data collection as inputs for ML integration and processing of deforestation and forest degradation drivers, carbon dynamics, biodiversity assessment, and bioeconomy indicators as outputs. Ex-situ monitoring will guide the most informative in-situ measurements, which in turn will ground-truth ex-situ data. Finally, bioeconomy business model co-creation will be optimized via AI systems dynamics for scenario planning and will incentivize monitoring by local communities who have this information readily available through the decision-support platform. This solution reduces redundancy and increases efficiency by utilizing indicators, methodologies, and technologies for multiple simultaneous exploration of forest dynamics. The remainder of this section details each pillar of this solution.

3.1   Pillar 1: Community Engagement and Data Collections Framework

The first component to the solution forms the core of its success. Our solution differentiates itself from current solutions by co-creating the monitoring system together with frontline communities to help close the digital divide by, e.g., combining local knowledge of deforestation and degradation drivers with real-time technology capacity. Current data collection frameworks are often not designed in collaboration with local communities, are solely top-down or bottom-up,[30] and are inaccurate at the scale needed by these communities,[52] which means slower, less effective, and more dangerous interventions.[26]

Indigenous peoples and local communities, including afro-descendant communities such as quilombos, are recognized as equally or more effective stewards of conservation than government managed protected areas,[12] often sustainably using forest resources for generations.[33] Furthermore, community managed forests—in which communities governance entails multiple land uses tenure schemes of forests[24]— have increased 40% over the past twenty years, and presently cover about a quarter of global forests.[10] In Latin America, one-third of the continent's forests and 45% of the Amazon are located within collectively owned territories resulting in greater species richness.[19] Yet, frontline communities tend to be digitally and geographically disconnected, lacking the information and resources necessary to effectively and efficiently monitor their forests as extensive ground monitoring is prohibitively expensive.[25] This results in delayed interventions that are less effective against deforestation and forest degradation, and also more dangerous for environmental stewards.[26] This underscores the need for coordination with local authorities, collaboration with neighboring communities, and local and regional academic institutions to implement the necessary training programs to complement and enhance traditional knowledge with new forestry monitoring technologies.

Through initial engagement with local partners in the Amazon region, four areas of monitoring have been identified including (1) deforestation and forest degradation drivers, (2) carbon dynamics, (3) biodiversity assessments, and (4) bioeconomy indicators. The first area concerns the monitoring of direct drivers of deforestation and forest degradation—such as road expansion, illegal logging, mining, agricultural expansion, and fires—via land-use change estimation. Monitoring approaches in this area have included satellite data[33] and associated products from Planet,[53] ESRI, MODIS MCD64, ESA FIRE CCI, NASA FIRMS, camera equipped UAVs, smartphones,[54] and remote acoustic sensors.[55,56]

We will assess, select, and deploy technology for high-resolution, cost-sensitive, in-situ monitoring systems, and will guide smart placement following five phases outlined in the project plan. Our solution encompasses the integration of satellite imagery with in-situ sensing (ground- and airborne-approaches).[57] In-situ approaches can provide ground-truthing for satellite imagery,[33] and inform the development of predictive algorithms to improve early warning systems (EWS). The satellite imagery and improved EWS can verify in-situ data streams[32] and guide the smart placement of sensing packages and networking capabilities to protect forested areas predicted to be in danger of imminent harm, creating a positive feedback loop.

The second area concerns the monitoring of carbon dynamics as they relate to the estimation of aboveground biomass (AGB) changes and forest health. Aboveground biomass can be easily estimated with top-down satellite data from the European Space Agency (ESA CCI AGB22 product) and the early warning systems PRODES and DETER of the Brazilian National Institute for Space Research (INPE). However, forest degradation has historically proven more challenging to monitor.[58] As real-time high-resolution data is prohibitively expensive, we are proposing a hierarchical monitoring scheme in which the low-resolution data guides the locations for acquiring high-resolution ex-situ or in-situ data. High-resolution data are newly available for Planet satellite data (~4m resolution),[59] synthetic aperture radar (SAR) aboard Sentinel-1, optical aboard Sentinel-2 and for the Brazilian Amazon CBERS-4A (~2m resolution), allowing us to monitor carbon losses associated with forest degradation more accurately.[60]

The third and fourth areas concern the monitoring of biodiversity of flora and bioeconomy indicators. While many US forests only contain tens of species,[61] tropical forests can contain thousands of species per hectare[7] indicating the extreme challenge in biodiversity estimation. Previous research has shown success in identifying tree species and tracking their dynamics (e.g., mortality, recruitment, growth) over time,[62] which can improve accuracy through deep learning processing.[31] We are leveraging those ex-situ capacities[31] together with in-situ data to monitor bioeconomy indicators that are strongly related with the density and distribution of biodiversity. This integrated monitoring approach creates incentives for communities to collect comprehensive data while gaining actionable information for the sustainable use and extraction of forest resources in their territories. See Appendix C for a summary of indicators per area.

This approach aims to empower communities across the Amazon biome by promoting hands-on education models, knowledge co-creation, and information sharing. A community-based planning process will be conducted to support local communities to assess local socio-environmental priorities and develop a collaborative process to co-create and deploy a package of in-situ sensing modalities and network capabilities that are appropriately aligned with conservation goals, local priorities and networking challenges. These could include solar-powered internet hubs to support in-situ monitoring systems with in-situ internet[63] in locations with limited connectivity, or other technologies that could support monitoring systems while contributing to closing digital divides. Community engagement has proven to be a critical part of monitoring systems that require a science-police-citizen interface for their effective operation, such as wildfire mapping and prevention (e.g. MAP-FIRE project by the TRopical Ecosystems and Environmental Sciences lab TREES). Through participatory workshops in data collection, analysis and operation and maintenance of in-situ systems, the engagement process aims to support continual development and refinement of indicators and appropriate technologies, and to strengthen local communities' capacities to expand their knowledge of the territory while increasing their technical skills.

3.2   Pillar 2: Data Processing, Forecasting, and Visualization Platform

Forest monitoring has relied on artificial intelligence, specifically machine learning, to refine quantitative estimates of carbon stocks and biodiversity, and to detect drivers of deforestation and forest degradation.[64,65,66] Nonetheless, current data visualization platforms display deforestation and disturbances such as degradation from fires, storms and landslides (e.g. WRI GFW[27]), but they lack short-term forecasts, information about degradation by selected logging, they do not attempt to integrate diverse indicators at the Amazon biome level nor do they attempt to provide optimized solutions in the form of bioeconomy opportunities. Furthermore, the use of the full spectrum of monitoring technologies such as SAR satellite information has been geographically limited.[29] Adoption and ownership of the decision-support platform depends on making information accessible and relevant to communities on the ground.[30,67] This can include integrating localized bioeconomy indicators and information to optimize resource use.

Pillar two involves the development of an integrated and adaptive framework for data processing, forecasting, and visualization at the biome-wide scale. Components of this pillar include the implementation of (1) a framework for integrating diverse data types that represents different indicators, interactions, and interrelations; (2) a model for processing and validating

data; (3) a model for forecasting patterns of deforestation and forest degradation; and (4) a platform for information sharing, visualization, and uptake.

The monitoring approach advanced through this project will integrate data collected using top-down and bottom-up approaches[68] offering a reliable foundation for evaluating forest dynamics[33,64] at different scales[22] and ground-truthing.[32] Appropriate data integration will accommodate large amounts of raw data,[66] different units of measurement, different data formats (e.g., satellite imagery, video, text, audio), and data collection frequency, posing AI research challenges in, e.g., physically-consistent generative modeling of missing data streams[69] or multimodal representation learning.[70] Furthermore, it will allow for the progressive integration of in-situ and ex-situ direct and indirect indicators (Appendix B and C) that reflect different temporal and spatial scales. Considerations of accuracy,[71] generalizability, and model sensitivity will be important criteria in determining the appropriate ML approaches (e.g., Random Forests, deep/convolutional/graph neural networks, Gaussian processes, and generalized linear mixed models).[34,71] In addition to ex-situ and in-situ data integration, ML can further optimize in-situ data processing by pruning neural networks to enable on-the-edge computing.[72] Most importantly, data from in-situ and ex-situ monitoring will be integrated iteratively to provide up-to-date information on the Amazon Biome in real-time and ahead of forest damage, facilitating the pre-placement of technological assets and trained organized monitoring parties to more effectively intervene in illegal activities[33,54,73] as well as national and regional programs such as Payment for Ecosystem Services, Zero Deforestation Agreements, and collective land titles for Indigenous Peoples and Local Communities, among others.

