

The path to robust evaluation of carbon credits generated by forest restoration and REDD+ projects[☆]

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ABSTRACT

Forest-focused Natural Climate Solutions (F-NCS) are crucial for climate change mitigation through emissions reductions and carbon sequestration. The Voluntary Carbon Market directs finance to F-NCS activities by the sale of carbon credits to offset emissions. However, inconsistent implementation and imprecise rules have led to over-crediting and other integrity challenges, reducing confidence in F-NCS effectiveness. Despite these concerns, assessments of the limitations of current protocols and how scientific advances could improve VCMs effectiveness have been piecemeal and limited in scope. To address this applied research gap, we review current and emerging methodologies for monitoring carbon impacts of forest protection and restoration activities, covering methods for monitoring carbon stock change, additionality, leakage, and non-durability, with an emphasis on integrating remote sensing (RS) technologies alongside field-based methods and emerging statistical approaches. We recommend 1) that the VCM needs to evolve as science advances. Carbon standards should also **improve carbon estimates** by 2) incorporating use of high-resolution maps of carbon stocks and change into standards; 3) establishing and sustainably financing a federated forest plots database for training and validation of carbon maps and testing new machine learning approaches; 4) **calculate additionality** for projects using causal inference methods that statisticians have developed for analysing changes in land cover and carbon density maps; 5) better understand the interaction between project and jurisdictional assessment of REDD+ projects; **address leakage** by 6) harnessing remote sensing to estimate its extent and evaluate the effectiveness of sustainable development measures designed to minimise it; 7) **factor in non-durability upfront in F-NCS projects** by leveraging map-based modelling of persistence. Implementation of these recommendations would improve accuracy and build confidence in the VCM, leading to real benefits for people, nature and the climate.

1. Introduction

Annual CO₂ net emissions, which stood at 41 gigatons in 2024 (Friedlingstein et al., 2024), will need to fall by 23 gigatons by 2030 in order to stand a reasonable chance of keeping global air temperature rises below 1.5 °C (Adams et al., 2021). Forest-focused natural climate solutions (F-NCS), which seek to protect, sustainably manage, and restore natural and modified forests could reduce net emissions by 16.2 gigatons CO₂e annually (Griscom et al., 2017), particularly in the tropics (Griscom et al., 2020), and provide substantial benefits for human livelihoods, biodiversity conservation and ecosystem service provision

(Seddon et al., 2020). However, they are not currently being created at scales commensurate with the biodiversity and climate crises (Balmford et al., 2023a).

F-NCS interventions include activities that reduce emissions into the atmosphere by avoiding deforestation (often termed Reducing Emissions from Deforestation and forest Degradation; REDD+), activities that remove carbon from the atmosphere through afforestation, reforestation and revegetation (ARR), and activities that increase carbon storage in managed forests (Improved Forest Management; IFM). Recognition of their large mitigation potential has led to the integration of F-NCS into the net-zero commitments of many countries, which are included in

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Nationally Determined Contributions (NDCs) to the United Nations Framework Convention on Climate Change (Committee on Climate Change, 2019; European Commission, 2020; Tong et al., 2020). For example, there are ambitious commitments to restore between 7.7 and 10 million km² of land to forest (Sewell et al., 2020). However, five years into the UN Decade on Ecosystem Restoration, progress in restoring and protecting forests falls far short of the levels needed to meet net zero commitments (Stanturf and Mansourian, 2020).

The voluntary carbon market (VCM) remains a key mechanism to channel private finance into forest conservation and restoration activities (Seymour and Langer, 2021). Standards bodies, such as Verra and Gold Standard, regulate the market by developing protocols for monitoring the carbon impact of projects, and calculating how many carbon credits (each equivalent to 1 metric ton of CO₂) can be sold. However, recent high-profile research has argued that many F-NCS projects have issued far too many carbon credits through these standards (“over-crediting”), based on re-evaluation of available data using alternative statistical approaches (West et al., 2020; Badgley et al., 2022b; West et al., 2023). These findings have led to a lack of investor confidence in the processes used to generate carbon credits which is contributing to the failure of F-NCS to mitigate climate change at a meaningful scale (Balmford et al., 2023a). In addition, media attention associated with these publications has accused major corporations of greenwashing, which has further dented confidence in F-NCS crediting (Lakhani, 2024; Swinfield et al., 2024).

While the discourse around F-NCS crediting has led to refinements in voluntary carbon market methodologies for both REDD+ and ARR projects, the integration of Remote Sensing (RS) data into methodologies remains somewhat limited. Current methods continue to heavily rely on a few time-consuming field measurements and expert knowledge, despite the emergence of transformative remote sensing technologies that enable large-scale and frequent monitoring at a relatively low cost. In parallel, recent advances in statistical inference, and probabilistic risk analyses applied to RS data offer potential for improving the reliability of F-NCS carbon credits. Yet, there is no comprehensive and critical review that assesses these new methods or explores how they could be effectively integrated into carbon verification and certification standards. Furthermore, Most methodological discussions have focused on REDD+ activities, which account for 87 % of nature-based carbon credits issued since 2002 (Haya et al., 2023a), while ARR (11 % of credits) and IFM (2 % of credits) have received less attention, though their share is expected to grow significantly in the coming years.

Here we address these knowledge gaps by reviewing current and emerging remote sensing methods for calculating carbon credits and by considering the transferability of methods between REDD+ and ARR projects. We are not addressing IFM activities as the inclusion of harvesting makes monitoring more complex and difficult to improve via remote sensing; assessment of IFM carbon monitoring has also been conducted in detail elsewhere (see: Haya et al., 2023b). The review is split into four sections that evaluate approaches used: (a) to track **forest carbon** through time; (b) to measure a project’s ‘**additionality**’ by comparing changes in the project area with predictions of what would have happened without the project intervention; (c) to evaluate the extent of ‘**leakage**’, which occurs when prevention of deforestation or agricultural expansion in a project area displaces these economic activities elsewhere, and to assess the effectiveness of sustainable development activities aimed at preventing leakage; and (d) methods to calculate the carbon credits given the likely ‘**non-durability**’ of a project. For each section, we review pertinent advances in remote sensing. We also evaluate the commonalities and disparities between REDD+ and ARR methodological approaches and provide recommendations for integrating emerging methods into VCM methodologies. We aim for this review to support the development of more unified, scientifically grounded remote sensing-based approaches that strengthen the credibility, environmental integrity, and overall effectiveness of nature-based carbon credit mechanisms.

2. Tracking forest carbon stocks

Accurately quantifying forest carbon stocks across space and time is a prerequisite to integrating F-NCS into the Voluntary Carbon Market (VCM). In this section, we summarize the development of systems for mapping aboveground forest carbon stocks (typically reported in Mg C per hectare), starting with field plots and land-cover maps, through airborne laser scanning, to the newest generation of spaceborne radar and LiDAR sensors (Fig. 1). We then describe the state of VCM carbon measurement within this context (Section 2.2), highlighting where newer remote sensing techniques can support improved monitoring of REDD+ and ARR projects.

2.1. Advancements in carbon mapping

2.1.1. Field plots and land-cover mapping

Field plots are the foundation of all systems that track forest carbon, but their contribution is evolving from primary information source to the training and validating dataset for remotely sensing products (Duncanson et al., 2019). With their origins in timber inventories, these plots are designed to estimate aboveground biomass (AGB, the total dry mass of plant material contained in an area of forest) with well-characterized accuracy (e.g. Coomes et al., 2002), from which carbon stock is calculated by multiplying by carbon content (Martin and Thomas, 2011). AGB is not usually measured directly in forest inventory plots but estimated from tree height and trunk diameter, which are then related to biomass by per-species or per-biome allometric equations (Chave et al., 2014; Réjou-Méchain et al., 2017). Allometric equations are typically calibrated using destructively sampled (felled) trees. However, due to the high cost and ecosystem impact of destructive sampling, often merchantable timber species and young trees are over-represented in calibration, while large old trees and protected species are underrepresented (Jucker et al., 2022). Forest plots have been widely used to monitor forest AGB as data collection requires widely available equipment and follow finely honed protocols upon which field teams can be trained. However, a core limitation of forest plots is their restricted spatial and temporal coverage: logistical challenges involved in data collection typically result in sparse, spatially clustered samples that may not represent entire landscapes or projects, as well as substantial potential for human error in measuring and recoding data (Cushman et al., 2023). Estimation of forest carbon from field plots has advanced thanks to the creation of global databases of wood densities (Zanne et al., 2009) and allometries (Henry et al., 2013), as well as standardised analysis packages (Réjou-Méchain et al., 2017). Terrestrial Laser Scanning (TLS) is starting to provide an extra layer of refinement – the high-pulse-density point clouds it produces are being used to generate 3D reconstructions of the aboveground volume of individual trees which, when combined with wood density estimates, can estimate AGB accurately without relying on traditional allometric models or destructive sampling (Demol et al., 2022).

The classic approach to estimating national / landscape-scale carbon stocks is to multiply the mean carbon stock within a vegetation type by the area of that vegetation type and then sum across all vegetation types (e.g. Coomes et al., 2002). Reviewing the remarkable advances in vegetation type mapping is beyond the scope of this review but is important for accurate project monitoring (but see, for example Xie et al., 2008; Pandey et al., 2021). Changes in carbon storage are then assessed by tracking deforestation, degradation and reforestation across regions of interest either with local or global products (Hansen et al., 2013; Vancutsem et al., 2021; Reiche et al., 2024). Similar approaches are employed in the VCS and in recently published REDD+ monitoring approaches such as CPACT, which uses GEDI estimates of carbon stock to generate mean values within different land cover types (Balmford et al., 2024). However, one often overlooked issue related to land cover mapping is differences in the rates of omission and commission errors which lead to bias in the deforestation estimates. For example, Hansen

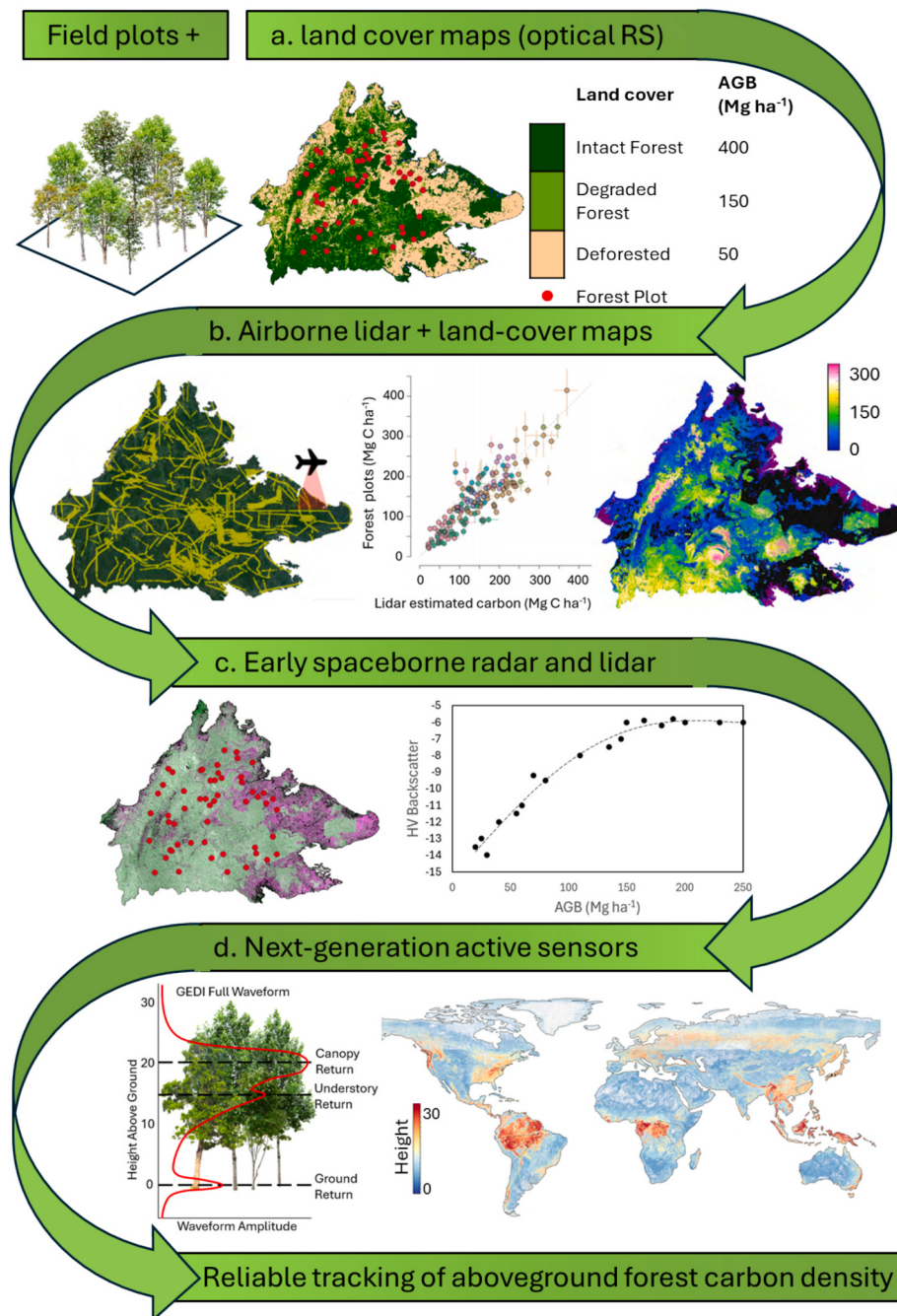


Fig. 1. The progression of forest carbon density mapping approaches illustrated using the Malaysian state of Sabah as an example region. A. Classically, field plot networks across a region were combined with land cover maps to estimate mean carbon density per land-cover class and multiplied by class areas to give carbon stocks. B. Airborne lidar surveys calibrated with data from field plots network have delivered high-resolution carbon density maps, with machine learning used to predict carbon density in regions which were not flown (Asner et al., 2018). C. The relationship between field plot AGB and L-band SAR backscatter can produce carbon maps but these saturate at low AGB, necessitating the integration of LiDAR. D. the availability of spaceborne lidar allows machine learning approaches to be conducted globally, using LiDAR waveform data as ground truth data, producing global maps of forest height (Ma et al., 2023), which can be used to estimate AGB from field or TLS data. (Land cover map in a. from Vancutsem et al., 2021, Figures in b. taken from Asner et al., 2018, SAR data in c. from ALOS PALSAR2 sensor, Global forest height map in d taken from Ma et al., 2023).

et al. (2013), has greater omission errors in the stable forest class than the deforestation class, leading to systematic underestimation of deforestation in a project area (Mitchard et al., 2023). To meet IPCC good-practice standards, deforestation estimates based on counting pixel area must be adjusted for the omission and commission errors inherent to RS-based maps using a high-quality local reference dataset (Olofsson et al., 2014). Despite the longstanding use of land-use change products in project monitoring, such adjustments are not required as they are

poorly understood, however could easily be incorporated into VCM methodologies to improve the accuracy of deforestation monitoring. More generally, locally calibrated maps especially those calibrated with TLS data (Krause et al., 2023) are likely to provide better performance than global maps of forest carbon stocks and land-use (Lui and Coomes, 2015), however there is a balance to be struck between using standardised global products across all projects versus potentially higher accuracy local products which require project level validation (Wang

et al., 2023).

