Towards more effective nature-based climate solutions in global forests

Supporting Information

Next Steps on Net Climate Impacts

We foresee two prominent ways that albedo could be incorporated into NbCS policies and protocols. These changes would be most important to incorporate into reforestation/afforestation protocols where a recent global analysis was published that enables direct quantification of albedo's impact[1]. First, voluntary carbon registries and compliance market bodies should revise protocols to use the 'albedo offset' map in Hasler et al. (2024)[1] to disallow afforestation or reforestation project development in grid cells where the radiative forcing impact from the change in albedo exceeds the radiative forcing benefit from carbon storage in a forest project. The 'albedo offset' map provides the fractional climate impact (radiative forcing) that albedo change would 'cancel out' from the carbon storage benefit of a given project. For example, a 50% albedo offset indicates that albedo change roughly negates around 50% of the climate mitigation benefit from carbon storage in a given grid cell. This exclusion threshold provides a very clear and straight-forward map of where the net climate impact of reforestation/afforestation is likely to be warming and thus should be avoided for programs with climate mitigation goals. We note that it might be useful to exclude projects that exceed a certain threshold of albedo offset lower than the 100% threshold (net warming) – a tiered approach – with the goal of conservative crediting, but this is a normative decision[2].

Second, voluntary carbon registries and compliance market bodies should revise protocols to fractionally reduce the credits issued using the 'albedo offset' map in Hasler et al.

(2024), in a similar manner to the current leakage deduction. Protocols could require carbon projects to upload a geographic project boundary or centroid point to the open-source tool from Hasler et al. (2024), extract the albedo offset for that project, and then adjust the crediting calculation by deducting the albedo offset fraction. Furthermore, projects could monitor albedo change with in situ or remote sensing measurements within the project boundary and update the albedo deduction dynamically with more granular, local data that would better account for specific project species composition, density, soil albedo, etc.

Concerning key near-term future research needs to improve the incorporation of cloud feedbacks, volatile organic compounds, and aerosol net climate impacts of NbCS projects[3–5], we believe a coordinated set of modeling experiments is needed to advance these areas to provide implementation-ready tools. In particular, a comprehensive series of model experiments that would generate Green's Function across a range of climate models (similar to those produced for sea surface temperatures[6,7]) to characterize climate response to local-to-regional scale changes in albedo evapotranspiration, VOCs, and aerosol emissions, individually, would be a critical step to moving beyond the radiative kernel approach from albedo[1]. This would capture not only the instantaneous local radiative effect of a change in land albedo, but also the change in planetary albedo (impacted by clouds and other processes) that is critically necessary for global (not just local) temperatures. Such Green's Functions could also be produced for other key surface properties (e.g. relating to aerodynamics and evaporation). The key difference between a radiative kernel versus a Green's Function is that the radiative kernel provides the instantaneous radiative effect of a given change (e.g. in land surface albedo at one location), without any adjustments or feedbacks to that change, while a Green's Function quantifies the full system response to a given change (e.g. a change in land surface albedo at one location), which is composed of the direct instantaneous effect and all the responses and feedbacks within the system[8].

Kernels are generated by running the radiative transfer code of a model offline at each timestep, once with no change (these are the fluxes passed to the model to integrate forwards) and once with the imposed change (e.g. in surface albedo; these fluxes are saved to the kernel, but are not passed to the model for the next time step – the model is unaware any change was made to surface albedo). In contrast, a Green's Function has a change imposed on it that impacts the forward integration of the model – the change in albedo alters surface and top-of-atmosphere (TOA) fluxes which alter atmospheric processes which potentially feedback on surface and TOA fluxes[8].

In the Green's Function experiment, a substantial amount of the net surface and net TOA radiative fluxes are mediated by atmospheric feedbacks to the surface change. In the radiative kernel, there are, by design, no feedbacks. The Green's Function approach has an additional benefit of not being restricted to local effects - it could capture changes in circulation. The radiative kernel can only capture the direct effect on the local column radiation balance.

Because a radiative kernel doesn't need to propagate information from imposed perturbations in either space or time, one can generate a kernel with one coupled model run. In contrast, a Green's Function approach requires running a fully coupled land-atmosphere simulation for each location one is interested in perturbing. This likely makes it impractical to run for a given NbCS project, but could theoretically be run for a substantial forest cover change within a jurisdiction. Thus, a suite of model experiments that developed Green's Functions for a range of NbCS jurisdictions across a range of climate models could provide a quantitative key basis of these additional feedbacks on radiative forcing and maps that could be incorporated into protocols similar to the approach described with albedo above, although uncertainties in constraining net TOA fluxes from satellites may be a barrier[9].