A robust monitoring approach will not only integrate data collected using multimodal approaches, it will also be able to optimize information to reduce data input and improve inference, prediction, and processing of deforestation,[66] forest degradation,[30] and biodiversity changes.[31] Nevertheless, this requires innovations in data processing beyond local computer systems. Cloud processing[74] of integrated forest monitoring systems has accelerated processing of shorter time-series data for more accurate and actionable information[36] but it is not widely available for environmental agencies in Latin America. High-resolution imagery, LiDAR, and SAR satellite data will serve to prioritize and focalize ground-based approaches[25,75] such as field surveys, UAV data collection flights, and acoustic and seismic/vibration monitoring, to detect tree cutting and falling and people driving through, respectively; in turn, ground-based approaches will serve for observation and documentation purposes, aid intervention, and ground-truthing to improve assessment and forecasting algorithms.[33] Within this continuous feedback loop, we will provide accurate mapping of the tree family distribution via locally acquirable RGB drone imagery, useful for measuring biodiversity, carbon,[31,76] and bioeconomy indicators. Databases of known selective logging locations will be used to train and test the DL and other ML models' ability to detect degradation at its lowest impact level, which is not yet captured by existing degradation products28. Similarly, detection of illegal logging through acoustic monitoring by way of machine learning (ML) will serve to accurately recognize logging activity by 94.42%,[55] making real-time monitoring possible and serving for early warning systems.[77]

A decision-support platform will be co-designed and implemented in collaboration with local organizations to ensure clear and equitable access to in-situ and ex-situ information relevant to a diverse array of local groups through a user-friendly interface. The platform will offer insights on the state of the Amazon forest, its structure and past and projected future dynamics. It will

visualize the drivers of deforestation and forest degradation risk as well as the potential for bioeconomy opportunities. Frontline communities will be able to interact with the platform, generate scenarios, and assess bioeconomy strategies and their effect of change in space and time increasing their understanding in a context of dynamic complexity.

3.3   *Pillar 3: Bioeconomy Business Model Co-Creation Incubator*

Progress towards sustainable development implies advancing simultaneously in the Sustainable Development Goals SDGs,[78] including economic growth, education, health, social protection and job opportunities while addressing climate action and environmental protection. Pillar three focuses on creating economic development pathways and socio-economic incentives for communities to monitor, protect and pioneer sustainable uses of forest resources, decreasing the reliance on flawed carbon and biodiversity credits and funding-restrained Payment for Ecosystem Services programs (PES). The bioeconomy presents such an opportunity along three visions: regenerative resource, biotechnology, and agroecology.[39] It encompasses establishing new value chains with products derived from biomass (regenerative resources); bioprospecting genetic resources (biotechnology); and promoting agroecological practices to reduce inputs, emissions and environmental impacts.[39,79] Particularly, the Amazon bioeconomy presents an alternative for sustainable development, as it entails economic sectors such as agriculture, bio-cosmetics, biopharmaceuticals, bio-pigments, bioremediation, energy, forestry, nutraceuticals[37,38,39] and their associated value chains utilizing the Amazon's unique biodiversity.[38] Currently it represents 0.17% of a $176.6B global market[42] and has the potential of creating millions of green jobs.

Nonetheless, ambitious public-private-people partnerships are necessary to support local communities whose ancestral knowledge offers a well-spring for more inclusive socio-economic development within ecological limits. A series of participatory workshops will support communities to combine ancestral knowledge with scientific advances to identify potential non-timber forest products, followed by an incubator program focused on co-creation of innovative circular bioeconomy business models that are able to create higher value products and services in value chains and will be coupled with the monitoring systems and scenario planning facilitated through the decision support platform. The development and scaling of traditional and ancestral knowledge into bioeconomy business models must ensure protection of intellectual property and data ownership (in the case of data on species of interest to bioeconomy businesses) for communities, as well as a means to incentivize community-driven monitoring.

The data generated through pillars one and two will facilitate connecting bioeconomy strategies with an ecosystem services restoration approach of degraded ecosystems that can achieve both conservation and socio-economic development goals.[37] Through deep engagement with the communities, monitoring systems will be leveraged to support monitoring of key species for the improvement of local bioeconomy strategies and sustainable extraction of forest resources, creating the incentives for the communities to operate the systems in the longer term as businesses will be dependent on well-functioning ecosystems. At a landscape level, this information will support the development of circular economy principles such as industry symbiosis to close material loops.[80] At the forest level, it will support the development of best practices that are essential to enhance production[37,81] within sustainable extraction limits.

Incubation programs will be co-created with local and regional higher education institutions and communities to leverage natural resource availability linked to cultural identities,[49] including training in circular business models (CBMs)[45] and business model innovation at the enterprise and wider business ecosystem level[82] to develop strategies for bioeconomy development in adherence to a sustainability paradigm.[39,47] This includes upstream activities such as circular production and sourcing, as well as downstream activities dematerialization, efficiency, collaborative consumption, product-service systems, and product life extension.[49,82,83] A focus at the business ecosystem level is necessary in order to align key activities, resources, and partners[49] and identify areas for mutual value creation,[84] especially given the nascent innovation ecosystems in the Colombian[85] and Brazilian[86] Amazon. Bioeconomy businesses will be anchored with indicators to monitor their sustainability and social impact, which are coupled with the environmental monitoring indicators and biodiversity assessments developed in pillars one and two.[87,88]

Financial sustainability for small agro-forestry producers remains challenging,[49] and the costs of monitoring and verification are common barriers to access revenue streams such as carbon and biodiversity markets. This solution includes identifying economies of scope, whereby value is created along all material flows, as a means of creating new revenue streams,[45] a proven method to increase local GDP and investment,[49] as well as robust information on sustainable extraction, facilitating access to programs that depend on monitoring and verification.

4   Project Plan

The project will be conducted over a period of five years, beginning with a pilot in the Colombian Amazon and expanding to Brazil and other Amazonian countries. Colombia is the ideal starting point for a wider investigation (i) being it the second-most biodiverse country in the world, (ii) accounting for an ethnically and linguistically diverse population of 50 million people, (iii) covering a major role in international environmental politics,[89] (iv) and retaining a longstanding relationship with MIT ESI. By the fifth year, the investigation will have broadened to other geographic regions, such as the Congo Basin and South East Asia, and the applicability of similar NCCS models will be explored for other critical ecosystems such as high-mountain forests, watersheds, and coastal ecosystems. The project plan is organized along the three pillars of the solution, and relevant phases and milestones are described. Nonetheless, the implementation of this project is non-linear. It is intended to be iterative and inclusive of community participation and feedback at every stage and across the three pillars. Refer to Appendix D for a detailed plan.