2.1.2. Airborne laser scanning

Airborne laser scanning (ALS) has significantly enhanced mapping of AGB in natural forests at regional scales (Disney et al., 2018). Lidar point clouds capture the three-dimensional structure of forests by measuring the height and distribution of surfaces such as leaves and branches, enabling detailed mapping of canopy properties. ALS surveys much larger areas than traditional field plots, surveying regions of around 400–1000 km² per day. The production of native forest carbon maps for the Malaysian state of Sabah illustrates the utility of ALS (Fig. 1; Coomes et al., 2017, Asner et al., 2018, Jucker et al., 2018). A statistical model was developed that related lidar top-of-canopy height (TCH) to above-ground carbon density (ACD), using ALS data combined with forest plot data. Uncertainty was quantified and propagated using Monte Carlo simulations, accounting for field measurement errors, allometric model uncertainty, and GPS location error, yielding distributions of ACD estimates that reflect error at hectare resolution. Maps of ACD generated for areas surveyed by ALS were then upscaled to wall-to-wall coverage via a deep learning approach that linked LiDAR-calibrated carbon values to these geospatial layers (including Landsat reflectance, radar and elevation) for every forested area in the state at 30 m resolution (Asner et al., 2018). However, the maps produced by ALS has limited use for REDD+ or ARR activities, as it provides a snapshot of aboveground carbon, rather than tracking changes through time.

2.1.3. Early space-based remote sensing

Space-based remote sensing can overcome limitations of field and ALS dataset by expanding data coverage across time and space. *Passive optical sensors* are one satellite technology capable of measuring forest bio-optical properties by recording reflected sunlight within different bands of set spectral ranges. The presence and density of vegetation can then be estimated from these measurements by exploiting reflectance properties of photosynthesizing cells, quantifying the “greenness” of a pixel (Chakraborty et al., 2018). *Active sensors*, which include Synthetic Aperture Radar (SAR) and LiDAR, are also widely used for carbon stock estimation. Active sensors emit electromagnetic waves and measure the return signal from objects on the earth’s surface. The wavelength of the SAR sensors determines the extent of its penetration through surface objects. Both C-band SAR (3.8–7.5 cm wavelength) and L-band SAR (15–30 cm wavelength) have been widely used for estimation of AGB (Mitchard et al., 2009).

Optical, and C-band SAR sensors interact mainly with the upper portion of the canopy in a dense forest, whilst L-band SAR interacts with forest structural components like trunks and large branches of similar size to its wavelength, producing backscatter signals correlated with AGB (Mitchard et al., 2011). However, signals from optical and short-wavelength SAR sensors tends to saturate, reaching a threshold beyond which they are no longer sensitive to biomass differences. For example, L-band SAR has been used to provide high-resolution (10 m resolution) biomass estimates in low-biomass woodland (McNicol et al., 2018), but signal saturates in high AGB forests, typically >150 Mg C ha⁻¹ (Fig. 1.b; Joshi et al., 2017). In addition, these sensors are affected by confounding variables, for example, passive optical signals respond strongly to seasonal changes in leaf greenness (Tang and Dubayah, 2017), whilst L-band SAR effectively measures vegetation moisture content, therefore backscatter signals change with drought conditions and diurnal water cycles (Kim et al., 2016).

2.1.4. Next-generation space-based remote sensing

Since 2018, a new generation of sensors have launched that are explicitly designed to measure forest structure and biomass, overcoming many of the limitations of earlier satellites. The Global Ecosystem Dynamics Investigation (GEDI) uses a LiDAR sensor that can penetrate dense forest canopies to create detailed vertical vegetation profiles and measure high-biomass regions without saturating (Duncanson et al.,

2022). The BIOMASS mission, launched in 2025, uses P-band (~70 cm) SAR, which has deep canopy penetration and primarily interacts with the high-biomass components of trees (i.e. large trunks) thereby significantly reducing confounding seasonal effects from foliage. Further, no significant signs of saturation even at values greater than 300 Mg AGB ha⁻¹, have been observed, meaning BIOMASS will enable repeatable mapping of AGB, enhancing our understanding of deforestation, degradation, and regrowth in tropical forests (Ramachandran et al., 2023). These new sensors promise to meet the criteria of global consistency and cost-effectiveness called for in prior research (Cook-Patton et al., 2021).

The Global Canopy Atlas (GCA) also represents a landmark advance for training and validating of new models produced by these next-generation sensors, offering the first harmonized, analysis-ready airborne lidar dataset covering over 3400 woody ecosystem sites and more than 55,000 km² across all major biomes worldwide (Fischer, 2025). As illustrated above, ALS is essential for upscaling from limited field datasets (Asner et al., 2018). By standardizing ALS data acquisition, processing, and quality control across a diverse range of landscapes, the atlas provides high-resolution (1 m²) maps of canopy height, terrain, and structural attributes that are robustly comparable between regions, addressing spatial, algorithmic, and metadata inconsistencies typical of earlier LiDAR collections. GCA will enable improved assessment of model performance, refinement of remote-sensing algorithms, and far more reliable estimation of forest carbon stocks and their dynamics across the world’s forests (Fischer, 2025).

2.2. Current VCM approaches to carbon monitoring across landscapes

All VCM methodologies have, until recently, relied on forest plot data to estimate carbon stocks (e.g. UNFCCC/CDM, 2015; VCS, 2023d). Whilst, remote sensing data has typically been limited to land cover and land-use change products for baseline estimation, selection of control areas and stratification of landscapes, rather than directly tracking changes in carbon stocks (VCS, 2015, 2020, 2023a, 2023d). For example, REDD+ projects have classically used land-use change maps (e.g. Table 1), combined with forest plots located in different forest strata across a project landscape, to estimate emissions following deforestation (e.g. Coomes et al., 2002). Meanwhile, ARR projects have typically relied on repeat-census plot data to estimate carbon sequestration rates or used space-for-time substitutions, with the observed rate of change in plots then scaled up to the project area (e.g. Wheeler et al., 2016).

Large quantities of field data will continue to be collected in REDD+ and ARR projects, due to its relative simplicity of use, coupled with the ability to collect site specific species data and engage local participants, promoting buy-in from communities, which often improves the success of project activities (Evans et al., 2018). However, currently, carbon standards do not require projects to submit forest plot data to any centralised database, or have quality control measures in place. Forest plot data is a key source of calibration and validation data for all RS maps of forest carbon stocks and land-use. Therefore, not fully compiling and utilizing data collected within validated REDD+ and ARR projects constitutes a substantial missed opportunity. If such data were made available it would be an invaluable repository for calibration and validation of regional and global carbon maps, greatly improving their accuracy.

2.2.1. Application of RS carbon mapping for REDD+

There is scope to make better use of RS derived carbon products to improve accuracy of avoided emissions estimates in REDD+ projects, beyond the widespread use of land-use change products. Rather than relying on a small number of field plot estimates, which are often spatially clustered, AGB maps (Xu et al., 2021; Santoro and Cartus, 2023b) could offer reliable estimates that account for mean project AGB, AGB variability and uncertainty across a project landscape.

Table 1

List of remote sensing products available for tracking land use change and AGB, with details of temporal and spatial resolution, geographic range and sensor.

Product	Product type	Time period	Temporal Resolution	Spatial Resolution	Geographical range	Sensors	Source
Joint Research Council Tropical Moist Forest (TMF) land use change	Annual land use change product Deforestation year & degradation year products	1990–2022 1982–2022	Annual	30 m	Tropical Moist forests	NASA Landsat archive (optical)	Vancutsem et al. (2021)
Hansen Global Forest Change	Forest change	2000–2023	Annual	30 m	Global	NASA Landsat archive	Hansen et al. (2013)
MapBiomass	Land cover & land use change	1985–2022	Annual	30 m	Latin America countries: Brazil, Bolivia, Colombia, Peru, Venezuela Asian countries: Indonesia Latin American biomes: Chaco, Amazonia, Atlantic Forest, Pampa	NASA Landsat archive	Souza et al. (2020)
ESA CCI Above Ground Biomass (V4)	AGB	2010, 2017–2020	Specific years	100 m	Global	ESA Sentinel 1 A & B (C-band SAR) JAXA ALOS2-PALSAR2 (L-band SAR) NASA GLAS ICESat (LiDAR) JAXA ALOS PALSAR	Santoro and Cartus (2023b)
Xu AGB Change Map	AGB change	2000–2019	Single time step	10 km	Global	Harmonisation of ESA CCI AGB & Bouvet et al. (2018)	Xu et al. (2021)
Spawn AGB/ BGB Map	AGB & BGB	2010	Specific year	300 m	Global		(Spawn et al., 2020)
Product	Product type	Time period	Temporal Resolution	Spatial Resolution	Geographical range	Sensors	Source
CTrees individual tree AGC	AGC (tree-level)	Early 2010's	Single time step	Tree level	Rwanda	Very high-resolution optical imagery: WorldView-2, Ikonos, Spot and QuickBird	Mugabowindekwe et al. (2023)
CTrees Land Carbon Map*	AGB	2000-present	Annual	100 m	Global	Aerial photographs NASA GEDI (LiDAR) NASA GLAS ICESat JAXA ALOS PALSAR	Based on Xu et al. (2021)
Planet Forest Carbon Diligence*	AGC/ Carbon height	2013-present	Annual	30 m	Global	Airborne LiDAR NASA GEDI (LiDAR)	
Planet Forest Carbon Monitoring*	AGC/ Carbon height	2021-present	Quarterly	3 m	Global	NASA Landsat Planet scope ESA Sentinel 1 & 2 JAXA ALOS PALSAR NASA GLAS ICESat	Planet Lab (2024)
Baccini AGB Map	AGB	Early 2000's	Single time step	500 m	Tropics	NASA MODIS (optical) NASA GLAS ICESat	Baccini et al. (2012)
Saatchi AGB Map	AGB	Early 2000's	Single time step	1 km	Tropics	NASA MODIS NASA QuikSCAT (Ku-band SAR)	Saatchi et al. (2011)
Avitabile AGB Map	AGB	Early 2000's	Single time step	1 km	Tropics	Harmonisation of Baccini & Saatchi maps	Avitabile et al. (2016)
GEDI L4a	AGB (LiDAR footprints)	2019–2023	Sampling	25 m diameter footprint	±51.6° latitude	NASA GEDI	Dubayah et al. (2022)
GEDI L4b	AGB (Gridded)	2019–2023	Sampling	1 km	±51.6° latitude	NASA GEDI	Dubayah et al. (2023)

This is a non-exhaustive list of LUC & AGB mapped products. Most global level products are presented but only a selection of regional/ national level products is included due to the large number of mapped products available. *These are commercial products and not available open source. <https://ctrees.org/products/land-carbon>

Additionally, AGB maps provide data from areas within the project boundary where no field data has been collected. AGB maps can have high pixel level uncertainties (Santoro and Cartus, 2023b), meaning AGB estimates of specific pixels are not always well correlated with AGB on the ground at a given point. However, due to large size of REDD+ projects, many >100,000 ha, averaging of predicted AGB values over entire project landscapes (or different strata within a project), can provide reliable estimates of mean project AGB, assuming that AGB values are averaged over a suitable spatial scale to reduce standard error of the mean to an acceptable level (Duncanson et al., 2021).