Next Steps on Durability

The immediate next steps to update buffer pools with the best-available science involve voluntary carbon registries and compliance market bodies updating protocols to require that buffer pool sizes and contributions be calculated from an independent, third-party dataset that provides rigorous buffer pool calculations that include climate change trends[10,11]. Similar to albedo, project developers would use an easily-accessible web tool to upload a geographic boundary file or centroid coordinate of the project and receive a buffer pool contribution set of scores. This initial tool provides disturbance-specific buffer pool sizes for wildfire, drought, and insect outbreaks in the United States and a single combined 'stand-replacing' disturbance score for forests globally. This tool can and should be updated to include additional granularity of other disturbances, such as wind and storm disturbances, and disturbance severity at jurisdiction and global scales. We note that there is substantial complexity, which is beyond the scope of this review paper to cover, around how buffer pools are capitalized and tapped by reversals that vary by protocol that must be carefully addressed in protocol updates[12].

Next Steps on Additionality and Baselines

The two approaches we highlight as potentially promising for baseline assessment that avoids overcrediting—dynamic baselines and jurisdictional approaches—are just starting to be used to generate carbon credits and so ongoing research on their effectiveness is needed to refine them over time, and to assess if they are able to reasonably avoid significant overcrediting. This analysis should be performed by independent researchers (i.e. without interest in the outcomes) either on their own or under contract by program administrators. Transparency is necessary to enable external analysis, and involves providing all the information needed for external analysts to assess data sources and assumptions, and to reproduce the baseline calculations, as required in California bill AB 1305 and as is standard for academic articles. Further, program administrators should nimbly improve methodologies as understanding improves. A shift to a contributions approach facilitates this process of analysis and improvement by reducing the legal risk associated with discovering that previous scientific understanding resulted in excess crediting.

Core datasets for estimation of dynamic and jurisdictional baselines include time-series calculations of carbon stocks (e.g. aboveground live carbon) from forest inventory plots and/or from rigorously-validated remote-sensing products, time-series maps of land use (e.g. agriculture, forest), and time-series maps of land management (e.g. timber harvest, forest degradation). Other ancillary data around climate, forest type, soil, distance to road, and land ownership data will also likely be important for dynamic baselines[13,14]. These remote-sensing products will likely need to be at high enough resolution to detect project-level changes and establish robust comparison control pixels to project pixels.

Dynamic baselines are considered best practice for baselines in the context of many similar activities and actors. Adverse selection remains a risk with dynamic baselines since methods for establishing control plots cannot capture all factors that affect what would have happened without the carbon finance[15].Other baseline-setting methods are needed for certain locations or landowner types where dynamic baselines are not viable[16]. For these, more research is needed to determine effective baseline setting methods.

Dynamic baselines can also account for additionality when baselines are an effective measure of additionality. Additionality and baselines are different assessments when projects involve a discrete action, like restoring a degraded forest, rather than a change in forest management over time such as extended rotations. For these projects, dynamic baselines can assess the baseline, but a separate additionality assessment is also needed. Additionality assessments involve understanding of the specific location and factors affecting decisions in that context which should be performed by independent analysts with contextual knowledge on a project category or individual project basis.

On jurisdictional REDD+, in addition to the datasets described above, multi-method case study analyses of specific programs will be important to explore how effectively programs address deforestation drivers and how criteria can be improved for determining which jurisdictional programs meet basic quality criteria. Effectiveness criteria includes how well programs address deforestation drivers, fairly engage with forest-dwelling communities in program design and implementation, and set accurate and conservative baselines.

Until we have more experience with these new baseline methods and they have been demonstrated to be reasonably accurate, baseline setting should lean heavily towards conservativeness to avoid the previously-observed pervasive overcrediting.

Next Steps on Leakage

Concerning flexibility in leakage zones, leakage zone calculations could be required to use an independent, third-party tool similar to the approach proposed here for buffer pool contributions for durability. Furthermore, prescribed minimum floors of activity leakage could at least partially address the challenges around flexibility.