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
Phases / pillars	*Developing Colombia Pilot*	*Expanding Colombia Pilot*	*Scaling-up to other Amazonian Countries*	*Replicating in Congo Basin and SE Asia*	*Exploring applications in other ecosystems*
Pillar 1: *Community Engagement and Data Collection Framework*	Identifying pilot study areas and engaging communities and local partners through a community-based planning process. Designing, architecting, testing, and refining prototype sensing package in the U.S. Designing data protocols and ownership models.	Deploying and testing sensing packages and building local technical capacities in pilot study areas. Monitoring technical results and community feedback to inform sensing package design iterations.	Identifying and engaging communities in two additional study areas. Implementing education programs and formulating best practices for local operations and maintenance of the systems.	Identifying and engaging communities in two additional study areas. Expanding educational programs and designing a production-ready sensing and networking package.	Transferring technological and technical capacities to local research and government institutions. Exploring relevance and applicability of sensing packages in other ecosystems.
Pillar 2: *Data Processing, Forecasting, and Visualization Platform*	Identifying and refining direct drivers indicators, and designing frameworks for data integration and forecasting models. Co-designing wireframes for the decision-support platform. Collecting initial data for AI training.	Identifying indirect drivers. Developing, testing and validating integration and forecasting ML models for biomewide dynamics. Creating decision-support platform prototype.	Integrating new indicators into the monitoring system. Developing and testing ML models for indirect drivers. Launching the decision-support platform.	Integrating additional indicators relevant to other regions. Testing applicability and accuracy of models in other regions. Expanding functiona- lity of the decision support platform.	Consolidating project methodologies and exploring applicability of models in other ecosystems. Training local leaders in the use of the decision support platform.
Pillar 3: *Bioeconomy Business Model Co-creation Incubator*	Mapping key flora species and ecological limitations in study area. Identifying stakeholders and bioeconomy opportunities and designing entrepreneurship training/ incubation mechanisms.	Co-creating business models and Circular Economy strategies. Conducting entrepreneurship/ incubation programs. Documenting bioeconomy portfolio.	Evaluating socio-economic and ecological impacts, and business model acceleration at study area 1. Begin stakeholder engagement in two other Amazonian countries.	Evaluating socio-economic and ecological impacts at study areas 2-3. Beginning mapping, stakeholder engagement and training in new regions.	Aggregating local projects to enable access to financial capital. Documenting success stories and strengthening knowledge sharing networks.

Figure 3. *Project Plan*

5 Project Risk Assessment

A project risk assessment was conducted for this project around six main risk areas, assessing risk impact (likelihood and severity) and identifying mitigation actions. See Appendix E for a complete project risk assessment matrix and scale framework.

Risk Type	Affected Area	Impact	Risk mitigation actions
Financial	Financial challenges to scale up bioeconomy businesses	High	Connecting businesses with regional and international investors through incubator program
Health	Communities, partners, and team members' health	Medium	All team members will strictly adhere to health protocols and vaccinations.
Political	Political interference in project implementation	Medium	Communicating regularly and establishing partnerships with local authorities.
Project Management	Project implementation delays	Medium	Establishing milestones and metrics for each pillar & yearly performance reviews.
Social	Low participatory data collection by communities or aversion to certain technologies	High	Facilitating community-based research and co-creation for the implementation of appropriate technological solutions and guaranteeing data co-ownership.
Social	Security of community members engaged in monitoring/ intervening	High	Coordinating interventions and monitoring actions with local authorities and developing secure data protocols.
Social	The violation of local communities' land rights	High	Coordinating intervention and monitoring actions with local authorities.
Technical	Feasibility to develop components of monitoring systems	Medium	Consolidating multidisciplinary team expertise, sound methodology, and continued testing protocols.

Figure 4. *Risk Assessment*

6   Economic Assessment

NCCS offer cost-effective means of mitigating global GHG emissions by up to a third[19] and the opportunity of transforming the economic development model in tropical forests.[11] While the most popular response to deforestation and forest degradation continues to be protected areas, these tend to be socially and economically costly to local communities.[90] Other responses seek solutions at higher levels along supply chains or legality of production processes (e.g., zero deforestation commitments) or ambitious protection schemes such as REDD+ that are structurally flawed as carbon offsets and struggle maintaining financing streams.[10] Indigenous peoples and local communities collectively owned lands and community managed forests[10] have garnered increased attention[91] for generating inclusive socio-economic development[92] and equally or more biodiverse areas at lower costs.[23] Yet, the role of local communities as stewards of the forest is being threatened by increasing pressures associated with the growing demand for food, energy, and material resources. There is an urgent need to support their forest management efforts, while generating local income and wealth.

Several organizations have developed deforestation monitoring systems with AI to predict deforestation (World Wildlife Fund WWF[67]) and provide data for forest monitoring and carbon stock estimates via combinations of satellite and in-situ data sources (the Global Forest Watch of World Resources Institute WRI and Maryland University[27]), SarVision, Restor, and Pachama. These platforms provide near real-time data, but are susceptible to weather conditions (GFW), do not cover the Amazon with the latest Synthetic Aperture Radar (SAR) (GFW), do not measure biodiversity and promote unsustainable carbon markets (Pachama), and are limited in geographic scope (SarVision), highlighting the need for true integrated monitoring technologies (e.g., SAR and LiDAR).[29] These platforms represent significant advances and are highly valuable within a complementary and integrated system. Nonetheless, none portend to fundamentally change the development paradigm around tropical forests through bioeconomy development and lack the socio-economic incentives for continuous community-based monitoring.

Efforts to empower local communities have proven effective[54,67] and collaborative partnerships at the national and local levels have been established to facilitate access to local communities from the early stages of the project. Moreover, multiple organizations with the mandate to monitor, protect and guarantee sustainable use of forests have manifested their interest in integrating (1) new breakthrough technologies for community-based monitoring systems, (2) advanced analytics and ML processing and forecasting models to provide insights that improve spatial and temporal scales, and (3) data-driven bioeconomy strategies within existing efforts and programs (see letters of support). This public-private-people collaboration model allows MIT to focus its efforts on generating the breakthroughs needed in the three areas along with capacity building, education and technology transfer programs, while helping reallocate and maximize the potential of existing resources in the implementation and long-term sustainability of the project.

7   Impact Assessment

The impact assessment framework focuses on measuring the effectiveness of the project outcomes' contributions to the overall goal of protecting and enhancing the natural carbon sinks of tropical forests and strengthening local communities conservation, restoration, and forest management efforts and can be broadly categorized into socio-economic benefits for Indigenous peoples and local communities and ecological benefits at the local, national, biome, and global scales. Intervention metrics will be developed with J-PAL to comparatively evaluate the study areas with non-intervention areas of similar socio-ecological characteristics. The main impacts and metrics by pillar are listed in the table below.

Pillars	Outcomes	Metrics
Community Engagement and Data Collection Framework	Increased local capacity for implementing and maintaining in-situ monitoring system	Nr. of community members engaged as local researchers participating in regional decision-making and in-situ data collection
	Public-private-people partnerships established	Nr. of organizations engaged in planning processes

	In-situ data collection systems deployed and operating	Areas under surveillance by in-situ sensing packages and networks (ha)
Data Processing, Forecasting, and Visualization Platform	Improved carbon sequestration	Changes in aboveground biomass (tC/year)
	Flora biodiversity	Biodiversity assessment (species count/ha)
	Real-time biome-wide monitoring for deforestation and degradation drivers	- Changes in deforestation/degradation rates between controlled and non-controlled areas - Area under integrated in-situ and ex-situ forest monitoring (ha) - Nr. of alerts emitted and verified by local/national authorities - Accuracy of forecasting models
	Decision-support platform adopted by local communities and partners	- Nr. of data providers for the platform - Nr. of local leaders trained in the use and dissemination of the platform - Monthly active users
Bioeconomy Business Model Co-creation Incubator	Regional added value[93] created	- Change in regional GDP - Jobs created through bioeconomy businesses - Job displacement by bioeconomy (from baseline) - Regional value chain profits
	Collaborations established among communities and stakeholders	- Nr. of new partnerships tied to new bioeconomy business models
	Incubation and innovation	- Nr. of business ventures supported through incubation program - Funding raised to support new ventures - Nr. of patents related to bioprospecting and biotechnology products

Figure 5. *Impact Assessment*

8   Conclusion

NCCS represent a cost-effective means of reducing global GHG emissions by up to a third, offering a proven strategy for countries' NDCs to the Paris Agreement. Nonetheless, deforestation and degradation in the Amazon, Central Africa, and South-East Asia is approaching critical tipping points and continues to weaken tropical forests' natural carbon capture potential. Local communities conserve and manage tropical forests effectively but often lack technological capacities and tools to support their conservation efforts, while generating local development.