The bigger challenge in carbon monitoring is for REDD+ projects that have degradation within the project boundary. Degradation – the reduction in AGB and ecosystem services within forested land – can lead to gradual and ongoing losses of AGB, which are much harder to detect and quantify using satellite data than deforestation (Gao et al., 2020). Whilst, advancements have been accomplished in degradation detection with the recent publication of global and regional maps (Vancutsem et al., 2021; Reiche et al., 2024), the associated emissions from degradation remain poorly understood (Berenguer et al., 2014). Spaceborne LiDAR along with ALS offer potential for better capturing degradation

emissions as they provide data related to forest vertical structure. For instance, multi-temporal ALS was used to identify tree mortality and gap dynamics in old-growth forests in French Guiana (Huertas et al., 2022), whilst GEDI was used to evaluate understory carbon losses caused by fire in the Amazon (Holcomb et al., 2024). However, the application of such approaches requires high level of technical expertise making degradation monitoring challenging to implement. In addition to LiDAR analysis, the BIOMASS mission, a P-Band SAR (70 cm wavelength), which is designed to work in high AGB forest, could be transformative for degradation estimates, delivering repeatable, wall-to-wall carbon loss mapping at scales relevant to REDD+ projects. Furthermore, guidance on degradation monitoring from VCM certification standards lags behind that of deforestation monitoring, for example, Verra have a dedicated tool (VMD0055; VCS, 2024) for quantifying emissions from deforestation but a similar tool for degradation is not yet available. Therefore, development of degradation monitoring in the VCM is needed to improve project monitoring.

2.2.2. Application of RS carbon mapping for ARR

ARR projects present distinct monitoring challenges, specifically related to quantifying carbon stock *change*, which is necessary to estimate ARR project carbon impacts. ARR projects often comprise of many small land parcels, typically under 1 ha, which complicates measurements and analysis. Monitoring carbon stock changes generally follows two main approaches, either, comparing AGB maps from different time points or modelling forest regrowth rates, both which have application within the VCM.

Some RS approaches have long-standing application in AGB mapping and remain valuable for ARR projects. For example, L-band SAR which can map carbon stock change in low AGB forests (McNicol et al., 2018), has application in young, planted forests. Furthermore, the availability of L-band SAR data from JAXA ALOS PALSAR/2 sensors since 2007 is beneficial in understanding carbon stock change in areas prior to projects starting, which is essential for establishing project additionality. Such analysis is not possible for some more recent sensors such as GEDI which has only collected data since 2019 (Duncanson et al., 2022).

Within the VCM sector there has been a recent surge in the availability of high spatial and temporal resolution AGB products, often using deep learning Artificial Intelligence (AI) and LiDAR. Commercial providers such as Planet Labs and CTrees offer annual AGB products at resolutions up to 3 m from as early as 2000 (Planet Lab, 2024; Table 1). These products show promise for monitoring carbon stock changes at relevant scales for ARR projects but are not open-source and both require local validation to ensure regional representativeness and credibility within a given project landscape.

A significant challenge associated with using annual AGB maps for change estimation is due to high pixel-level uncertainties in AGB estimates, which can be between 30 and 40 % (Turton et al., 2022). This uncertainty can be larger than the actual change between two time points, making it difficult to determine whether observed differences in AGB stocks are real or simply the result of substantial pixel-level uncertainty. Uncertainties in AGB estimates are often due to either a mismatch in size between field plots and mapping pixel resolution, geolocation errors which make co-registration between field plots and RS data challenging (Duncanson et al., 2021) or limited availability of calibration/ validation data. Most regional/ global-level AGB products were developed to look at *large scale* trends in carbon stocks for national-level reporting or to feed into climate models (Harris et al., 2021; Santoro and Cartus, 2023a), thus may not be ideally suited for estimating local-level carbon stock change as required by VCM projects. Both ESA (2023) and Spawn et al. (2020), highlight this issue cautioning against the use of their maps for pixel-level predictions and quantifying carbon change between maps due to high uncertainty. For project-level assessment of carbon stock change it may be preferable to assess change over longer time intervals (e.g. every five years, which is the typical validation period in the VCM), rather than annually, as change

over five years will likely exceed pixel-level map uncertainties. Averaging rates of carbon stock change across different project activities and for each cohort of planted stems will also reduce pixel-level uncertainties in estimates (Duncanson et al., 2021).

There is also a growing body of research quantifying forest regrowth rates at the landscape or regional scale under different climatic conditions or land-use history (Heinrich et al., 2021; Holcomb et al., 2023). For example, Heinrich et al. (2021) used a space-for-time substitution approach combining data on secondary forest age with AGB maps, to quantify rates of secondary forest regrowth across Amazonia under different climatic conditions. Machine learning approaches have also been used to quantify forest regrowth globally at 1 km resolution to account for spatial (Cook-Patton et al., 2020), and temporal variability (Robinson et al., 2024) in forest regrowth rates. These products, which predict forest regrowth rates, are particularly valuable for *ex-ante* predictions of likely carbon impacts of ARR projects and therefore have broad application at the early stages of project development.

2.2.3. Integrating RS carbon mapping approaches into the VCM

VCM standards ideally should have carbon monitoring tools approved by verification bodies, which are flexible and allow for the inclusion of advancing RS approaches, rather relying predominantly on field plot data. This is beginning to be seen in newer standards bodies such as Isometric, which is encouraging the use of LiDAR data in project monitoring (e.g. Isometric, 2024). Secondly, independently verified best practice guidelines regarding the use of RS data for carbon monitoring, which is regularly updated could help support project development. This is where the scientific community could work more closely with industry. For example, industry bodies such as the Integrity Council for the Voluntary Carbon Market (ICVCM) could coordinate academic working groups to develop best practice guidelines which it endorses, meaning guidance is independent of standards bodies. By following such guidance projects could ensure they are developing high quality monitoring approaches in line with state-of-the-art science and investors would have confidence that projects are adhering to best in class monitoring, which ultimately will increase the value of carbon credits generated by a project (Procton et al., 2024).

3. Additionality

3.1. Current approaches

Additionality is the concept that a given project must demonstrate that it has produced an environmental benefit (e.g. cutting emissions, preserving ecosystems, or generating renewable energy) that would not have happened otherwise. It's the "additional" gain that can be directly credited to the project intervention, beyond what would naturally occur under business-as-usual conditions. In the case of REDD+ projects, the need to demonstrate additionality means that projects cannot simply report that deforestation has decreased within a project boundary. Instead, they must show that forest loss has continued at a faster rate in counterfactual area(s) that were initially under similar deforestation pressure. To be comparable, project and counterfactual sites should be as similar as possible, in terms of their drivers and risk of deforestation, ecological conditions and socio-economic context (Schleicher et al., 2020). VCM methodologies have set out criteria for identifying suitable control sites, which includes variables related to rainfall, topography, vegetation type, population density, land tenure and governance (see Table S1 and Table S2). However, REDD+ methodologies have typically stopped short of requiring projects to use statistical matching approaches (see next section), or even to provide empirical justifications of control site choices, relying instead on expert opinion to provide a narrative-based justification (e.g. VCS, 2014). Without robust data-driven approaches to selecting control sites, REDD+ projects are vulnerable to human error or deliberate exploitation, with projects able to cherry pick baseline scenarios with high deforestation rates, thereby

generating more carbon credits and profit (Seyller et al., 2016; Swinfield et al., 2024). Recent analyses suggest widespread over-crediting among REDD+ projects (West et al., 2020; West et al., 2023), generating low quality credits upon which major companies have grown excessively dependent for achieving net-zero targets (Trencher et al., 2024). A consequence of over-crediting is perceptions that REDD+ projects are high-risk investments, this has led to ongoing updates to REDD+ methodologies to improve perceptions of project across the sector.

A second problem is that the VCM has principally relied on static baselines for calculating additionality (VCS, 2014, 2023a). Under this approach, the baseline is calculated every 10 years using historical information rather than being adjusted dynamically as circumstances change (e.g. VCS, 2014, 2023a). For REDD+ projects, historical rates of forest loss are compared between the project and control areas in the 10 years preceding the project and used to predict the likely carbon impact (i.e. *ex-ante* predictions) of the project (e.g. Guizar-Coutiño et al., 2022), assuming the same trends would continue in the absence of the project. This reference point is set when the project's crediting period begins and remains unchanged throughout that period, even as local forest conditions, land use pressures, or broader environmental factors may shift over time. While static baselines provide clarity and ease of calculation for project developers anticipating the volume of carbon credits, they may lose accuracy if actual ecological or socio-economic trends diverge from original assumptions, potentially resulting in the over- or under-issuance of credits. For example, deforestation rates can be heavily influenced by shifts in government policy, such as those observed in Brazil following changes in government (Silva Junior et al., 2021; Rodrigues, 2023). This has led to calls for the introduction of dynamic baselines, with some newer standards bodies such as Isometric, adopting dynamic baselines within F-NCS methodologies (Isometric, 2024). Despite the potential benefits of dynamic baselines, we acknowledge that it may not always be feasible to use them due to lack of appropriate data, high variance in the matching variables, or inability to find good matches, especially in regions with high deforestation, where the only non-deforested areas are already protected.

For ARR projects, the baseline scenario is usually relatively simple to determine: the forest has already been disturbed or clear cut, and the baseline scenario is often business-as-usual. For this reason, ARR projects have typically made before-after comparisons of carbon stocks, without comparing against counterfactual sites. Some protocols specify that project areas must have been unforested for the 10 years preceding the project, with very limited chance of recovering without project activities (e.g. Gold Standard, 2020). An issue with this approach is that landowners who periodically clear woodlands naturally establishing on their economically marginal farmland are ineligible to receive carbon credits and have no incentive to protect, rather than clear, these early successional forests. This is likely shortsighted as natural establishment is a potentially low cost and effective option for sequestering carbon (Chazdon et al., 2016; Brancalion et al., 2024). The lack of counterfactual comparisons in early ARR projects also make it more challenging to incorporate natural regeneration in project areas, as the more simplistic before-after comparison makes a de-facto assumption that all carbon sequestered within project areas is additional. However, this thinking is beginning to be challenged with more complex ARR methodologies which use counterfactual sites being introduced such as Verra VM0047, and Isometric Reforestation methodologies (VCS, 2023b; Isometric, 2024).

3.2. Research advances

Recognition of the need for robust counterfactuals has driven the rapid development of more sophisticated “causal inference” or “quasi-experimental” approaches for project evaluation. These approaches are statistical methods that create comparable groups for causal inference in observational studies where randomisation is not possible (Ferraro, 2009). Developed for econometric analysis in the 1960s, matching

approaches have become widely used to assess the impacts of conservation and sustainable development programmes, such as the effectiveness of protected areas and payments for ecosystem services schemes (Ferraro et al., 2015; Oliveira Fiorini et al., 2020). In the context of REDD+ this means identifying areas that are under similar levels of threat from deforestation as the project (Ferraro et al., 2015; Oliveira Fiorini et al., 2020), whereas for ARR projects this means identifying areas with a similar likelihood of undergoing restoration. These include approaches that (a) match pixels (or clusters of pixels) within project areas with pixels in the surrounding landscape that face a similar risk of deforestation and (b) matching a few project-size patches (synthetic controls). An overview of causal inference approaches are provided in Supplementary Information. A study that included 43 REDD+ projects showed that these causal inference approaches on average produced only 22 % of the carbon credits generated by first-generation VCS methods, suggesting that project developers have previously made methodological decisions that advantaged the projects financially by issuing more carbon credits than was justified (Haya et al., 2023; Swinfield et al., 2025), suggesting that integration of these approaches into VCM methodologies is warranted.

3.2.1. Integrating causal inference approaches into the VCM

Verra's VM0048 is a new, consolidated methodology, focusing on standardizing how deforestation risk and project baselines are determined to improve transparency and integrity in voluntary carbon markets. Instead of letting each project create its own reference region and baseline, VM0048 assigns baselines set at the jurisdictional (region or country) level using satellite-derived risk maps provided by Verra, not by the project developer directly. These risk maps allow for consistent and transparent allocation of crediting baselines across entire regions, helping to avoid inflated emission reductions from optimistic local estimates. Projects submit their specific geographic area to Verra, which then supplies an Activity Data report defining the expected baseline emissions for that area, based on mapped deforestation risk. Actual deforestation (measured by ongoing monitoring) is compared against this baseline to determine the credits issued. Reassuringly, a study of Colombian REDD+ projects found that this risk map approach generated similar estimates of additionality to the pixel- and patch-based approaches described in the supplementary information, i.e. were aligned with other causal inference approaches (Pankhurst, 2025; Swinfield et al., 2025). Jurisdictional approaches are garnering support from academics and businesses to rebuild confidence in F-NCS (von Essen and Lambin, 2021; DeFries et al., 2022; Barata, 2024). Additionally, the ICVCM has recently approved the VM0048 methodology, and Verra has mandated that all its REDD+ projects must transition to it by the end of 2025 (Verra, 2025). Meanwhile, ART TREES v2.0 (Architecture for REDD+ Transactions, 2023) provides an architecture for project-level implementation alongside jurisdictional accounting. These VCM initiatives align well with long-standing United Nations ambition to create a new global carbon market, under Article 6.4 of the Paris Agreement Crediting Mechanism. However, governance issues such as distribution of benefits remain a considerable challenge (Streck, 2021).