Leakage mitigation can take many forms. For REDD+, leakage mitigation activities can involve addressing underlying drivers of deforestation, including by engaging local communities in program design, and coordinating across broader geographical scales to manage land use changes comprehensively[17,18]. In general, when an NbCS project results in a reduction in production (e.g., timber or agriculture), mitigation activities can increase production in ways that do not lead to further loss of forest carbon, such as pairing extended rotation projects with forest restoration activities that include thinning, and forest protection with agricultural intensification. The outcomes of these mitigation activities should be monitored and conservatively quantified and leakage deductions should be made for the portion of leakage not made up by mitigation activities. More rigorous quantification of the effectiveness of some of these activities could involve periodic re-assessment of activity leakage rates with remote sensing data[19].

Models can help illuminate how the expected magnitude of leakage varies by region, project type, market, and policy coverage. Higher leakage rates are expected where policy coverage is narrow (e.g. smaller geographic scales), smaller scales of activity displacement, more connected or integrated markets, higher producer flexibility in the market, availability of proximal alternative lands for production, and higher carbon emissions from the leakage zones than the project areas[18,20]. Policy coverage and scales of activity displacement are generally known at a protocol-level via what regions are in scope and how many projects have been developed or proposed to date. Market connectivity and producer flexibility are more challenging to estimate but a range of social science and econometric methods can provide insights and constraints. The availability of relevant nearby alternative lands and carbon emissions from the leakage zones can partially be estimated with remote-sensing data to track similar lands to proposed projects and carbon losses from those alternate lands.

Next Steps on Transparency

Transparency – which refers to publicly providing all necessary information to enable full, independent, third-party analysis of the effectiveness of NbCS initiatives (including location, nature, and all information that an external analyst would need to recalculate the benefits and understand the source of data and assumptions) – is paramount for ensuring rigorous and successful NbCS outcomes. Transparency in NbCS carbon credits is higher than in many NbCS interventions, but more is still urgently needed. Transparency is essential for independent and third-party assessment of project and program success in delivering on promised climate goals. Transparency is needed for the datasets, meta-data and models/tools used in program and protocol design, including baselines, leakage, and durability risks. Transparency at a project level is crucial in terms of the location and project physical boundary (e.g. shapefile), forest composition and age, the design and validation of remote sensing data sets, management history and proposed management changes, and other dimensions of project design. Transparency in the claims made and calculations of emissions reductions or removals is critical, especially as there is movement in this space to shift towards mitigating emissions within a corporation's value chain. Within value chain mitigation activities for companies must provide the same level of transparency expected elsewhere in the NbCS space so that uncertainties, assumptions, and limitations are not simply hidden behind proprietary walls.

Transparency practices vary widely in the voluntary carbon market today. Most carbon crediting programs provide some information about how climate benefits are calculated, but coverage varies and frequently excludes at least some relevant information. For example, it is uncommon for voluntary carbon market projects to provide shapefiles in their public registry listings. Industry norms and formal regulation are both encouraging additional disclosures through voluntary standards from the Integrity Council for the Voluntary Carbon Market and a mandatory disclosure law in California known as Assembly Bill 1305, the Voluntary Carbon Market Disclosure Act. Voluntary carbon registries should update protocols to require the key components of transparency for projects.

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Supplementary Boxes, Figures, and Tables

---------------------------------- Box S1: Definitions and Key Terms-----------------------------------

Additional: NbCS efforts that lead to climate mitigation beyond what would have happened absent those efforts, typically assessed as compared to a counterfactual baseline scenario. For example, if a given forest was unlikely to be degraded or deforested absent the NbCS initiative, but a carbon credit claimed that its baseline scenario involves significant degradation or deforestation, then the avoided emissions are likely not additional.

Avoided Conversion: Avoided conversion protocols in carbon markets that are supposed to prevent forests likely to be converted to remain standing.

Afforestation: Direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land.

Albedo: Reflectivity of a surface, primarily used here in terms of the visible/shortwave radiation spectrum.

Carbon credits: A quantified reduction or removal of greenhouse gas emissions that purportedly represents one ton CO_2e reduced or removed from the atmosphere for a predetermined period of time, which can be used to make either compensation (e.g. offsetting) or contribution claims.

Carbon offsets: Carbon credits that are used to justify a compensation claim.

Compensation claim: A claim that an entity's greenhouse gas emissions have been canceled out, negated, or neutralized. Most people who use the term "carbon offsets" are referring to the use of carbon credits to justify a compensation claim.

Compliance carbon market: A market for emission allowances and/or carbon offset credits that is established, run, and regulated by a government body to meet regulatory requirements.