This white paper describes an approach for protecting tropical forests through targeted technology breakthroughs, deep community engagement, and innovative bioeconomic opportunities supported by monitoring of (1) deforestation and degradation drivers, (2) carbon dynamics, (3) biodiversity, and (3) bioeconomy indicators with integrated in-situ and ex-situ technologies, providing real-time forest monitoring, early warning, and forecasting aided by AI/ML processing and enabling real-time and high-resolution data for more strategic intervention.

To the knowledge of the project team, no other platform attempts an integrated community-led approach at this scale, utilizing a full spectrum of data collection systems and breakthrough ML advances for data processing and forecasting and bioeconomy development. Over the course of five years, pilot studies in strategic study areas will strengthen local capacity and provide proof of concept of the multidimensional benefits of scaling-up data-driven community-led conservation and bioeconomy development strategies. This solution has focused on tropical forests, but the frameworks and platform developed along the course of the project will serve as a model for other ecosystems such as wetlands, coastal ecosystems, and other types of forests. These natural systems will serve as expanded opportunities for the development of new methods, technologies and strategies for expanding MIT's much-needed contributions to protecting and enhancing natural carbon sinks and global biodiversity.

9   Appendix A: Team and Collaborators

9.1   *Team Leadership*

1. **Fernández, John E;** Director MIT Environmental Solutions Initiative, Professor Department of Architecture
2. **Rus, Daniela;** Andrew (1956) and Erna Viterbi Professor of EECS, Director of CSAIL, and Deputy Dean of Research for Schwarzman College of Computing
3. **de Zegher, Joann F;** Maurice F. Strong Career Development Professor & Assistant Professor, Operations Management Group, Sloan School of Management

9.2   *MIT Collaborators*

1. **Terrer, Cesar**; Assistant Professor, CEE
2. **Newman, Dava J**; Director and Professor, MIT Media Lab
3. **Rigobon, Roberto**; Society of Sloan Fellows Professor of Management and Professor of Applied Economics, Sloan School of Management
4. **Campbell, Deborah**; Senior Staff Scientist, Climate Change Initiative Lead, Lincoln Laboratory
5. **Aldridge, John;** Assistant Leader, Humanitarian Assistance & Disaster Relief Systems Group, MIT Lincoln Laboratory
6. **Angel, Marcela**; Research Associate, MIT Environmental Solutions Initiative
7. **Murillo-Urrutia, Luis Gilberto;** MLK fellow, MIT ESI.
8. **Loomis, John J.;** Visiting Scientist, MIT Environmental Solutions Initiative; Professor, Graduate Program in Environmental Management (PPGAMB), Universidade Positivo, Curitiba, Brazil
9. **Fabbri, Alessandra**; PhD candidate, Department of Architecture
10. **Lütjens, Björn;** PhD candidate, Department of Aeronautics and Astronautics

9.3   *External Collaborators*

1. **Nobre, Carlos A.;** Senior Researcher, Institute of Advanced Studies, University of São Paulo, Brazil
2. **Val, Adalberto L**; Senior Scientist, Department of Biodiversity, Brazilian National Institute for Research of the Amazon (INPA, Brazil)

9.4   *Designated Technical Contact Persons for Institutional Collaborations*

1. **Rodriguez, Rodolfo;** Leader Zero Deforestation Agreements Leader, Ministry of Environment and Sustainable Development of Colombia
2. **Cano, Jorge;** Coordinator of the Implementation of Misión de Sabios, Advisor to the vice-ministry of Social Appropriation of Knowledge, Ministry of Science, Innovation and Technology, Colombia

3. **Galindo, Gustavo A;** Ecosystems and Environmental Information Direction, Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) Colombia
4. **García, Felipe;** Head of Biodiversity Sciences Program, Alexander von Humboldt Research Institute for Biological Resources, Colombia
5. **Mosquera, Moises;** Principal Investigator Productive Projects, Institute for Environmental Research of the Pacific IIAP, Colombia
6. **Rodriguez, Sandra;** Risk Management Specialist and Climate Change Plan coordinator, Environmental Planning Direction, Corpoamazonia
7. **Cuesta, Luis Armando;** Sub-director of Sustainable Development, Codechocó
8. **López, Nelson A;** Leader of the Environmental Science, Technology and Innovation Group, Cormacarena
9. **Garcia, Mariana;** Mariana Garcia, Environmental Resources Direction, General Command, National Military Forces, Colombia
10. **Bonilla, Oscar;** Sustainable Strategies Manager, CI Colombia
11. **Aragão, Luiz E. O. C.;** Senior scientist at National Institute for Space Research (INPE, Brazil), and Head of INPE's Earth Observation and Geoinformatics Division.
12. **Dalagnol, Ricardo;** Post-doctoral Researcher at the Earth Observation and Geoinformatics Division of INPE, Brazil
13. **Ribas de Oliveira, Cíntia M;** Assistant Coordinator of the Graduate Program in Environmental Management (PPGAMB), Universidade Positivo, Curitiba, Brazil

10 Appendix B: Drivers and Responses to Deforestation and Degradation

The UN Millennium Ecosystem Assessment[94] identified both direct and indirect drivers impacting ecosystem change, which has proven to be the framework employed for deforestation and degradation more specifically[7,10] and listed in Table 1. Direct drivers included habitat changes (land-use change and physical modification of rivers or water withdrawal from rivers), overexploitation, invasive alien species, pollution, and environmental disturbances such as fires. Indirect drivers include cultural, demographic, economic, environmental, technological, and political factors. Direct and indirect drivers are interlinked and complex in their causation as they are determined by the context, here they are discussed sequentially but at times, intermittently.

Direct drivers often take the form of land-use change such as agricultural expansion, which is credited as the largest direct driver in Latin America[10] and often follows road networks linked to other direct drivers.[95] In many regions of the Amazon, conventional agriculture is inefficient as the soil is poor after the top layer of organic matter is removed, this is evident by the low rate of return for monocultures such as soybeans as well as pastures for cattle.[18,96] This form of and other forms of land-use change have very high impacts on biodiversity, damaging the ecological function of forests.

The other direct drivers include logging, mining, and the development of infrastructure (e.g., roads, hydroelectric dams). Logging, credited as the largest direct driver of degradation,[10] often precedes deforestation and greatly impacts biodiversity.[94] In the case of infrastructure development, it is argued that the expansion of road networks may be the single most powerful factor causing deforestation as settlement directly follows road expansion, starting a cycle of public demand for government provision of other social services, such as health services, education, and policing.[7] Other direct drivers such as fires are the result of natural disturbances and will become more common with climate change, but are also driven by anthropological activities such as "slash and burn" agricultural practices as well as use of timber as fuelwood and charcoal.[10] Greater frequency of fires transform forests into ecosystems increasingly degraded and more vulnerable to permanent forest loss.[97] These direct drivers are influenced by the underlying indirect drivers that vary by region.