Remote sensing is central to the implementation of these emergent approaches for assessing the additionality of REDD+, by producing maps of the drivers of deforestation/degradation risk to be updated regularly (Sims et al., 2025), as well as tracking carbon stocks through time (as reviewed above). To give one example of driver mapping, roads are among the strongest predictors and primary facilitators of forest loss, especially in tropical regions, with road expansion opening previously intact and remote forests to a range of destructive activities. Recent studies have achieved significant progress in mapping small roads in tropical regions using remote sensing, overcoming previous obstacles related to dense vegetation, persistent cloud cover, and the subtlety of informal routes (Sloan et al., 2024). Specifically, application of convolutional neural networks to high-resolution satellite imagery to automatically detect both legal and illegal roads in tropical forests

reveal much greater road networks than official records indicated (Slagter et al., 2024).

New remotes sensing approaches are also making their way into ARR methodologies. VM00047 now addresses the challenge of monitoring carbon stock change by allowing project developers to use remotely sensed “stocking indices” as proxies for AGB, provided these indices’ correlation to field measurements is rigorously demonstrated. This is illustrated by a recent approach to monitoring land-use transitions, such as converting degraded pastures to species-rich agroforestry. TESSERA is a geospatial foundation model that derives embeddings: multidimensional features generated using deep neural networks from timeseries of Sentinel 1 and 2 imagery (Feng et al., 2025). These embeddings were used in combination with GEDI LiDAR height metrics and random forest regression to construct a stocking index. This index, after validation and calibration with in situ biomass data from multiple agroforestry sites, demonstrated superior performance to several leading global canopy and AGB products. Ultimately, this advancement exemplifies the shift under VM00047 towards scalable, transparent, and accurate carbon monitoring frameworks that are fully aligned with the capabilities of today’s Earth observation and machine learning technologies.

4. Leakage in F-NCS

4.1. Current approaches

Leakage – the displacement of economic activities away from a project area – significantly undermines climate benefits (Filewod and McCarney, 2023; Daigneault et al., 2025). Its impacts are often underestimated, leading to up to 70 % over-crediting of REDD+ credits (Filewod and McCarney, 2023). Local leakage, often termed ‘activity shifting’ leakage, occurs when subsistence activities, such as swidden agriculture, move immediately outside project boundaries (Streck, 2021). Market leakage arises when deforestation is displaced to other regions, potentially geographically distant, due to reduced commodity supply. For example, the Soy Moratorium in the Brazilian Amazon reduced soy-related deforestation but led to increased production in the Cerrado region about 1000 km away (Magalhães et al., 2020). The complexities of global supply chains, and the difficulties of attribution to specific projects within a jurisdiction complicates efforts to address leakage comprehensively (Meyfroidt et al., 2020; Streck, 2021). For ARR activities, market leakage is less likely, as the probability that ARR projects will take place in areas producing commodity crops on a commercial scale is low, due to high opportunity costs. Indeed, Gold Standard does not even account for market leakage in their methodology (Gold Standard, 2023). However, the exception is reforestation of low-productivity grazing lands used to rear beef cattle, which could lead to market leakage (i.e., displacing cattle rearing to newly deforested areas) unless it is associated with sustainable intensification of production. Sustainable intensification is possible where cattle ranching occurs at very low densities, such as in the Brazilian Atlantic Forest, where even moderate intensification could free up large areas of land for other uses (da Silveira et al., 2022).

Currently the VCM suggest that projects undertake leakage mitigating activities, but they are not obligatory and there are limited requirements to quantify their efficacy (Streck, 2021). Mitigation actions can include economic opportunities for locals that would reduce conversion (e.g. employment outside of forestry), sustainable increases in production of agricultural crops or timber resources to meet local demand or helping communities to secure land tenure which may incentivise land holders to reduce clearance (e.g. VCS, 2014). F-NCS projects are required to quantify the carbon emissions associated with local leakage, based on the assumption that any mitigation actions will reduce the rate of leakage. For both ARR and REDD+ projects, across standards bodies, relatively similar approaches are used to quantify local leakage. Understanding of the spatial dynamics of pre-project activities and the

likely area where leakage will take place is necessary to calculate leakage emissions. Certifiers assume projects have some knowledge of where leakage will occur, but this is challenging due to displacements beyond national boundaries, time lags in supply responses and the effects of a single project not being large enough to be noticed at a market-level (Henders and Ostwald, 2012; Streck, 2021). Furthermore, evidence for justifying leakage claims is often minimal, with many projects using the lowest possible discount factor available (Atmadja et al., 2022; Filwod and McCarney, 2023).

4.2. Improving leakage estimation and mitigation in the VCM

Improvements to quantification of local leakage can be achieved via quasi-experimental pixel matching approaches, such as those outlined in Section 3 and supplementary information. Such approaches have been used to quantify carbon losses resulting from local leakage in REDD+ projects certified under the VCS (Guizar Coutiño, 2023), and are reliant on RS data to identify suitable leakage counterfactuals and track land use change through time. The key difference between using such approaches for leakage estimation rather than additionality, is that matches are made between a pre-defined leakage belt around a project area, and its surrounding landscape (Guizar Coutiño, 2023). Another proposed enhancement for addressing market leakage is adopting a jurisdictional approach (Seymour, 2020; VCS, 2023c), as leakage associated with deforestation is captured in national greenhouse gas accounting (Streck, 2021). However, this method faces challenges. For instance, cross-boundary shifts in deforestation have been observed after implementing national forestry policies that restrict timber harvesting (Meyfroidt and Lambin, 2009), meaning jurisdictional approaches may not capture all market leakage and cross-jurisdictional approaches may be needed. Additionally, these approaches apply primarily to avoided deforestation activities transitioning to jurisdictional methods (e.g. VM0048; VCS, 2023c) and are not suitable for ARR projects where jurisdictional approaches are not being considered. To address the trans-boundary nature of market leakage modelling approaches, rather than purely remote sensing derived approaches, may show more promise, approaches using Global Timber models and GTAP (Global Trade Analysis Project) models have both been used to quantify leakage due to market shifts (Villoria et al., 2022). These approaches may improve carbon accounting in the face of leakage, but do not address the underlying causes of the problem. Efforts are being emerging to improve leakage mitigation in ARR projects such as the Verra ABACUS label, launched in 2023, which combines dynamic additionality baselines with stronger constraints on avoiding displacement of food production to mitigate leakage (Verra, 2024).

Building sustainable development into REDD+ and ARR projects benefits local people and reduces the chance of leakage. For example, crop yields produced by subsistence farmers are often well below what is possible (van Ittersum et al., 2016), so providing with higher-yielding crop varieties and agronomic training could spare land for reforestation (Phalan et al., 2016; Woittiez et al., 2017). Similarly, fuel-efficient stoves can reduce wood consumption if charcoal production drives deforestation (Bensch et al., 2021). A considerably body of recent work demonstrates that remote sensing can be used to accurately measure certain aspects of human development, especially economic well-being (Wang et al., 2025), which correlates with local leakage through the environmental Kuznets curve (Caravaggio, 2020). However, remote-sensed indices can be inaccurate, and indices trained in one geography may generalize poorly. Thus, field based evaluation of the effectiveness of sustainable development programmes linked to carbon credits are needed.

5. Durability of F-NCS

5.1. Current approaches

Carbon stocks in forest ecosystems are at risk of depletion due to degradation or land-use conversion, potentially releasing previously sequestered carbon. This vulnerability raises concerns about the continued additionality of F-NCS projects, as significant carbon losses may occur, jeopardizing their intended impact. Currently, to mitigate the risk of non-durability, F-NCS projects typically allocate 20 % of their generated credits to a *buffer pool*, which serves as insurance against future reversals, such as small fires within the project boundary (Gold Standard, 2023, Plan Vivo, 2024). In such circumstances projects are required to ‘pay back’ these emissions into the buffer pool using unsold credits. If reversals occurred during the project’s life, buffer credits are cancelled from the pool to cover those losses, safeguarding buyers from non-permanence risk.

The simplicity of the buffer pool approach makes it appealing for the VCM; however, this approach has two significant flaws. Firstly, it assumes that people living in or around the project area, including people who migrate into a project area, will maintain tree cover without financial incentives past the end of the project (Balmford et al., 2023a). Secondly, after catastrophic events such as wildfires, there may be insufficient credits in the buffer pool, essentially meaning high-risk projects may need to buy credits from lower-risk projects, effectively requiring lower-risk projects to compensate for higher-risk ones. California’s experience illustrates these limitations, with wildfires depleting 20 % of the total buffer pool and 95 % of the wildfire-specific pool in less than a decade (Badgley et al., 2022a). This rapid depletion challenges the effectiveness of buffer pools in ensuring long-term carbon storage, especially in fire-prone regions, and suggests that changes are needed to build confidence in nature-based carbon credits.

Several factors increase the risk of non-durability. Firstly, ARR projects need to persist for decades to sequester substantial carbon (Poorter et al., 2016). However, regenerating forests are often at high risk of re-clearance at relatively young ages (Reid et al., 2019). In Latin America alone, an estimated 4.15 million hectares of regenerating forest were re-cleared between 2000 and 2014, representing 70 % of all regenerating forests (Schwartz et al., 2020). Secondly, climate change poses significant challenges to the durability of carbon storage in F-NCS projects, as increasing disturbance rates from drought, fire, and storms, lead to widespread tree mortality (Anderegg et al., 2020) and heightened risks of reversals. While climate change can contribute to non-durability, ARR and REDD+ projects can still offer climate benefits if carbon releases are accounted for and do not exceed additionality (Balmford et al., 2023b; Rau et al., 2024). Finally, anthropogenic factors significantly influence project durability, as human interactions in forest landscapes create variability in outcomes (Gregorio et al., 2020; Nerfa et al., 2021). Evidence suggests, that in the case of restoration, social rather than ecological factors, are more important in determining durability (Nerfa et al., 2021), emphasizing the need for ARR activities to address local community needs to incentivise long-term maintenance of forest cover.

5.2. Improving durability assessment in the VCM

There is a clear need to improve on the current buffer pool approach used across the VCM, which is out of step with the risk to forest cover in the coming decades (Anderegg et al., 2020). Recent research has suggested that a better approach would be to consider F-NCS credits as impermanent, acknowledge the benefits of impermanent carbon storage and build mechanisms to account for potential reversals (Matthews et al., 2022). Non-durability of nature-based carbon credits can be measured by continuing to monitor –after project funding has ended – any changes in carbon stocks in project areas compared to carefully matched counterfactual sites, enabling the quantification of any subsequent reversals over time. Non-durability is quantified as a decline in

this additionality through, for example, deforestation or fire; these events can thus be precisely dated and measured using remote sensing technologies. This dynamic, data-driven approach means that non-durability can be quantified retrospectively (Balmford et al., 2023b; Matthews et al., 2023). The complication, though, is that non-durability must be factored into the up-front price because these credits may only deliver climate benefits temporarily before the stored carbon is eventually released due to events like deforestation and fire. To ensure that the price reflects the true, time-bound climate value, the market could use the concept of “equivalent permanence” which discounts the value of temporary carbon storage relative to permanent sequestration (Rau et al., 2024). This is done by forecasting potential future reversals and reducing the credit’s value according to the expected social cost of these releases. By pricing in the risk of reversal and “discounting” the future release, the up-front cost of an impermanent credit fairly reflects its adjusted climate benefit compared to a durable offset option. This is a modelling rather than remote sensing approach (Balmford et al., 2023b), nevertheless RS data is fundamental input data for modelling across project landscapes and therefore is essential to predict the likely durability of F-NCS projects.

An alternative approach is to make F-NCS carbon credits valid for a fixed period (e.g. 10–20 years) and stipulating that buyers must purchase credits again, if they wanted to ensure emissions are fully offset (Hunnable et al., 2024). These repeat purchases would either be buying more F-NCS carbon credits or permanent carbon credits, from technological carbon drawdown projects such as direct air carbon capture and storage (DACCS). This approach has several benefits. Firstly, if future purchases were for technological credits this would provide an additional 10–20 years to develop the technology to help reduce implementation costs and increase supply (Küng et al., 2023). Secondly, in another 10–20 years several international commitments to halt deforestation (UKCOP26, 2021) and restore large areas of land (Sewell et al., 2020) should be well underway, and the VCM would be far more developed in terms of the methodologies. Therefore the ‘early’ VCM nature-based credits being issues now, which are relatively cheap (World Bank, 2023) but have more uncertainties related to durability, should be superseded by high quality credits that are developed within a very different land use change policy landscape, and could have greater assurances of being durable. However, there are also challenges for this approach. There is no real mechanism to force buyers to repurchase credits. Further, even if legal frameworks were developed to ensure repurchase, one cannot guarantee credit purchasing entities will continue to exist, so the responsibility for repurchasing becomes unclear. Unless this issue is resolved F-NCS might simply be removed from VCMs because they are regarded as risky investments compared with engineering solutions.