Contribution claim: A claim that an entity has provided a financial contribution to a NbCS or other climate mitigation activity beyond its own value chain, without claiming to cancel out, negate, or neutralize any of their own emissions. Instead, they can claim they have contributed to global climate mitigation efforts, whether through the procurement of carbon credits or other mechanisms to support external climate mitigation efforts.

Improved Forest Management: Improved forest management changes in forest management designed to reduce emissions from forest management, reduce risk, and/or increase carbon stocks within a forest.

Jurisdiction: The extent of a government authority over a particular geographic area. In the NbCS space, jurisdictions are increasingly used for REDD+ programs. Typical jurisdictions are subnational (e.g. Acre, Brazil) or national (e.g. Guyana).

Leakage: The indirect impact and corresponding spatial shifting of an NbCS activity in one place and time on carbon storage in another place and/or time, which reduces the net effect of the intended intervention.

Methodology or Protocol: The rules that carbon crediting programs set for designing and implementing different kinds of carbon crediting projects. Each methodology includes eligibility criteria, methods for assessing emissions reduced or carbon removed, and methods for monitoring these reductions or removals for a specific project type or family of project types.

NbCS: Human actions that protect, better manage, and restore nature for climate mitigation.

REDD+: A climate mitigation framework that stands for reducing emissions from deforestation and forest degradation and other activities to enhance forest carbon stocks, developed by Parties to the United Nations Framework Convention on Climate Change (UNFCCC).

Reforestation: Establishment of forests on land that was previously forested, but currently is not (e.g. due to historical land clearing).

Registry: An entity that issues carbon credits such as Verra, the American Carbon Registry, the Climate Action Reserve, or Gold Standard.

Reversal: A reversal occurs when credited carbon that is stored outside the atmosphere is emitted or committed to be emitted to the atmosphere (e.g. when a tree dies from drought or fire). Carbon crediting programs often distinguish between avoidable reversals (such as elective decisions to harvest timber) from unavoidable reversals (such as a wildfire caused by lightning).

Voluntary carbon market: A market for trading carbon credits typically established and run by a non-governmental body, traditionally developed to help carbon credit buyers achieve voluntary emissions reduction goals.