Indirect drivers including cultural factors and demographic change interact to increase demand on land and forest resources. Population growth, which means expanding urban centers, increases demand for land, water, energy, and forest products, such as timber, which incentivizes companies to meet the demand.[95] In order to bring products to markets, road infrastructure is needed that facilitates migrations to these frontier areas for a variety of economic reasons. Domestic markets predominate for most forest products as causes of deforestation[10]. Underlying political factors such as unclear tenure rights or weak enforcement in frontier regions leads to loss of land for Indigenous peoples and local communities.[98]

While economic growth and ecosystem services are slowly being decoupled, they continue to rise.[6] Global trade in the forest sector shows how it is a magnifying force either for more sustainable practices in the case of strong institutional frameworks, or less sustainable practices in the cases of weak frameworks and management.[9] Illegal economic activities can be the result

of failure to comply with land regulations,[99] global demands, market demands of products such as timber,[7] ties with criminal organizations,[100] or spurred on by development of processing facilities with global supply chains.[101]

These economic and technological factors and incentives operate in political and institutional landscapes, and as already touched upon in this section, governments may implement policies that directly (e.g., land tenure for cleared land) or indirectly (e.g., national energy plans that favor hydroelectricity, export subsidies, industry specific policies) encourage activities that lead to deforestation. Technological advances particularly in agriculture (genetically modified crops) and food processing (e.g., greater demand for palm oil) have allowed for further expansion into frontier areas. These technological advances are often aided by development policies, often these development policies see agricultural expansion as a means of poverty relief in frontier regions. Just as importantly, the lack of regulatory frameworks and enforcement can result in weak enforcement, regulatory capture, and outright corruption. Even strong regulations confront the challenges of low financial and political support as well as the wider economic landscape that favors extractive industries and expansion of agriculture.[102] This highlights the challenge of multilevel governance as well as the need for innovative policy solutions between public and private actors.[103]

Finally, environmental factors, especially climate change and its manifestations of extreme events act as multipliers of other drivers and can initiate feedback cycles. Longer dry seasons weaken the ecological structures and functions of tropical forests, making them more prone to fires leading to forest degradation.[6] Such degradation negatively impacts biodiversity, which negatively impacts ecosystem function in a continuous cycle as species who do not adapt either migrate or die out, and in the case of tropical forests there are many instances of cross-pollination, mutualisms, and a tight nutrient flow from primary producers to consumers to decomposers[7] which suffer from species loss.

Driver	Description
Direct drivers	
Wood, mining and other extractive industries	Extractive industries tend to follow global commodity cycles and thus result in the clearing of land during boom cycles.

Expansion of agriculture	The expansion of agriculture, both shifting cultivation and permanent pasture cultivation result in practices of "slash and burn" that degrades the soil following temporary increase in soil fertility. The expansion of permanent monocultures soybean and the expansion of ranching have contributed the most and also are vulnerable to global commodity markets.
Development of infrastructure	Extractive industries and expansion of agriculture depend on the expansion of infrastructure, in particular roads, but large hydroelectric dams and other mega infrastructure projects cause major negative social and environmental impacts.
Other	Other direct drivers of degradation and deforestation include forest fires.
Indirect drivers	
Cultural factors	The views, norms, values, and beliefs towards land use, property rights, and forests influence people's perceptions of the relationship between humans and the rest of nature. Tropical forests on public lands whose common pool resources are perceived as free are susceptible to tragedy of the commons situations due to overexploitation. Dietary changes that include larger consumption of meat is also an indirect driver.
Demographic change	Population growth can lead to encroachment around protected areas as well as migration to these areas. Growing urbanization can also generate greater demand for forest products.
Economic factors	Continued world economic growth and globalization means the distance to markets shortens thus increasing demand and incentivizing further settlement. Countries trying to service large national debts may incentivize development and extractive industries. Rural poverty also serves as a labor force for extractive industries and illegal activities.
Climate Change	Indirect drivers of degradation and deforestation include climate change and feedback cycles initiated by other direct and indirect drivers that are magnified by climate change. These include degradation of soil by extractive industries and agriculture, which

Political and institutional factors	Decision-making is increasingly more open and transparent and subject to more interest groups. Governments may also have geopolitical concerns about control over frontier territories. Governments also develop policies that directly incentivize deforestation activities such as tax incentives and tenure rights for cleared land as well indirectly through the promotion of certain industries in development policies. The lack of governmental policy especially concerning the enforcement of environmental laws can be a driver of deforestation.

Table 1. *Drivers of deforestation and degradation*[7,10,94,95]

Understanding how to respond to these drivers involves integrated approaches of multi-stakeholder governance as the limitations of a solely state led approach has become evident.[102] Pacheco et al.10 delineated six singular approaches and two integrated approaches, all of which are not mutually exclusive, these are summarized in Table 2.

Singular approaches include securing the land rights and autonomy of indigenous peoples and local communities (IPLCs). Often tenure land rights are unclear in frontier areas, which leaves IPLCs vulnerable to land speculators and settlers resulting in conflict, thus local enforcement and monitoring are crucial.[92] IPLCs linked to community forest management have been shown to be one of the most effective in biodiversity conservation and deforestation reduction,[23] CO_2 mitigation goals, promotion of local livelihoods, and fire management, especially in Latin America and Asia.[104] Still, this approach needs initial start-up capital and technical assistance[105] and is dependent on favorable political, social, and economic factors.[106] An example of this involves indigenous communities in the Peruvian Amazon who have reduced deforestation using satellite imagery data and remote-monitoring smartphone applications.[54]

The next approach involves the conservation of areas high in biodiversity, typically along one of the six management categories of International Union for the Conservation of Nature (IUCN) that can range from strict preservation to multi-use.[107] Protected areas have been effective at reducing forest loss, but require significant technical and financial resources.[90] This remains a central conservation approach, and protected areas reach 16.64% in 2020,[108] just shy of the 17% set in the Aichi Target 11 of the Convention on Biological Diversity (CBD), yet biodiversity continues to decline,[109] highlighting the concern of ecosystem degradation. It has been effective when integrated with IPLC.[110]

Enhancing and enforcing regulatory frameworks around land uses particularly in the agriculture and forestry sector has been another approach to reduce deforestation linked to production of certain products, especially soy and cattle10. In Brazil this came about through moratoriums on soy and cattle produced on deforested lands, although Nepstad et al.[111] point out that determining the effectiveness of the moratoria from the many other factors is difficult. Traceability remains a challenge, in the case of the Brazilian cattle agreement, indirect suppliers avoided the moratorium system.[10]

The commodity or sector approach has aimed at increasing the sustainability of supply chains through certification schemes and zero deforestation commitments.[112] Business initiatives and

commitments are not always representative of industry practices as it tends to be implemented by companies already undergoing other sustainability compliance measures and those further down the supply chain as upstream companies tend not to reap the rewards of such green marketing. Traceability of sustainable and non-sustainable products is a crucial element and in the case of timber wood anatomy and DNA technologies have been able to identify origin (Pacheco et al., 2021). The Accountability Framework (AFI), a collaboration of environmental and human rights organizations is attempting to integrate more social dimensions into this approach.[113]

The payment for ecosystem services (PES) has also served as the basis for ecosystem services (ES) approaches whereby ES such as carbon sequestration are monetized. PES has the potential to change underlying economic incentives for landowners even after payment ceases if the available land uses are financially sustainable.[114] Challenges remain concerning MRV and payment modes, and tying PES program design to desired outcomes.[115] Only Brazil had a national program from 2011-2018, which had carbon sequestration benefits worth an estimated $335M over the course of 2011 to 2015, three times the cost of the program,[116] in 2021 Brazil established a new national PES.[117] The future use of PES, in addition to continued integration with REDD+ projects, may also benefit nature-based solutions that aim to mitigate climate change and restore biodiversity, an important part of Nationally Determined Contributions of the Paris Agreement10.

Ensuring finance to sustainable agricultural and forestry practices has had the aim of de-risking investment in such endeavors. Given the capital needs of forestry and agricultural industries, banks and other financial institutions can potentially accelerate sustainable changes in business strategy and supply chains. Regulators can help make this the norm, although there are already initiatives such as the Sustainable Banking Network,[118] multilateral development banks are aligning investment policies with the Paris Agreement,[119] Principles for Responsible Investment, and Principles for Responsible Banking.[10] Innovative financing such as blended finance (i.e., the use of public or philanthropic funds to mobilize additional external private commercial finance), green bonds (i.e., bonds linked to environmental aims), and crowdfunding (i.e., pooling of small donors) may be the key to scaling up landscape approaches.[50,120] The UNEP[121] echoes the call for more blended finance and has called for investments in NBS to triple by 2030, especially in the areas of restoration of natural vegetation and afforestation.