6. A case study: contributions of remote sensing to evaluating the effectiveness of the Gola REDD+ project

Gola Rainforest National Park (henceforth Gola) in Sierra Leone is one of the largest remaining tracts of mature lowland moist forest in West Africa, covering an area of approximately 750 km² (Fig. 2a). It represents a critical habitat for biodiversity conservation: hosting over 60 threatened species, including chimpanzee and pigmy hippo, and over 160 tree species; Gola also stores and sequesters significant carbon (Lindsell and Klop, 2013). Natural forests in West Africa are under immense threat: deforestation rates are double the tropical average, attributable largely to expansion of cacao production and swidden agriculture (Goldman and Weisse, 2024). The landscape around Gola is predominantly used for shifting agriculture on nutrient poor soils, involving the creation of small fields that are cultivated for just a few years before abandonment and gradual succession back to forest (Fig. 2b). Biodiversity conservation work began in 2004, supported entirely through donations. In the hope of securing more long-term support for conservation and sustainable development, two charities

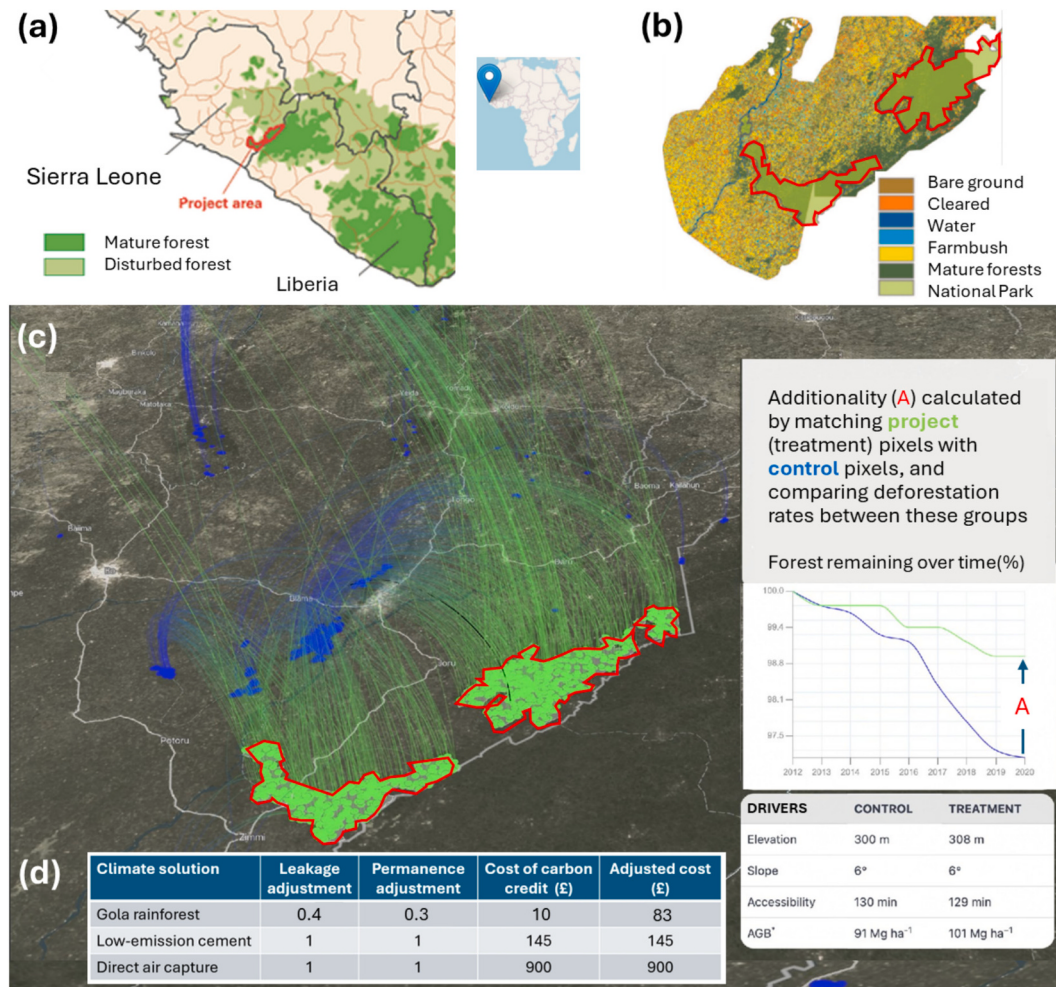


Fig. 2. The Gola REDD+ project in Sierra Leone illustrates several of the concepts discussed in this review. (a) This carbon-dense and biodiverse remnant of rainforest sits within the increasingly human-dominated landscapes of West Africa; (b) outside the boundaries of Gola, the land is largely used for shifting agriculture and cacao production; (c) additionality and leakage associated with the REDD+ project can be assessed used pixel-matching approaches; along with forest carbon density measurements made by GEDI, a space-borne lidar sampler; (d) the cost of each carbon credit needs to be adjusted upwards from market prices based on older approaches, in recognition that recently employed matching approaches tend to generate fewer carbon credits and that adjustments are needed to account for local leakage and the likely non-durability of nature-based climate solutions; note that values given in this table are illustrative only. An advantage of this approach is comparability of prices against other climate change mitigation solutions such as low-emission concrete and direct air capture.

partnered with the Sierra Leonean government to create a not-for-profit company, which aimed to generate income through a REDD+ programme registered with Verra. The project began in 2012 and is scheduled to continue until 2042 (RSPB, 2021). To measure carbon stores using VCS methodologies, a network of 639 forest plots (each 0.125-ha) was established in 2006 (Lindsell and Klop, 2013). Using the Verra standard, it was estimated that the project would generate 439,000 carbon credits per year within its first decade (RSPB, 2021).

The Gola REDD+ project has worked closely with remote sensing scientists, advancing approaches for the mapping of LULC mapping, forest biodiversity, forest disturbance and carbon. Neural networks were used to create accurate land cover maps, based on high-resolution optical imagery combined with L-band SAR imagery (Vaglio Laurin et al., 2013) while spectral unmixing approaches were used to map the complex land uses around Gola (Lui and Coomes, 2015). In addition, an ALS and hyperspectral survey, conducted in 2012, provided opportunities to evaluate cutting-edge high-resolution approaches. These studies showed that forest carbon can be mapped with greater accuracy if hyperspectral data is used alongside well-developed lidar approaches (Vaglio Laurin et al., 2014b). About a third of Gola was selective logged in the 1960–1990 period and, although detailed records had been lost, the

legacies of logging persist (Lindsell and Klop, 2013). Airborne lidar is effective at detecting now-subtle differences in forest structure between intact and logged forests (Kent et al., 2015) and hyperspectral imaging can map tree species richness, opening new opportunities to track ecological recovery through time (Vaglio Laurin et al., 2014a). However, given the prohibitive costs of airborne lidar and hyperspectral surveys, the adoption of these cutting-edge approaches has thus far been limited in the VCM, although airborne remote sensing has played a vital role in calibrating spaceborne sensors such as GEDI (Duncanson et al., 2022).

The Canopy PACT Tropical Moist Forest methodology (see Section 5.2 for overview and Balmford et al. (2024) for details) uses a combination of remote-sensing, causal-inference and risk-analysis approaches to generate estimates of additionality, local leakage and the consequences of non-durability (Fig. 2.c). For additionality calculations, Canopy PACT uses pixel-based within-country matching, based on pairing control and project pixels that have similar deforestation pressures, based on seven well-recognised drivers of deforestation (Fig. 2.c). Avoided deforestation is calculated by comparing deforestation rates within these matched pixels, using the TMF land cover product (Vancutsem et al., 2021) of the wet tropics as the source of deforestation

data (see time series in project and control pixels in Fig. 2.c). Emissions reductions are then calculated by multiply the average forest carbon stock, based on foot-print-level biomass estimates from GEDI (Dubayah et al., 2022). A similar approach is used to estimate local leakage, this time matching forested pixels in the project's buffer area with pixels under similar deforestation pressure across the wider landscape; leakage reduces the number of carbon credits produced by a project (i.e. the leakage adjustment of 0.4 in Fig. 3.d, which is illustrative). Under the pessimistic scenario that, once the REDD+ project ends in 2042, deforestation will accelerate to twice the rate observed in counterfactual pixels, the Canopy PACT approach is able to make a further adjustment to accommodate the impacts of non-durability, based on financial-risk analysis approaches (i.e. the non-durability adjustment of 0.32 in Fig. 2.d, which is also illustrative). Significantly fewer carbon credits tend to be generated by applying the Canopy PACT methodology than issued by VERRA using its standards. The hope is that purchasers of carbon credits will have greater trust in these methodologies, translating into a willingness to pay considerably more for each carbon credit (Fig. 2.d). Preliminary analyses based on these approaches suggest that carbon credits generated by F-NCS are often cost effective than engineering solutions such as direct air capture and reduced-emissions

concrete production (Swinfield, 2023), and deploying these solutions now is far cheaper than repairing the damage caused by greenhouse gas emissions later Balmford et al. (2024).

Sustainable development within a buffer zone around Gola is a central aim of the REDD+ project. Socio-economic impacts have been evaluated using a BACI framework: the treatment group comprised 126 communities within the 4-km buffer zone around Gola (Malan et al., 2024). The control group comprised 328 communities that are 4–20 km from the park boundary. For control and treatment groups, deforestation statistics taken from the Hansen maps and aggregated to village level (Wilebore and Coomes, 2016) were compared for the period 2001–2018, covering before and after the REDD+ project started in 2014. Household survey data was collected in before and during the project's implementation, from REDD+ and non-REDD+ communities. By examining forest loss in eight other protected areas in Sierra Leone, the study confirmed that Gola is successful at reducing deforestation. It also reduced deforestation in buffer zone communities by 30 % compared to control areas. The program appears to have shifted labour away from forest-clearance-dependent farming by increasing the value of alternative income sources like cacao and other non-timber forest products. The social survey revealed no significant impact on economic wellbeing or conservation attitudes, which may reflect the relatively modest income generated from the sale of carbon credits, particularly after the administrative costs are factored in.

The Gola case study highlights opportunities for transforming voluntary carbon markets using emergent technologies but also identifies some significant challenges. Remote sensing technologies are rapidly advancing on multiple fronts. It is not clear which products are best in which circumstance, and we should recognise that different approaches will generate different numbers of carbon credits. Unfortunately, this means that “standards” which are supposed to underpin the market become outdated and outmoded as technology improves, as happened with Verra standards (West et al., 2020). Further, we must recognise that additionality and leakage calculations are fundamentally modelling exercises attempting to understand what would have happened in the absence of a project, and as such are sensitive to arbitrary choices made in the modelling process. We now know that additionality calculated by various matching approaches are more consistent with one another than they are with legacy Verra methodologies (Swinfield et al. In review) but differences can still be substantial. Unfortunately, the VCMs have given insufficient thought to these problems.

7. Discussion

The Voluntary Carbon Market (VCM) aims to channel private finance towards F-NCS activities to mitigate climate change while providing co-benefits for biodiversity and livelihoods. Although the VCM alone cannot fully address climate change impacts, the emission reductions and removals it facilitates can create a viable path to decarbonization, allowing more time for phasing out fossil fuels and reducing peak warming (Griscom et al., 2017; Girardin et al., 2021). To achieve these goals, emissions from F-NCS projects must result in real changes on the ground (Greenfield, 2023; West et al., 2023). In this review we have assessed the limitations of existing VCM methodologies and outlined the latest research advances which have potential to improving on the *status quo*.

Recent research has revealed over-crediting in REDD+ projects (West et al., 2020; West et al., 2023), emphasizing that more statistically robust methods such as pixel matching can enhance project monitoring (Guizar-Coutiño et al., 2022). Current VCM methodologies are also likely to underestimate leakage (Atmadja et al., 2022; Filewod and McCarney, 2023), and the buffer pool approach is inadequate for addressing non-durability (Badgley et al., 2022a). Certifiers are updating methodologies in response to these issues (e.g. VCS, 2023c, b). However, most of the developments have been around baseline setting and selection of reference areas; other areas of project monitoring,

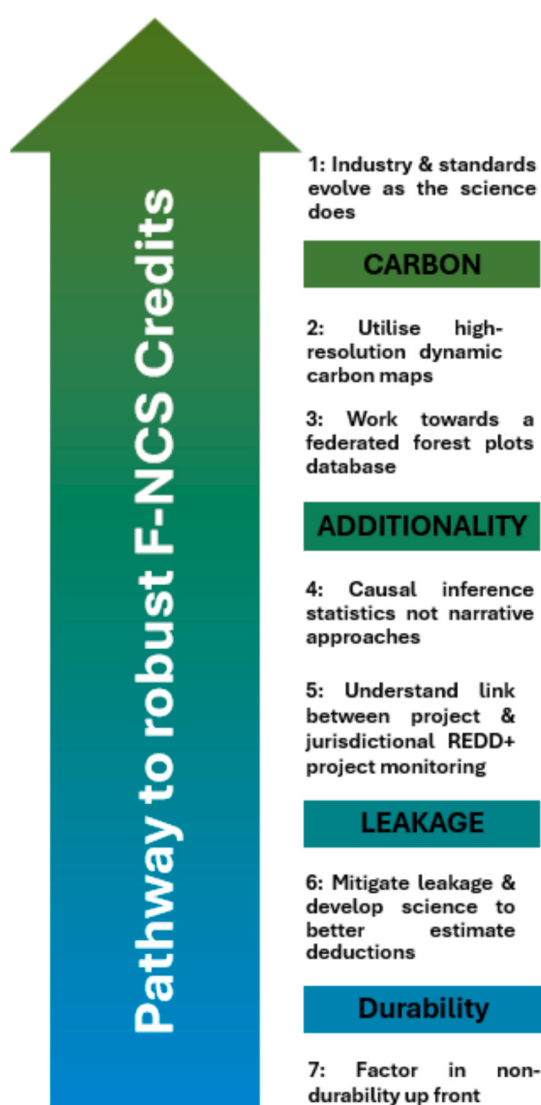


Fig. 3. Recommendation for improving F-NCS project monitoring and better incorporating scientific advances for carbon, additionality, leakage and permanence.

including carbon estimation, leakage and permanence, have not received the same level of attention within methodologies, with scientific advances outpacing developments. Furthermore, whilst recent Verra methodologies (e.g. Verra's VM0047 & VM0048) both update baseline setting using more dynamic approaches, they have tackled baselines in very different ways, with REDD+ methodologies moving towards jurisdictional approaches and ARR methodologies using a project level approach, making integration of REDD+ and ARR activities across a region challenging.