-- END BOX --

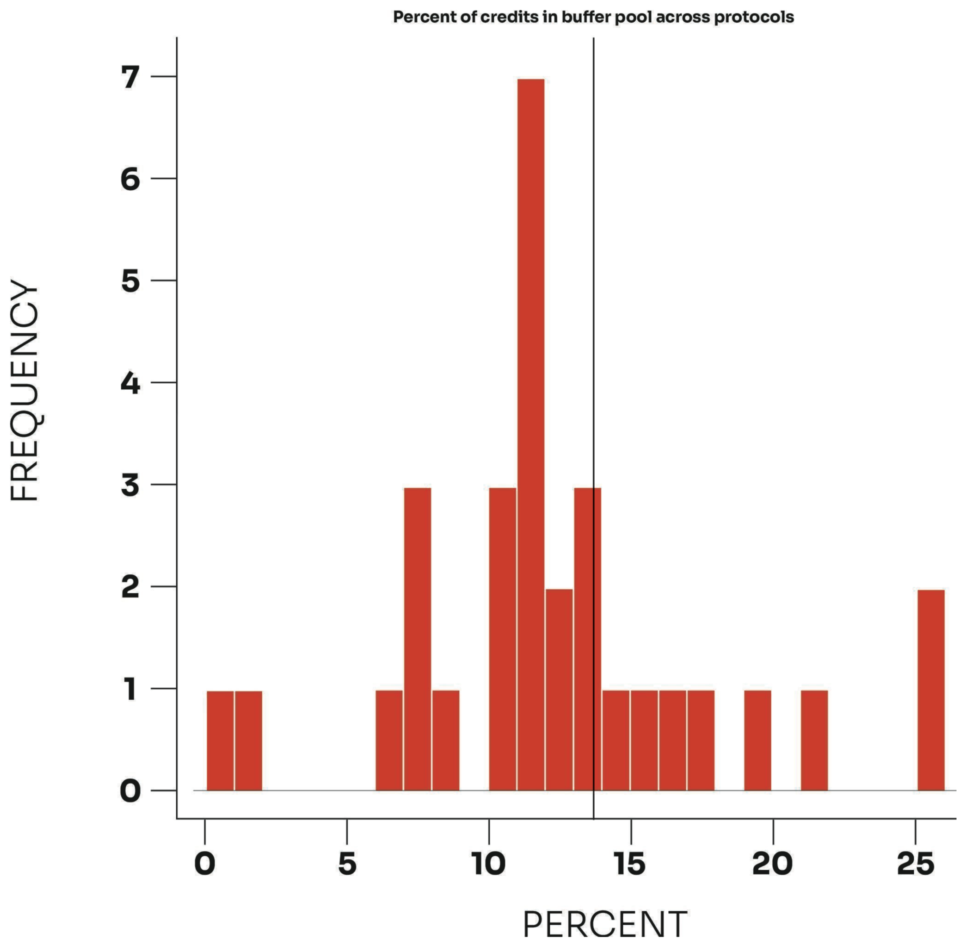

Figure S1: Buffer pool total sizes as a percentage of credits issued across currently active protocols in the voluntary carbon market as of December 2023. Black line is the credit-weighted average across protocols.

Supplementary Tables

Current Problem	Immediate Solutions	Near-Term Solutions and Research Needs
Net Climate Impact - No NbCS efforts to date account for the total climate impact of a given intervention - Changes in albedo may weaken or reverse climate benefits of reforestation or avoided deforestation efforts in some regions	Voluntary carbon registries and compliance market bodies should: - Incorporate albedo in NbCS carbon crediting protocols, and consider it in protocols for interventions and initiatives where albedo change is likely high (**Data**: Ref 38) - Disallow projects in places where albedo change outweighs the carbon storage benefit and fractionally reduce estimated climate benefits based on albedo changes	- Models and maps of the net climate impacts of a change in forests on cloud feedbacks, VOC and aerosol effects on climate, including direction and relative importance of different processes - Hydrologic cycle feedbacks (e.g. evapotranspiration) quantified and included in net climate impact maps
Durability - Most NbCS efforts do not base durability risks (e.g. buffer pool size) on robust, independent, spatially-varying data on natural and social risks - The role of climate change in increasing durability risks is rarely considered - Durability commitment is often far shorter (e.g. 20-40 years) than that needed for realizing climate mitigation benefits (>70-100 years) - Physical incommensurability of temporary forest carbon compared to fossil fuel carbon	Voluntary carbon registries and compliance market bodies should: - Update buffer pool contributions used by major forest NbCS efforts to reflect the current science (**Data**: Refs 61-62) - Use independent durability risk maps instead of projects selecting their own risk levels. - Strive for at least a 100 year lifetime in protocols - Allow durability mitigation to reduce buffer pool contributions only when based on empirical, region-, and intervention-specific science Carbon credit buyers should consider: - Durability of carbon storage needs to match the claim being made. Contribution claims could play a role	- Open-source tools to allow protocols and projects to extract their durability risk profiles for a given region, point, or project - Data-constrained and spatially-explicit estimates of the social risks to forest projects - Better inclusion of climate trends into durability risks and higher specificity for the risks by species or forest type - Syntheses on which management actions influence disturbance risk by biomes and regions - Liability could be transferred to the buyer of the carbon credit in the case of a reversal
Additionality - Extensive additionality and baseline problems in many NbCS protocols have led to widespread over-crediting - Little additionality has	Voluntary carbon registries and compliance market bodies should: - Shift to dynamic baselines where feasible - Improve jurisdictional baselines, which should be based on the best-available, consistent,	- Improvements in remote-sensing and ground measurements to map carbon stocks and fluxes at high resolution - Development of accurate and dynamic maps of past,

Current Problem	**Immediate Solutions**	**Near-Term Solutions and Research Needs**
been observed post hoc in most analyses to date	transparent, and independently-derived estimates of future forest loss and forest management Registries and carbon credit buyers should: - Increase transparency of baselines	current, and projected future management practices for additionality tools
Leakage - Leakage estimates in most NbCS protocols are too coarse and likely underestimated - Robust calculation of both activity and market leakage are exceptionally challenging to do currently	Voluntary carbon registries and compliance market bodies should: - Base leakage zones upon independently developed, third-party data and tools - More rigorously quantify leakage mitigation activities and not assume that activities eliminate all/most leakage - Require a market leakage deduction and account for international market leakage when a project reduced production of a commodity - Update leakage rates to conservatively reflect rates documented in the literature	- Maps and time-series datasets to distinguish the drivers (natural and human-driven) of forest loss over a region - Fusion of forest economic and land-use models with remote-sensing data to yield extensively-validated regional leakage rates - Shift to focus on projects where the climate benefits are unlikely to be undone by leakage
Structural challenges - Low transparency of direct emissions reductions vs carbon credits - Low transparency of climate benefit calculations - Lack of independence of verifiers creates potential conflicts of interest - Offsets and ton-for-ton accounting incentivize a 'race to the bottom' - Increasing legal risks to buyers of low-quality offsets	Policy-makers should: - Require separate disclosure of organization's direct emissions reductions and carbon credits used - Require transparency of critical data for recreating NbCS project climate benefits, including geographic boundaries, and baselines Voluntary carbon registries and compliance market bodies should: - Restructure verification process to financially decouple verifiers from project developers Carbon credit buyers should: - Expand funding models to include money-for-ton and money-for-money approaches	- Policy needed to require improved transparency - Further implement and test alternate claiming mechanisms, including a contribution approach to NbCS - Fund independent assessment of program effectiveness and dataset/tool development and updates