More robust integrative responses have included REDD+ and sustainable jurisdictional approaches. Within the REDD+ framework there is rigorous monitoring, reporting, verification as well as results based financing schemes, but it has not been able to address indirect drivers that incentivize deforestation and degradation.[122] Furthermore, its co-benefits, e.g., payments to local populations and sustainable use of forest resources, have been characterized as insignificant.[123] Such co-benefits require careful project design and adjustments to context if it is to benefit and not harm local populations.[124] Flexible designs may involve use of community forest management[125] as well as decision-making that is transparent, representative, and participatory.[126]

The other integrated approach takes place at the subnational level whereby multiple stakeholders are engaged to form public-private partnerships to identify low-carbon or carbon neutral development options in a given jurisdiction or landscape.[127] This approach appears promising for upscaling,[10,120] but requires careful design. Bastos Lima et al.[128] (2017) point out

that initial political leadership (while resilience to political change is also necessary), participatory design (for long-term success), sustainable finance (aligned to needs and deliverables), explicit private sector roles (to balance expectations and asks), storytelling (to build support), and expectation management (to avoid unachievable goals or time frames) are critical for success.

Response	Description	Evaluation	References
Singular approaches			
Indigenous peoples and local communities (IPLCs) rights'	Area based approach in which IPLCs tenure rights are secured, local autonomy and resource management are prioritized.	Empowers local populations, but may fall to elite capture. So far there have been limited results for improving livelihoods, but clear evidence that it reduces deforestation. Subject to external pressures and actors, need institutional and legal conflict resolution support.	(Pacheco et al., 2021)
Conservation	Demarcated areas with high biodiversity value closed to land conversion, which can take the form of publicly protected areas and OECMs.	Clear definitions of land use, but requires intense technical and financial resources. It is subject to changes in government policy.	(Pacheco et al., 2021)
Legality of production	Aims to ensure compliance with legal and regulatory frameworks around land use or specific agricultural or forestry products, such as moratorium on products causing deforestation and degradation.	Effective when focused on land use, still heavy focus on procedures not substance.	(Pacheco et al., 2021)

Sustainable supply chains	Promote suppliers complying with sustainability measures and excluding non-compliance through transparency, rewards, certification.	Adoption of the measures often follows and does not initiate other sustainability goals of companies. Unclear on possibilities of leakages.	(Pacheco et al., 2021)
Environmental services (ES)	Focus on guaranteeing provision of ES and compensation (monetarily – PES or otherwise).	The ES approach and PES policy have strong potentials, but lack financial flows and transaction costs. It hasn't been developed at scale to change current underlying economic incentives. Opportunities for NBS that contribute to protecting intact and primary forests.	(Pacheco et al., 2021)
Responsible finance	Using leverage of financial institutions to craft sustainable investment and credit policies, need critical mass of support for ESG criteria to become the norm.	High penetration in market segments already in compliance, low penetration in micro-credit and will need further clarity around ESG and financial institutions' capacities to implement policies.	(Pacheco et al., 2021)
Integrative approaches			
REDD+	This is an integrated policy framework that compels long-term perspectives, monitoring, reporting, verification (MRV), using payments in exchange for carbon sequestration and storage projects.	It is formalized in the Paris Agreement (art. 6). It involves robust methodologies for MRV, but has not changed the underlying development paradigm around forests. Co-benefits for local populations are ambiguous. It lacks financing for large-scale projects.	(Pacheco et al., 2021)

Sustainable jurisdictions	These approaches seek to align interests and goals of multiple stakeholders and their activities and are often carried out at the landscape level. The aim is to scale up sustainable practices.	Meaningful engagement between local populations, private, and public sectors, but can fall to elite capture. Optimal use of land subject to local stakeholder negotiation. May result in leakage.	(Pacheco et al., 2021)

Table 2. *Responses to deforestation and degradation.*[10] *ES: ecosystem services; ESG: environmental, social, and corporate governance; ICCAs: areas conserved by Indigenous peoples and local communities (ICCAs); IPLC: Indigenous peoples and local communities; MRV: monitoring, reporting, and verification; OECMs: other effective area based conservation measures; PES: payment for ecosystem services; REDD+: Reducing emissions from deforestation and forest degradation, and forest conservation, sustainable management of forests, and enhancement of forest carbon stocks.*

11 Appendix C: Indicators Table

This appendix shows Table 3, which lists the priority indicators to be integrated into the monitoring system. The grey rows show the five major monitoring components: carbon dynamics, biodiversity, early warning indicators, direct drivers of deforestation and degradation, and the bioeconomy. Further detail of each component is detailed in the subsequent rows per component. The columns show the indicators, possible technologies, and datasets.

	Indicator(s)	Technology (in-situ)	Technology (ex-situ)	Dataset
Carbon Dynamics				
Aboveground Biomass (AGB)	Landcover, Tree species family, heigh, condition/crown	UAV (LiDAR), field plot	AGB European Space Agency (ESA) Climate Change Initiative (CCI) (combination of C-Band, L-band Synthetic Aperture Radar, and LIDAR), CBERS-4A, Sentinel-1, Sentinel-2	(Global maps ABG mid 1990s, 2010, 2017 and 2018 - 1 km grid spacing, error < 20% where AGB exceeds 50 Mg ha-1) https://climate.esa.int/en/projects/biomass/about/
Forest Degradation	Canopy Cover Loss (>20%), Continuous forest coverage (area)	UAV (camera), field plot	JRC TMF product (Landsat 30m resolution)	https://forobs.jrc.ec.europa.eu/TMF/
Biodiversity				
Species distribution (flora)	Mapping of Indicator Species	UAV (LiDAR), field plot	Planet, CBERS-4A	Planet (Spatial Resolution: 4.77m per pixel) - https://www.planet.com/nicfi/ ; (Brazilian Amazon) CBERS-4A (Spatial Resolution: 2m per pixel) https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/cbers-4a#references
Early Warning Indicators	Road expansion	UAV (cameras)	Planet	Planet (Spatial Resolution: 4.77m per pixel) - https://www.planet.com/nicfi/

Direct Drivers of Deforestation and Degradation				
Logging, Mining, Agricultural Expansion, Infrastructure Development	Land cover change area, commodity prices, supply chain analysis, sounds of equipment, visible machinery	Smartphone application (documentation), UAVs (cameras), Seismic sensors, Acoustic sensors Other commercial off the shelf sensors to detect people/machinery coming in (EO/IR/PIR, etc.)	ESRI, Satellite (optical, SAR), LIDAR	https://livingatlas.arcgis.com/landcover/ , International Resource Panel (IRP) Global Material Flows Database https://www.resourcepanel.org/global-material-flows-database Farm Trace - https://farmtrace.com/
Fires	Hot areas, smoke, air quality changes Fire map	Air temperature and humidity sensors	MODIS MCD64, ESA FIRE CCI, NASA FIRMS	https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms https://firecast.conservation.org/ https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms https://firecast.conservation.org/ https://firecast.conservation.org/
Bioeconomy				
Sustainable production/extraction	Species distribution (flora)	UAV (LiDAR)	Planet, CBERS-4A	https://www.planet.com/nicfi/ ; International Resource Panel (IRP) Global Material Flows Database https://www.resourcepanel.org/global-material-flows-database ; (Brazilian Amazon) CBERS-4a https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/cbers-4a#references

Table 3. *Priority indicators*

12 Appendix D: Project Plan

This appendix shows the detailed project plan in Table 4. Each of the three pillars are shown in the first column with their component parts in the second column. Major milestones are shown for each year in the remaining columns.