The issue of over-crediting is one of the biggest hurdles that needs overcoming to improve accuracy in F-NCS project monitoring. Most criticism so far has been related to poor baseline setting (Section 3.1) and how broad rules allow for 'gaming the system' (Seyller et al., 2016). Recent research suggests that using impact evaluation techniques such as pixel matching (Schleicher et al., 2020) are likely the most promising approach for accurate assessment of project carbon impacts (Swinfield et al., 2025) and are also compatible with dynamic baseline approaches (Section 3.2). Here we provide a set of recommendations for project developers and standards bodies-and, to a lesser extent, credit purchasers-outlining how to improve monitoring of F-NCS projects by embracing recent advances in remote sensing, computer science and statistics (Fig. 2). These recommendations are not designed to comprehensively capture all areas that require development, but rather highlight specific points where we feel scientific advancements and technology are able to make useful contributions.

7.1. Co-evolution of standards and science

1) Industry & standards that evolve as the science does: We recommend that the VCM community adopt a structured approach to integrating emerging insights from academic and space agency research, ensuring that standards evolve in line with robust and maturing evidence. Specifically, VCM methodologies should explicitly recognise that F-NCS projects extend beyond carbon metrics and must incorporate co-dimensions such as albedo, disturbance dynamics, below-ground processes, and leakage (Ellis et al., 2024).

Where the evidence base is already strong, e.g. satellite-derived assessments of albedo (Hasler et al., 2024; Healey et al., 2025), methods should be updated without delay; in areas where near-term advances are imminent, such as remote sensing of degradation (Holcomb et al., 2024), frameworks should be prepared for rapid integration; and in domains where evidence is still contested, such as methane fluxes (Gatica et al., 2022; Gauci et al., 2024) and impacts of trees on below-ground processes (McKinley, 2019; Friggens et al., 2020), methodological caution and ongoing review are necessary.

Given that global-scale leakage estimation demands complex system models beyond the capacity of individual projects (Daigheault et al., 2025), these issues should be addressed collaboratively at the standard-setting level rather than through project-level requirements that push additional costs onto project developers. To ensure credibility and trust, REDD+ needs to forge alliances similar to the one Symbiosis has formed for ARR (Symbiosis Coalition, 2025). Organisations such as the ICVCM should establish scientific boards to define when a topic is sufficiently mature for incorporation into crediting methodologies, while also committing to parity in scrutiny between F-NCS and engineering-based removals.

As new digital monitoring, reporting and verification tools are deployed, their quality, comparability, transparency, and *ex-post* consistency must be guaranteed through clear protocols for benchmarking, disclosure of assumptions, and independent evaluation, ensuring that methodological evolution strengthens, rather than undermines, confidence in the market. We recognise the challenge here; regular revision of standards could be expensive and confusing. But we believe that evolution of standards is more feasible than ever as the standards bodies shift to using automated approaches to estimated carbon credits, so the

burden on individual project developers and implementers should be minimal. In response, we hope that the carbon credits market will respond by increasing the base price of carbon credits to reflect the additional methodological trust, thereby paving the way for making new F-NCS project development feasible to meet our global goals.

7.2. Carbon monitoring

2) Carbon standards bodies should adjust methodologies to accommodate high-resolution dynamic carbon maps for the estimation of project impacts. There is increasing adoption of RS derived carbon products within VCM methodologies (e.g. VCS, 2015), particularly by newer standards, such as Isometric, who are promoting the use of LiDAR to quantify forest carbon stocks (Isometric, 2024). However, many methodologies remaining reliant on field based estimated of carbon stocks (e.g. VCS, 2023b), despite considerable research developments in the field of carbon mapping (Xu et al., 2025). There is now a wealth of carbon mapping products available both regionally and globally (Table 1) and ideally development of the carbon mapping sector would involve globally accessible, open-source products, produced annually, justified by their foundation in publicly funded research and their role in serving the common good. However, the current landscape is characterized by commercial providers filling this niche through proprietary, potentially incomparable, services, such as Planet (Planet Lab, 2024), CTrees (Reiner et al., 2022), and Space Intelligence (Space Intelligence, 2024). This arrangement may be acceptable provided that oversight resides with independent accreditation bodies such as Sylvera (Sylvera, 2023), rather than commercial developers or certification standards, and robust mechanisms exist for independent validation of resulting products. The critical imperative lies in establishing autonomous verification systems to assess the quality and accuracy of these RS carbon products, utilizing established validation methods such as plot-based and LiDAR measurements (Duncanson et al., 2021). However, significant questions remain regarding the institutional responsibility and financial mechanisms necessary to implement such comprehensive validation frameworks.

3) Creating a federated database for calibrating and validating remote sensing products: Currently, field data availability is uneven; for instance, the ESA Biomass maps were calibrated with only 630 plots in South America versus 84,000 in Europe (Santoro et al., 2021). Additionally, existing national forest inventories often focus on undisturbed forests, limiting their applicability for recovering ecosystems. However, substantial volumes of forest plot data are being collected in F-NCS projects that are typically not open-access but could contribute significantly to development of mapping products. While sharing sensitive data can be complex, remote sensing methods necessitate field data for calibration and validation (Duncanson et al., 2021). Sharing these across the VCM through a loose federation would help reduce map uncertainties. Field data could be compiled into federated databases, where project proponents retain ownership of data but others are able to request access. This would allow for industry and researchers to enhance models of carbon stock change and land use change dynamics. Standards bodies already make data related to project information and credit issuance publicly available in repositories, therefore a starting point would be including details of field data available for projects with details of how to request access.

The EO community is establishing principles for federation driven by the scale of the datasets (Mohr et al., 2025), and similarly site-specific data is being compiled into more comprehensive databases to enable large scale analysis of forest change by the scientific community. For example, the open-access ALS-derived Global Canopy Atlas will be foundational for testing and training next-generation satellite products (Fischer, 2025). Global initiatives have also generated open-source

wood density database (Zanne et al., 2009), and allometry databases for estimating AGB from stem dimensions and canopy dimensions (Jucker et al., 2022). Finally, the new PANGAEA initiative is committed to collecting tropical forest plot data and making it openly available (Ordway et al., 2025). Therefore, compilations of calibration and validation data is gaining traction, but should not just be led by the scientific community. Whilst integration of field data into accessible databases is challenging, requires funding and an organisation driving action forward, there are strong arguments to encourage its development for the overall good of the VCM.

7.3. Additionality

4) **Use causal inference statistics not expert-led approaches.** For project level monitoring, a shift away from narrative-based determination of project baselines, which are open to exploitation (Seyller et al., 2016), towards more statistically robust approaches is required. We recommend that VCM methodologies remove loopholes that allow for projects to select favourable baselines and specify that projects must select reference areas using statistically rigorous methods. Causal inference approaches are one option for more statistical selection of baselines and quantification of project additionality, but as highlighted in Section 4.2 also have potential application in assessing activity-shifting leakage. Positive steps are being made by standards to adopt such techniques. Both the Verra VM0047 methodology, through its “performance benchmark” (VCS, 2023b), and the Isometric Reforestation protocol (Isometric, 2024) incorporate counterfactual baseline setting, promoting the use of matching approaches in ARR project, which represents a significant advancement on previous methodologies,

However, most research into causal inference approaches, in relation to the VCM, has focused on REDD+ projects (West et al., 2020; Guizar-Coutiño et al., 2022; West et al., 2023; Swinfield et al., 2025), with little research into their application in ARR projects. The adoption of such approaches for ARR aims to address the issue of projects historically attributing all carbon gains directly to a project, without accounting for underlying recovery happening across the landscape, which risks overestimating additionality if spontaneous natural regeneration occurs in the surrounding areas. However, there are challenges in implementing causal inference approaches in ARR projects relates to data required to identify counterfactuals. For example, land tenure data is important in determining the eligibility of land for reforestation but rarely covers entire jurisdictions and isn't frequently updated (Sparovek et al., 2019). The location of other ARR activities is also needed to remove them as potential counterfactual sites, however, comprehensive ARR project polygon databases are non-exhaustive as data is not always open source. The existing databases of NCS projects (e.g. Karnik et al., 2024) are a good starting place, but continual updating is required to ensure they don't become obsolete. This requires more standardised publication of project polygons on standards registries alongside project documentation so all relevant data is available. Additionally the research community could support the industry by deepening understanding of causal inference approaches in the context of ARR.

Whilst we advocate for the use of causal inference approaches for ARR project monitoring, we also caution against the potential perverse disincentives for adoption in areas with high rates of natural regeneration. Natural regeneration is one of the most effective carbon removal approaches, in terms of available area (Williams et al., 2024), carbon sequestration (Lewis et al., 2019) and cost effectiveness (Busch et al., 2024). Yet, these “easy wins” are often overlooked in the VCM due to misalignment with methodologies (Brancalion et al., 2024). For example, regions like Brazil's Atlantic Forest have abundant naturally regenerating forests, presenting significant opportunities for recovery (Siminski et al., 2021). Unfortunately, landowners often clear young regenerating forests to maintain payments from agri-environment

schemes and avoid land reclassification as conservation areas. However, current carbon project requirements mandate that land must be deforestation-free for ten years to qualify as ARR projects (e.g. VCS, 2023b), excluding these regenerating forests, providing no financial alternative to land holders. Further work is needed to better facilitate the inclusion of such landscapes into ARR project areas.

5) **Advance understanding of the interaction between project level and jurisdictional REDD+ baselines:** REDD+ methodologies are increasingly shifting towards jurisdictional approaches instead of project-level monitoring. This shift removes the responsibility of selecting baseline reference areas from individual projects, reducing the risk of manipulation that could inflate project impacts (Rifai et al., 2015). Additionally, it ensures that REDD+ activities within the VCM comply with Article 6 of the Paris Agreement (UNFCCC/CDM, 2015), allowing parties to engage in decarbonisation efforts while maintaining consistency among projects and preventing double counting (Seymour, 2020).

Significant progress has been made in the implementation of jurisdictional REDD+ frameworks. Initiatives like Verra's REDD methodology VM0048, assigns baselines by calculating forest loss rates and generating deforestation risk maps. Despite this progress the integration of project-level REDD+ initiatives with dynamic baselines into these jurisdictional REDD+ frameworks presents fundamental methodological challenges, as jurisdictional baselines—constrained by the practical impossibility of constructing credible counterfactuals for large administrative units—necessarily remain static, while sub-jurisdictional projects may employ adaptive baseline methodologies. This asymmetry creates a complex reconciliation problem because dynamic project baselines must ultimately aggregate and align with fixed jurisdictional reference levels (Alvarez Campo and Stokeld, 2025). Whilst there has been some comparison between estimated deforestation rates using jurisdictional baselines and causal inference approaches (Tosteson et al., 2024) it is far from comprehensive, therefore further research efforts are needed to understand the correspondence between approaches. The nested architecture of project to jurisdictional level accounting requires novel mechanisms to balance the flexibility needed for effective project-level incentives against the accountability demands of jurisdictional commitments.

7.4. Leakage

6) **Designed projects to mitigate leakage and develop science to estimate leakage deductions where needed.** Recognising that leakage impacts are currently underestimated (Streck, 2021; Filewod and McCarney, 2023), we recommend that VCM methodologies make leakage mitigation actions compulsory rather than advisory, providing a clear pathway to reduce emissions displacement instead of merely quantifying leakage impacts. Building leakage mitigation into project design, requires projects to firstly, assume an upper bound of estimated leakage risks, which in practice may be 100 % (Filewod and McCarney, 2023). Secondly, quantify the current level of production, within a project and undertake actions to compensate fully for that foregone production, which would address both activity-shifting and market leakage concerns. However, such actions may be more effective in areas dominated by subsistence activities, where yield gaps can be addressed (Belachew et al., 2022) or through agroforestry practices that enhance sustainability and farmer income whilst maintain production (Thorlakson and Neufeldt, 2012). Finally, where full mitigation of foregone production is not possible, such as where commercial production (e.g. timber) is being reduced, improved analytical tools are needed to assess leakage impacts. For activity shifting leakage, this is where the use of remote sensing is most applicable in combination with higher-quality remote sensing and quasi-experimental approaches (e.g.

Guizar Coutiño, 2023), to identify where shifts in landcover have occurred. However for market leakage, modelling approaches, which account for how shifts in supply will affect market demand are likely the way forward (Daigneault et al., 2025). In theory modelling approaches could capture all forms of leakage making the division between activity shifting and market leakage redundant. However, further research development is needed in this space to address the complex interactions between commodity economics and land use change, in response to needs from the industry.