Table S1: Outline of steps towards more rigorous NbCS in forests with current problems, immediate solutions, and near-term solutions and research needs in each of the four components of rigor and structural challenges.

Registry	Minimum Lifetime	Project Type/ Activities	Methodology/Protocol	N Reg Proj	Issued Credits to 12-2023
ACR-ARB	100	AC	ARB Compliance Offset Protocol: U.S. Forest Projects	4	7891272
		IFM	ARB Compliance Offset Protocol: U.S. Forest Projects	55	120182254
ACR Voluntary	40	ARR	AR-ACM0001: Afforestation and Reforestation of Degraded Land	2	6285796
		IFM	Improved Forest Management (IFM) on Non-Federal U.S. Forestlands	71	21290376
CAR-ARB	100	AC	ARB Compliance Offset Protocol: U.S. Forest Projects	1	244767
		IFM	ARB Compliance Offset Protocol: U.S. Forest Projects	70	74329960
CAR-Mexico	30	Forestry - MX	Mexico Forestry Protocol	150	3882275
CAR Voluntary	100	AC	U.S. Forest Protocol	5	1434257
		Conservation	U.S. Forest Protocol	2	464044
		IFM	U.S. Forest Protocol	17	8914408
GS	30	A/R	Afforestation/Reforestation GHG Emissions Reduction & Sequestration Methodology	23	5276349
Verra	20	ARR	AR-ACM0001: Afforestation and reforestation of degraded land	9	18547279
			AR-ACM0002: Afforestation or reforestation of degraded land without displacement of pre-project activities	1	58122
			AR-ACM0003 Afforestation and reforestation of lands except wetlands	41	12125521
			AR-AM0003: Afforestation and reforestation of degraded land through tree planting, assisted natural regeneration and control of animal grazing	1	42625
			AR-AM0005: Afforestation and reforestation project activities implemented for industrial and/or commercial uses	1	753975
			AR-AM0014: Afforestation and reforestation of degraded mangrove habitats	5	1678419
			AR-AMS0001: Simplified baseline and monitoring methodologies for small-scale A/R CDM project activities implemented on grasslands or croplands with limited displacement of pre-project activities	10	1782813
			AR-AMS0005: Simplified baseline and monitoring methodology for small-scale afforestation and reforestation project activities under the clean development mechanism…	1	78003
			AR-AMS0007: Afforestation and reforestation project activities implemented on non-wetlands	2	177917
		IFM	VM0003 Methodology for Improved Forest Management through Extension of Rotation Age	2	347696
			VM0005 Methodology for Conversion of Low-Productive Forest to High-Productive Forest	2	522431
			VM0010 Methodology for Improved Forest Management: Conversion from Logged to Protected Forest	11	5638882
			VM0011 Methodology for Calculating GHG Benefits from Preventing Planned Degradation	1	182347
			VM0012 Improved Forest Management in Temperate and Boreal Forests (LtPF)	5	5876946
		REDD	VM0004 Methodology for Avoided Planned Land Use Conversion in Peat Swamp Forests	1	33625616
			VM0006 Methodology for Carbon Accounting for Mosaic and Landscape-scale REDD Projects	3	7592929
			VM0007 REDD+ Methodology Framework	26	135341480
			VM0009 Methodology for Avoided Ecosystem Conversion	8	68125930
			VM0010 Methodology for Improved Forest Management: Conversion from Logged to Protected Forest	2	241539
			VM0015 Methodology for Avoided Unplanned Deforestation	20	56477932

Table S2: Forest NbCS carbon credits issued as of December 2023 by registry, project type, protocol, and minimum required project lifetime.