		Milestones				
		YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
Phases / pillars	Components	*Developing Colombia Pilot*	*Expanding Colombia Pilot*	*Scaling-up to other Amazonian Countries*	*Replicating in Congo Basin and South East Asia*	*Exploring applications in other ecosystems*
Pillar 1: *Community Engagement and Data Collection Framework*	Community Engagement Process	Identifying pilot study areas and engaging communities and local partners in the Colombian/Brazilian Amazon through a community-based planning process. Choosing one pilot study area for development in Year 2. Beginning discussions with local communities about roles to play in sensor placement and forest monitoring. Working with community members to advise sensor development teams on end-user requirements.	Developing the initial pilot study area in the Colombian Amazon. Working with community members to place sensors and test the prototype decision-support platform.	Identifying and engaging communities in two additional study areas within the Colombian/Brazilian Amazon. Beginning discussions with local communities about roles to play in sensor placement and forest monitoring. Working with community members to advise sensor development teams on end-user requirements. Implementing education programs and formulating best practices for local operations and maintenance of the systems.	Identifying and engaging communities in two additional study areas (e.g., Peru, Brazil, Congo, SE Asia). Beginning discussions with local communities to determine similarities and differences between deployment in those areas and in the original Colombian sites. Expanding educational programs.	Using expertise from previous years, develop a model of community-engagement and ecosystem monitoring. Exploring relevance and applicability of model of community-engagement and ecosystem monitoring in other ecosystems.

	High-res In-situ Monitoring Systems	Using literature surveys and discussion with experts to identify top candidates for in-situ sensing modalities and networking capability. Designing and architecting a prototype sensing package. Performing local testing, then identifying appropriate location in CONUS (within Continental US) for safe but meaningful testing of the sensing package (e.g., in logging regions and/or in temperate rainforests). Using this testing to refine the sensing package and networking strategy. While performing community discussions in Colombia, collecting background data as appropriate to help inform sensor development. Designing data protocols and ownership models.	Using the prototype designed in Year 1, produce an appropriate number of sensing units and networking equipment. Bringing this technology to the pilot study area. Deploying and testing sensing packages with the local community. Monitoring technical results and community feedback to inform sensing package design iterations.	Using feedback from Year 2, design additional units for the new pilot study areas as well as replacement units for the original pilot study area. Continuing literature search to ensure technology is best of breed.	Improving sensing packages by integrating local communities' feedback. Using feedback from both years of testing, design a final production-ready sensing and networking package, combined with full system documentation, manuals, operations and maintenance instructions. Beginning discussions with industry partners to transition the system for mass production.	Transferring technological and technical capacities to local research and government institutions. Completing transition of sensing and networking packages to industry partners.

Pillar 2: *Data Processing, Forecasting, and Visualization Platform*	Data Collection (e.g., direct and indirect drivers' indicators, collection protocols)	Using literature surveys, discussion with experts, and discussion with community members, identify top-candidates for ex-situ data collection modalities (e.g., carbon dynamics, biodiversity, bioeconomy, deforestation and forest degradation). Determining and securing access to ex-situ data sources. Designing and architecting a prototype data collection package. Performing local testing and using this testing to refine the data collection package.	Using the prototype designed in Year 1, begin data collection for the pilot study area. Monitoring both the technical results and community feedback to identify modifications to data collection modalities for next iteration.	Integrating new drivers' indicators into the monitoring system. Using feedback from Year 2, collect additional data for study areas 2-3. Implementing education programs and formulating best practices for operations and maintenance of the data collection package. Continuing literature searches to ensure data collection best practices.	Using the prototype, begin data collection for new study areas. Beginning discussions with local communities to determine similarities and differences between data collection in those areas and in the original Colombian sites. Integrating additional drivers' indicators relevant to new study areas. Using feedback from both years of testing, design a final production-ready data collection package, combined with full process documentation, manuals, operations and maintenance instructions. Expanding education program.	Exploring the relevance of drivers' indicators and data collection packages in other ecosystems.
	ML processing (e.g., integration, assessment, validation)	Using literature survey, discussion with experts, and discussion with community members to identify the most appropriate methodology for integration and processing of data with different formats (e.g., audio, text, images, 3D models, etc.) and scales (e.g., temporal, spatial). Designing and architecting a prototype for	Developing, testing, and validating integration methodology and prototype for direct drivers' indicators and their physical signatures. Using literature survey and discussion with experts, identify the most appropriate methodology for the integration and processing of indirect drivers' indicators and their physical and non-physical signatures. Designing and	Using feedback from Year 2, improve the prototype for processing and integrating direct drivers' indicators and their physical signatures. Developing, testing, and validating integration methodology and prototype for indirect drivers' indicators and their physical and non-physical signatures at appropriate temporal and spatial scales.	Using feedback from Year 3, improve robustness, accuracy, and efficiency of the models by adding indicators and datasets iteratively. Testing and evaluating performance of models.	Exploring relevance and applicability of processing models in other ecosystems.

		integrating and processing direct drivers' indicators and their physical signatures.	architecting a prototype for integrating and processing indirect drivers' indicators and their physical and non-physical signatures.			
	Forecasting	Using literature surveys and discussion with experts to identify the most appropriate forecasting models (e.g., accuracy, generalizability, and model sensitivity).	Developing, testing, and validating forecasting models for biome-wide dynamics and patterns of deforestation and forest degradation. Monitoring technical results and community feedback to inform those forecasting models.	Using feedback from Year 2, improve forecasting models to accommodate data from the new study areas as well as training data for the original pilot study area. Implementing education programs and formulating best practices for local operations and maintenance of the models. Continuing literature search to ensure technology is best of breed.	Implementing education programs and formulating best practices for local operations and maintenance of the model.	Exploring relevance and applicability of forecasting models in other ecosystems.
	Decision Support Platform and Visualization (back-end and front-end)	Beginning discussions with community members, NGOs, and authorities at all levels to determine opportunities and limitations of the decision-support platform. Co-designing wireframe for the decision-support platform. Performing tabletop experiments with	Creating decision-support platform prototype. Developing, testing, and validating decision-support platform prototype for scenario development and actionable bioeconomy solutions at appropriate temporal and spatial scales for effective and efficient interventions.	Using feedback from Year 2, to improve the decision-support platform to accommodate data from two new study areas. Monitoring technical results and community feedback to inform the decision-support platform.	Improving support-decision platform by integrating local communities' feedback. Using feedback from both years of testing, design a final transition-ready decision-support platform. Beginning discussions with NGOs and/or industry partners to transition the platform.	Transferring technological and technical capacities to local research and government institutions. Completing transition of decision-support platform as appropriate. Exploring the relevance of the decision-support platform for other ecosystems and socio-economic contexts.

		community members to improve wireframe design.				
Pillar 3: *Bioeconomy Business Model Co-creation Incubator*	Business Models Co-Creation.	Beginning stakeholder engagement in the pilot study area. Identifying bioeconomy business opportunities in the pilot study area, including current and potential non-timber products (NTFPs), current technological, technical, and financial capabilities. Beginning discussions with local communities about entrepreneurship training/incubation mechanisms.	Co-creating business models and Circular Economy strategies to incentivize sustainable use of natural resources. Co-designing and conducting entrepreneurship/incubation programs with local communities. Exploring innovative financing options. Documenting bioeconomy portfolio.	Beginning stakeholder engagement in two other Amazonian countries. Identifying bioeconomy business opportunities in study areas 2-3. Co-designing and conducting entrepreneurship training/incubation programs with local communities in other Amazonian countries.	Using feedback from Year 3, test and improve business models and Circular Economy strategies in study areas 2-3. Beginning mapping stakeholder engagement and training in two additional study areas. Identifying bioeconomy business opportunities in new study areas. Co-designing and conducting entrepreneurship training/incubation programs with local communities in new regions.	Aggregating local projects to enable access to financial capital. Documenting success stories and strengthening knowledge sharing networks.