7.5. Non-durability

7) Factor in non-durability upfront using data driven modelling approaches. The current buffer pool approach used across the VCM appears insufficient to address the risks associated with F-NCS projects. The widely used 20 % deduction of credits is also not associated with actual durability risks in projects, such as those with high fire risk (Badgley et al., 2022a). Rather the buffer pool is used as an insurance policy against any unanticipated reversal. This approach is widely endorsed across the sector including in the IC-VCM's Core Carbon Principles (CCP) which promote high-quality carbon projects, with many standards moving to comply with their CCP (ICVCM, 2024). The CCP emphasizes that GHG emission reductions or removals must be permanent, with any reversals compensated. However, this is only valid within a 40-year monitoring window, and therefore even for projects adhering to the highest integrity standards, the long-term durability of carbon benefits is not guaranteed. This approach undervalues the benefits of non-durable carbon credits and assumes there are no methods available to account for project non-durability, which is not the case. Using a combination of historic RS data on land cover change and economic discounting techniques, it is possible to quantify the equivalent permanence of a F-NCS carbon credit (Section 5.2) and provide a metric to determine how many credits should be purchased to fully offset emissions (Balmford et al., 2023b). F-NCS carbon credits face inherent risks from reversals due to anthropogenic and environmental factors. To enhance confidence in F-NCS credits and achieve higher prices, the VCM needs to shift its approach to durability away from the current buffer pool model. A more detailed understanding of potential future forest losses through modelling is essential (Rau et al., 2024), however, such analysis approaches could be integrated into project validation and verification. If projects were to adopt such approaches and quantify potential future releases, based on data-driven predictive models, it may result in fewer total credits being generated but the resulting credits would be of far high quality as they account for potential non-durability upfront. This is quite a step-change in thinking, moving from the idea of 'permanent' carbon removals to accounting for durability and building it into quantification of carbon credits.

8. Conclusion

Overall, we find that advances in REDD+ and ARR monitoring techniques have been made in recent years, and whilst implementing these is still at the early stages, things appear to be moving in the right direction. However, gaps remain in the quantification of carbon stocks in F-NCS projects and moving forward, better integration of remote sensing bases approaches will likely improve monitoring. Many of the lessons learnt and methodological developments made around REDD+ can also be applied to ARR project monitoring, but emissions removal activities also have a unique set of challenges that need careful consideration. This is in part due to the wider range of activities covered by ARR but a bigger challenge is the monitoring of carbon stock changes in regenerating forests using remote sensing. To scale up ARR, remote sensing is necessary but current methods for quantifying subtle increases in carbon stocks are still developing and not yet being widely adopted by

ARR projects. However, with the advent of new technology, such as TLS, and understanding of what constitutes best practice, integration of remote sensing of carbon stock changes is possible. Rapid shifts in the VCM are likely over the next few years, and therefore this stocktake of the limitations of current methodologies and assessment of promising new methodological advancements can help guide future direction and ensure that vitally needed tropical forest conservation efforts can continue to be implemented.

CRedit authorship contribution statement

Charlotte E. Wheeler: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Felipe Begliomini:** Writing – review & editing, Writing – original draft. **Amelia Holcomb:** Writing – review & editing, Writing – original draft. **Srinivasan Keshav:** Writing – review & editing, Supervision. **Anil Madhavapeddy:** Writing – review & editing, Funding acquisition. **David Coomes:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Perplexity.AI to improve readability. After using this tool/service, the author(s) reviewed and edited the content as needed to ensure content was accurate and take(s) full responsibility for the content of the published article.

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Appendix A. Supplementary data

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Data availability

No data was used for the research described in the article.

References

- Adams, T., Winters, B., Nazareth, A., 2021. Task Force on Scaling Voluntary Carbon Markets. <https://ppp.worldbank.org/public-private-partnership/library/taskforce-scaling-voluntary-carbon-markets-final-report>.
- Alvarez Campo, C., Stokeld, S., 2025. The REDD+ and JREDD+ DataMisalignment: When ForestData Doesn't Add Up. Sylvera. <https://www.sylvera.com/blog/the-redd-and-jredd-data-misalignment> (Accessed: 30/08/2025).

- Anderegg, W.R.L., Trugman, A.T., Badgley, G., Anderson, C.M., Bartuska, A., Ciais, P., Cullenward, D., Field, C.B., Freeman, J., Goetz, S.J., Hicke, J.A., Huntzinger, D., Jackson, R.B., Nickerson, J., Pacala, S., Randerson, J.T., 2020. Climate-driven risks to the climate mitigation potential of forests. *Science* 368, eaaz7005.
- Architecture for REDD+ Transactions, 2023. The REDD+ Environmental Excellence Standard (TREES) Version 2.0 – Executive Summary. https://www.artredd.org/wp-content/uploads/2021/12/TREES-2.0-June-2023-Executive-summary_EN.pdf. Accessed 30/08/2025.
- Asner, G.P., Brodrick, P.G., Philipson, C., Vaughn, N.R., Martin, R.E., Knapp, D.E., Heckler, J., Evans, L.J., Jucker, T., Goossens, B., Stark, D.J., Reynolds, G., Ong, R., Renneboog, N., Kugan, F., Coomes, D.A., 2018. Mapped aboveground carbon stocks to advance forest conservation and recovery in Malaysian Borneo. *Biol. Conserv.* 217, 289–310.
- Atmadja, S.S., Duchelle, A.E., De Sy, V., Selviana, V., Komalasari, M., Sills, E.O., Angelsen, A., 2022. How do REDD+ projects contribute to the goals of the Paris agreement? *Environ. Res. Lett.* 17, 04038.
- Avitabile, V., Herold, M., Heuvelink, G., Lewis, S.L., Phillips, O.L., Asner, G.P., Armston, J., Ashton, P.S., Banin, L., Bayol, N., 2016. An integrated pan-tropical biomass map using multiple reference datasets. *Glob. Chang. Biol.* 22, 1406–1420.
- Baccini, A., Goetz, S., Walker, W., Laporte, N., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P., Dubayah, R., Friedl, M., 2012. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nat. Clim. Chang.* 2, 182–185.
- Badgley, G., Chay, F., Chegwidan, O.S., Hamman, J.J., Freeman, J., Cullenward, D., 2022a. California's forest carbon offsets buffer pool is severely undercapitalized. *Frontiers in forests and global. Change* 5.
- Badgley, G., Freeman, J., Hamman, J.J., Haya, B., Trugman, A.T., Anderegg, W.R.L., Cullenward, D., 2022b. Systematic over-crediting in California's forest carbon offsets program. *Glob. Chang. Biol.* 28, 1433–1445.
- Balmford, P.H.S., Brancalion, D., Coomes, B., Filewod, B., Groom, A., Guizar-Coutiño, J. P.G., Jones, S., Keshav, A., Kontoleon, A., Madhavapeddy, Y., Malhi, E.O., Sills, B.B. N., Strassburg, F., Venmans, T.A.P., West, C., Wheeler, Swinfield, T., 2023a. Credit credibility threatens forests. *Science* 380, 466–467.
- Balmford, A., Keshav, S., Venmans, F., Coomes, D., Groom, B., Madhavapeddy, A., Swinfield, T., 2023b. Realizing the social value of impermanent carbon credits. *Nat. Clim. Chang.* 13, 1172–1178.
- Balmford, A., Coomes, D., Dales, M., Ferris, P., Hartup, J., Jaffer, S., Srinivasan, K., Lam, M., Madhavapeddy, A., Message, R., Rau, E., Swinfield, T., Wheeler, C., Williams, A., 2024. PACT Tropical Moist Forest Accreditation Methodology v2.1. Cambridge Open Engage.
- Barata, P.M., 2024. In: Fund, E.D. (Ed.), VCM 2.0: Navigating High-Integrity Carbon Markets for Corporate Impact. <https://blogs.edf.org/climate411/2024/09/18/carbon-markets-for-corporate-impact/> (accessed 30.8.25).
- Belachew, K.Y., Maina, N.H., Dersseh, W.M., Zeleke, B., Stoddard, F.L., 2022. Yield gaps of major cereal and grain legume crops in Ethiopia: a review. *Agronomy* 12, 2528.
- Bensch, G., Jeuland, M., Peters, J., 2021. Efficient biomass cooking in Africa for climate change mitigation and development. *One Earth* 4, 879–890.
- Berenguer, E., Ferreira, J., Gardner, T.A., Aragão, L.E.O.C., De Camargo, P.B., Cerri, C.E., Durigan, M., Oliveira, R.C.D., Vieira, I.C.G., Barlow, J., 2014. A large-scale field assessment of carbon stocks in human-modified tropical forests. *Glob. Chang. Biol.* 20, 3713–3726.
- Brancalion, P.H.S., Balmford, A., Wheeler, C.E., Rodrigues, R.R., Strassburg, B.B.N., Swinfield, T., 2024. A call to develop carbon credits for second-growth forests. *Nat. Ecol. Evol.* 8, 179–180.
- Busch, J., Bukoski, J.J., Cook-Patton, S.C., Griscom, B., Kaczan, D., Potts, M.D., Yi, Y., Vincent, J.R., 2024. Cost-effectiveness of natural forest regeneration and plantations for climate mitigation. *Nat. Clim. Chang.* 14, 996–1002.
- Caravaggio, N., 2020. A global empirical re-assessment of the environmental Kuznets curve for deforestation. *Forest Policy Econ.* 119, 102282.
- Chakraborty, A., Seshasai, M., Reddy, C.S., Dadwahl, V., 2018. Persistent negative changes in seasonal greenness over different forest types of India using MODIS time series NDVI data (2001–2014). *Ecol. Indic.* 85, 887–903.
- Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrizar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Péliissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G., Vieilledent, G., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. *Glob. Chang. Biol.* 20, 3177–3190.
- Chazdon, R.L., Broadbent, E.N., Rozendaal, D.M., Bongers, F., Zambrano, A.M.A., Aide, T.M., Balvanera, P., Becknell, J.M., Boukili, V., Brancalion, P.H., 2016. Carbon sequestration potential of second-growth forest regeneration in the Latin American tropics. *Sci. Adv.* 2.
- Committee on Climate Change, 2019. Net Zero: The UK's contribution to stopping global warming. <https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/>.
- Cook-Patton, S.C., Leavitt, S.M., Gibbs, D., Harris, N.L., Lister, K., Anderson-Teixeira, K. J., Briggs, R.D., Chazdon, R.L., Crowther, T.W., Ellis, P.W., Griscom, H.P., Herrmann, V., Holl, K.D., Houghton, R.A., Larrosa, C., Lomax, G., Lucas, R., Madsen, P., Malhi, Y., Paquette, A., Parker, J.D., Paul, K., Routh, D., Roxburgh, S., Saatchi, S., van den Hoogen, J., Walker, W.S., Wheeler, C.E., Wood, S.A., Xu, L., Griscom, B.W., 2020. Mapping carbon accumulation potential from global natural forest regrowth. *Nature* 585, 545–550.
- Cook-Patton, S.C., Shoch, D., Ellis, P.W., 2021. Dynamic global monitoring needed to use restoration of forest cover as a climate solution. *Nat. Clim. Chang.* 11, 366–368.
- Coomes, D.A., Allen, R.B., Scott, N.A., Goulding, C., Beets, P., 2002. Designing systems to monitor carbon stocks in forests and shrublands. *For. Ecol. Manag.* 164, 89–108.
- Coomes, D.A., Dalponte, M., Jucker, T., Asner, G.P., Banin, L.F., Burslem, D.F., Lewis, S. L., Nilus, R., Phillips, O.L., Phua, M.-H., 2017. Area-based vs tree-centric approaches to mapping forest carbon in southeast Asian forests from airborne laser scanning data. *Remote Sens. Environ.* 194, 77–88.
- Cushman, K.C., Saatchi, S., McRoberts, R.E., Anderson-Teixeira, K.J., Bourg, N.A., Chapman, B., McMahon, S.M., Mulverhill, C., 2023. Small field plots can cause substantial uncertainty in gridded aboveground biomass products from airborne Lidar data. *Remote Sens.* 15, 3509.
- da Silveira, J.G., de Oliveira Neto, S.N., do Canto, A.C.B., Leite, F.F.G.D., Cordeiro, F.R., Assad, L.T., Silva, G.C.C., Marques, R.D.O., Dalarme, M.S.L., Ferreira, I.G.M., Conceição, M.C.G.D., Rodrigues, R.D.A.R., 2022. Land use, land cover change and sustainable intensification of agriculture and livestock in the Amazon and the Atlantic Forest in Brazil. *Sustainability* 14, 2563.
- Daigneault, A., Sohngen, B., Belair, E., Ellis, P., 2025. A global assessment of regional Forest carbon leakage. In: PREPRINT (Version 2) available at Research Square.
- DeFries, R., Ahuja, R., Friedman, J., Gordon, D.R., Hamburg, S.P., Kerr, S., Mwanga, J., Nouwen, C., Pandit, N., 2022. Land management can contribute to net zero. *Science* 376, 1163–1165.
- Demol, M., Verbeeck, H., Gielen, B., Armston, J., Burt, A., Disney, M., Duncanson, L., Hackenberg, J., Kükenbrink, D., Lau, A., Ploton, P., Sewdien, A., Stovall, A., Takoudjou, S.M., Volkova, L., Weston, C., Wortel, V., Calders, K., 2022. Estimating forest above-ground biomass with terrestrial laser scanning: current status and future directions. *Methods Ecol. Evol.* 13, 1628–1639.
- Disney, M.I., Boni Vicari, M., Burt, A., Calders, K., Lewis, S.L., Raunonen, P., Wilkes, P., 2018. Weighing trees with lasers: advances, challenges and opportunities. *Interface Focus* 8, 20170048.
- Dubayah, R.O., Armston, J., Kellner, J.R., Duncanson, L., Healey, S.P., Patterson, P.L., Hancock, S., Tang, H., Bruening, J., Hofton, M.A., Blair, J.B., Luthcke, S.B., 2022. GEDI L4A Footprint Level Aboveground Biomass Density, Version 2.1. ORNL DAAC, Oak Ridge, Tennessee, USA.
- Dubayah, R.O., Armston, J., Healey, S.P., Yang, Z., Patterson, P.L., Saarela, S., Stahl, G., Duncanson, L., Kellner, J.R., Bruening, J., Pascual, A., 2023. GEDI L4B Gridded Aboveground Biomass Density, Version 2.1. ORNL DAAC, Oak Ridge, Tennessee, USA.
- Duncanson, L., Armston, J., Disney, M., Avitabile, V., Barbier, N., Calders, K., Carter, S., Chave, J., Herold, M., Crowther, T.W., 2019. The importance of consistent global forest aboveground biomass product validation. *Surv. Geophys.* 40, 979–999.
- Duncanson, L., Armston, J., Disney, M., Avitabile, V., Barbier, N., Calders, K., Carter, S., Chave, J., Herold, M., MacBean, N., 2021. Aboveground Woody Biomass Product Validation Good Practices Protocol V1.0.
- Duncanson, L., Kellner, J.R., Armston, J., Dubayah, R., Minor, D.M., Hancock, S., Healey, S.P., Patterson, P.L., Saarela, S., Marselis, S., Silva, C.E., Bruening, J., Goetz, S.J., Tang, H., Hofton, M., Blair, B., Luthcke, S., Fatoyinbo, L., Abernethy, K., Alonso, A., Andersen, H.-E., Aplin, P., Baker, T.R., Barbier, N., Bastin, J.F., Biber, P., Boeckx, P., Bogaert, J., Boschetti, L., Boucher, P.B., Boyd, D.S., Burslem, D.F.R.P., Calvo-Rodriguez, S., Chave, J., Chazdon, R.L., Clark, D.B., Clark, D.A., Cohen, W.B., Coomes, D.A., Corona, P., Cushman, K.C., Cutler, M.E.J., Dalling, J.W., Dalponte, M., Dash, J., de-Miguel, S., Deng, S., Ellis, P.W., Erasmus, B., Fekety, P.A., Fernandez-Landa, A., Ferraz, A., Fischer, R., Fisher, A.G., García-Abriol, A., Gobakken, T., Hacker, J.M., Heinrich, M., Hill, R.A., Hopkins, C., Huang, H., Hubbell, S.P., Hudak, A.T., Huth, A., Imbach, B., Jeffery, K.J., Katoh, M., Kearsley, E., Kenfack, D., Kijun, N., Knapp, N., Král, K., Krůček, M., Labrière, N., Lewis, S.L., Longo, M., Lucas, R.M., Main, R., Manzanera, J.A., Martínez, R.V., Mathieu, R., Memiaghe, H., Meyer, V., Mendoza, A.M., Monerris, A., Montesano, P., Morsdorf, F., Nasset, E., Naidoo, L., Nilus, R., O'Brien, M., Orwig, D.A., Papathanassiou, K., Parker, G., Philipson, C., Phillips, O.L., Pisek, J., Poulsen, J.R., Pretzsch, H., Rüdiger, C., Saatchi, S., Sanchez-Azofeifa, A., Sanchez-Lopez, N., Scholes, R., Silva, C.A., Simard, M., Skidmore, A., Stereńczak, K., Tanase, M., Torresan, C., Valbuena, R., Verbeeck, H., Vrska, T., Wessels, K., White, J.C., White, L.J.T., Zahabu, E., Zgraggen, C., 2022. Aboveground biomass density models for NASA's global ecosystem dynamics investigation (GEDI) lidar mission. *Remote Sens. Environ.* 270, 112845.
- Ellis, P.W., Page, A.M., Wood, S., Fargione, J., Masuda, Y.J., Carrasco Denney, V., Moore, C., Kroeger, T., Griscom, B., Sanderman, J., Atleo, T., Cortez, R., Leavitt, S., Cook-Patton, S.C., 2024. The principles of natural climate solutions. *Nat. Commun.* 15, 547.
- ESA, 2023. CCI Biomass Product User Guide V4.0. European Space Agency. https://climate.esa.int/media/documents/D4.3_CCI_PUG_V4.0_20230605.pdf.
- European Commission, 2020. EU Biodiversity Strategy to 2030. <https://op.europa.eu/en/publication-detail/-/publication/31e4609f-b91e-11eb-8aca-01aa75ed71a1>.
- Evans, K., Guariguata, M.R., Brancalion, P.H.S., 2018. Participatory monitoring to connect local and global priorities for forest restoration. *Conserv. Biol.* 32, 525–534.
- Feng, Z., Jaffer, L., Knezevic, J., Sormunen, S., Young, R., Lisaius, M., Immitzer, M., Ball, J., Atzberger, C., Coomes, D.A., Madhavapeddy, A., Blake, A., Srinivasan, K., 2025. TESSERA: Temporal Embeddings of Surface Spectra for Earth Representation and Analysis. Available at: <https://arxiv.org/abs/2506.20380v1> [Accessed on: 20/10/2025].
- Ferraro, P.J., 2009. Counterfactual thinking and impact evaluation in environmental policy. *N. Dir. Eval.* 2009, 75–84.
- Ferraro, P.J., Hanauer, M.M., Miteva, D.A., Nelson, J.L., Pattanayak, S.K., Nolte, C., Sims, K.R.E., 2015. Estimating the impacts of conservation on ecosystem services and poverty by integrating modeling and evaluation. *Proc. Natl. Acad. Sci.* 112, 7420–7425.
- Filewod, B., McCarney, G., 2023. Avoiding Leakage from Nature-Based Offsets by Design. London School of Economics and Political Science, pp. 2515–5709.