Monitoring Sustainable Extraction and Socio-Economic Indicators.	Working with community members, identify and map key bioeconomy flora species and ecological limitations in the pilot study area. Designing protocols for sustainable production, extraction, processing, and distribution.	Working with community members, monitor key bioeconomy flora species in the pilot study area and integrate this information in the decision-support platform.	Evaluating socio-economic and ecological impacts, and business model acceleration at the pilot study area. Improving protocols for sustainable production, extraction, processing, and distribution. Working with community members, identify and map key bioeconomy flora species and ecological limitations in study areas 2-3.	Working with community members, monitor key bioeconomy species in study areas 2-3 and integrate this information in the decision-support platform. Evaluating socio-economic and ecological impacts, and business model acceleration in study areas 2-3. Improving protocols for sustainable production, extraction, processing, and distribution. Working with community members, identify and map key bioeconomy flora species and ecological limitations in new regions.	Working with community members, monitor key bioeconomy species in new regions and integrate this information in the decision-support platform. Evaluating socio-economic and ecological impacts, and business model acceleration in new regions. Improving protocols for sustainable production, extraction, processing, and distribution. Exploring relevance and applicability of strategies in other ecosystems.

Table 4. *Detailed project plan*

13 Appendix E: Risk Assessment Matrix

This appendix shows the risk assessment matrix in Table 5. The risks are listed in the first column across commercial, health, political, social, and technical areas. Each corresponding row then details the project areas, timeframe, severity, likelihood, risk impact, and recommended actions. The estimated risk impact was done using the scale in Table 6. Each risk is discussed in more detail here. The overall success of the project, given the risks, remains high, but each risk has feasible mitigation and management solutions.

Financial risks: These involve the financial viability of sensing packages and bioeconomy business models. These risks are possible and unacceptable and therefore represent a high-risk impact. The success of the bioeconomy business models underpins the long-term financial stability of the solution as well as incentivizing community-driven monitoring. Strong training and incubator programs and the use of in-situ monitoring systems, advanced analytics, and capacity building in these areas will serve to manage the risk and attract new funding streams. Sensing packages will be tested, iterated, and developed to the level of production-ready designs and industry transfer.

Health risks: These involve health risks for the local communities, local partners, and project team members who participate on the ground in study areas. Many of the communities, especially indigenous peoples are susceptible to outside diseases, therefore all project members will adhere to strict health protocols in coordination with local communities and local authorities to ensure low exposure of communities to possible health risks. All project team members participating in field research will observe all necessary health requirements before embarking to study areas. With these mitigation measures this risk's likelihood is unlikely, but its severity is unacceptable and therefore presents a medium risk impact.

Political risks: These involve possible interference by public authorities, especially regarding regulatory compliance that may lead to project delays. The likelihood of this risk's occurrence is judged to be possible, but tolerable, and therefore represents a medium risk impact. To mitigate these, the project team has established ties with local authorities in Colombia at all levels of government, and has begun to establish ties with local authorities in Brazil. More importantly, the project has been developed in partnership with local and national authorities, and will continue to be advanced in regular communication and coordination with these authorities.

Project management risks: These risks involve project implementation delays and/or increased costs of materials and technology. While possibly likely, these risks are tolerable, thus representing medium risk impact. They can be adaptively managed with clear project milestones and performance reviews. An overall project budget has been created, but a flexible procurement strategy will be pursued considering the local needs of communities.

Social risks: These include the choice of local communities to not participate in the in-situ monitoring system, use certain monitoring technologies (e.g., UAVs), or adopt the decision-support platform, the security of community members engaged in forest monitoring and intervention, the violation of land rights of communities, and the choice of communities to not

use certain in-situ monitoring technologies. The first of these risks of non-participation in the in-situ monitoring system or adoption of certain technologies or the decision-support platform is possible and generally unacceptable, therefore it represents a high risk for the solution. Given the severity and likelihood, community-based planning and participatory implementation of technological solutions will be prioritized, local project co-ownership will be encouraged. The second social risk involves the security of community members and their data involved in monitoring of forests in socio-environmental conflict prone areas. This risk's likelihood is possible and its severity is generally unacceptable, therefore it represents a high risk. To mitigate this risk, community member safety and data security protocols will be developed in coordination among communities and local authorities, socio-economic impacts will be evaluated every year, and additional mitigation strategies designed. The third social risk involves the violation of communities' land rights, which has a probable likelihood given the increasing rates of illegal deforestation activities, yet is tolerable from the perspective of project implementation, since community-driven monitoring and intervention can continue in coordination with local authorities, thus it is evaluated as a high-risk impact. This risk's mitigation highlights the need for deep coordination between local communities and authorities in prompt intervention against illegal activities to increase the likelihood of success. The co-creation of the solution with local communities and authorities that the project team has established will facilitate and strengthen lines of communication among all involved parties.

Technical risks: These risks involve the development and integration of the monitoring system and the necessary algorithms for data processing. While the severity of these risks is generally unacceptable, their likelihood is low: each member of the team has been carefully selected to provide a deep set of multidisciplinary expertise and complementary experience in each of the areas of work of the project, thus the risk impact is judged to be of medium risk.

RISK TYPE	PROJECT AREAS AFFECTED	TIMEFRAME	SEVERITY	LIKELIHOOD	RISK IMPACT	RECOMMENDED ACTION(S)
Financial	The financial inviability and scaling of bioeconomy business models could impede community-driven monitoring system and long-term sustainability of the solution.	Entire project	Generally unacceptable	Possible	High	There will be open and participatory workshops will aim to connect co-created business models with regional and international value chains and investors through an incubator program.
Health	The health of the communities, local partners, and project team members could be negatively impacted.	Initial phase of each study area	Generally unacceptable	Not likely	Medium	All team members will require necessary vaccinations and strictly adhere to local health protocols.

Political	Political interference in the form of delays due to pending approval by public authorities could delay project implementation.	Entire project	Tolerable	Possible	Medium	Regular communication will be done with local authorities to ensure regulatory compliance.
Project Management	Project implementation delays and/or increased costs of materials and technology could jeopardize the success of the solution.	Entire project	Tolerable	Possible	Medium	The project has established milestones for each pillar of the solution and performance review will be conducted by project leaders. There is an overall budget for the solution and flexible procurement strategies will be pursued.
Social	Local communities choose not to participate in the monitoring system, choose not to use certain technologies (e..g, UAVs), or do not adopt the decision-support platform, thus jeopardizing the long-term sustainability of the solution.	Entire project	Generally unacceptable	Possible	High	Open and participatory workshops for connecting local needs with business opportunities, community-based planning and participatory implementation of technological solutions will be prioritized, and local project co-ownership will be encouraged.
Social	The security of community members engaged in monitoring and intervening in illegal deforestation activities is put at risk.	Entire project	Generally unacceptable	Possible	High	Together with local communities, the project team will coordinate intervention and monitoring actions with local authorities and ensure secure data protocols.

Social	The violation of local communities' land rights by private actors could impede the monitoring system and data collection and jeopardize the long-term sustainability of the solution.	Entire project	Tolerable	Probable	High	Together with local communities, the project team will coordinate intervention and monitoring actions with local authorities.
Technical	Delays in developing monitoring system and data collection could jeopardize the success of the solution.	First year of project	Generally unacceptable	Not likely	Medium	The project team will consolidate multidisciplinary expertise to develop state of the art methodologies, implement continued testing of technical solutions, and conduct regular communication and management.

Table 5. *Risk assessment matrix*

		SCALE OF SEVERITY		
		ACCEPTABLE	TOLERABLE	GENERALLY UNACCEPTABLE
SCALE OF LIKELIHOOD	NOT LIKELY	LOW	MEDIUM	MEDIUM
	POSSIBLE	LOW	MEDIUM	HIGH
	PROBABLE	MEDIUM	HIGH	HIGH

Table 6. *Risk assessment scale*

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