- Fischer, F.J., 2025. In Review. The Global Canopy Atlas: Analysis-Ready Maps of 3D Structure for the World's Woody Ecosystems.
- Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Hauck, J., Landschützer, P., Le Quéré, C., Li, H., Luijckx, I.T., Olsen, A., 2024. Global carbon budget 2024. *Earth Syst. Sci. Data Discuss.* 2024, 1–133.
- Friggens, N.L., Hester, A.J., Mitchell, R.J., Parker, T.C., Subke, J.-A., Wookey, P.A., 2020. Tree planting in organic soils does not result in net carbon sequestration on decadal timescales. *Glob. Chang. Biol.* 26, 5178–5188.
- Gao, Y., Skutsch, M., Paneque-Gálvez, J., Ghilardi, A., 2020. Remote sensing of forest degradation: a review. *Environ. Res. Lett.* 15, 103001.
- Gatica, G., Elena Fernández, M., Paula Juliarena, M., Gyenge, J., 2022. Does forest management affect the magnitude and direction of the afforestation effect on soil methane fluxes? A meta-analysis. *For. Ecol. Manag.* 507, 120009.
- Gauci, V., Pangala, S.R., Shenkin, A., Barba, J., Bastviken, D., Figueiredo, V., Gomez, C., Enrich-Prast, A., Sayer, E., Stauffer, T., Welch, B., Elias, D., McNamara, N., Allen, M., Malhi, Y., 2024. Global atmospheric methane uptake by upland tree woody surfaces. *Nature* 631, 796–800.
- Girardin, C.A., Jenkins, S., Seddon, N., Allen, M., Lewis, S.L., Wheeler, C.E., Griscom, B.W., Malhi, Y., 2021. Nature-based solutions can help cool the planet—if we act now. *Nature* 593, 191–194.
- Gold Standard, 2020. Land Use & Forests Activity Requirements Version: 1.2.1. <https://globalgoals.goldstandard.org/203-ar-luf-activity-requirements/>.
- Gold Standard, 2023. GHG Emissions Reduction & Sequestration Product Requirements V2.2. <https://globalgoals.goldstandard.org/501-pr-ghg-emissions-reductions-sequestration/>.
- Goldman, E., Weisse, M., 2024. Deforestation Linked to Agriculture Indicator. World Resources Institute. <https://research.wri.org/gfr/forest-extent-indicators/deforestation-on-agriculture>.
- Greenfield, P., 2023. Revealed: More than 90% of Rainforest Carbon Offsets by Biggest Certifier are Worthless, Analysis Shows. *The Guardian*. <https://www.theguardian.com/environment/2023/jan/18/revealed-forest-carbon-offsets-biggest-provider-worthless-verra-aoe>.
- Gregorio, N., Herbohn, J., Tripoli, R., Pasa, A., 2020. A local initiative to achieve global forest and landscape restoration challenge—Lessons learned from a community-based forest restoration project in Biliran province, Philippines. *Forests* 11 (4), 475.
- Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R.T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M.R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S.M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F.E., Sanderman, J., Silvius, M., Wollenberg, E., Fargione, J., 2017. Natural climate solutions. *Proc. Natl. Acad. Sci.* 114, 11645–11650.
- Griscom, B.W., Busch, J., Cook-Patton, S.C., Ellis, P.W., Funk, J., Leavitt, S.M., Lomax, G., Turner, W.R., Chapman, M., Engelmann, J., Gurwick, N.P., Landis, E., Lawrence, D., Malhi, Y., Murray, L.S., Navarrete, D., Roe, S., Scull, S., Smith, P., Streck, C., Walker, W.S., Worthington, T., 2020. National mitigation potential from natural climate solutions in the tropics. *Philos. Trans. R. Soc. B* 375, 20190126.
- Guizar Coutiño, A., 2023. Chapter 4: prevailing spillover effects in redd+ projects : implications for forests and carbon. In: *Forest Conservation through Voluntary Carbon Offsetting Interventions*. University of Cambridge, pp. 58–80. <https://doi.org/10.17863/CAM.99064> (thesis).
- Guizar-Coutiño, A., Jones, J.P.G., Balmford, A., Carmenta, R., Coomes, D.A., 2022. A global evaluation of the effectiveness of voluntary REDD+ projects at reducing deforestation and degradation in the moist tropics. *Conserv. Biol.* 36, e13970.
- Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Turubanova, S.A., 2013. High-resolution global maps of 21st-century Forest cover change. *Science* 342, 850–853.
- Harris, N.L., Gibbs, D.A., Baccini, A., Birdsey, R.A., de Bruin, S., Farina, M., Fatoyinbo, L., Hansen, M.C., Herold, M., Houghton, R.A., Potapov, P.V., Suarez, D.R., Roman-Cuesta, R.M., Saatchi, S.S., Slay, C.M., Turubanova, S.A., Tyukavina, A., 2021. Global maps of twenty-first century forest carbon fluxes. *Nat. Clim. Chang.* 11, 234–240.
- Hasler, N., Williams, C.A., Denney, V.C., Ellis, P.W., Shrestha, S., Terasaki Hart, D.E., Wolff, N.H., Yeo, S., Crowther, T.W., Werden, L.K., Cook-Patton, S.C., 2024. Accounting for albedo change to identify climate-positive tree cover restoration. *Nat. Commun.* 15, 2275.
- Haya, B.K., Alford-Jones, K., Anderegg, W.R.L., Beymer-Farris, B., Blanchard, L., Bomfim, B., Chin, D., Evans, S., Hogan, M., Holm, J.A., McAfee, K., So, I.S., West, T.A.P., Withey, L., 2023. Quality Assessment of REDD+ Carbon Credit Projects. Berkeley Carbon Trading Project. <https://gssp.berkeley.edu/research-and-impact/centers/cepp/projects/berkeley-carbon-trading-project/REDD+>.
- Haya, B.K., Abayo, A., So, I.S., Elias, M., Voluntary Registry Offsets Database, V10. Berkeley Carbon Trading Project. <https://gssp.berkeley.edu/research-and-impact/centers/cepp/projects/berkeley-carbon-trading-project/offsets-database>.
- Haya, B.K., Evans, S., Brown, L., Bukoski, J., Butsic, V., Cabiyo, B., Jacobson, R., Kerr, A., Potts, M., Sanchez, D.L., 2023b. Comprehensive review of carbon quantification by improved forest management offset protocols. *Front. For. Glob. Change* 6, 958879.
- Healey, S.P., Yang, Z., Erb, A.M., Bright, R.M., Domke, G.M., Frescino, T.S., Schaaf, C.B., 2025. Enhanced observation of forest albedo reveals significant offsets to reported carbon benefits. *Environ. Res. Lett.* 20, 074025.
- Heinrich, V.H.A., Dalagnol, R., Cassol, H.L.G., Rosan, T.M., de Almeida, C.T., Silva Junior, C.H.L., Campanharo, W.A., House, J.I., Sitch, S., Hales, T.C., Adami, M., Anderson, L.O., Aragão, L.E.O.C., 2021. Large carbon sink potential of secondary forests in the Brazilian Amazon to mitigate climate change. *Nat. Commun.* 12, 1785.
- Henders, S., Ostwald, M., 2012. Forest carbon leakage quantification methods and their suitability for assessing leakage in REDD. *Forests* 3, 33–58.
- Henry, M., Bombelli, A., Trotta, C., Alessandrini, A., Birgazzi, L., Sola, G., Vieilledent, G., Santenoise, P., Longuetaud, F., Valentini, R., 2013. GlobAllomeTree: international platform for tree allometric equations to support volume, biomass and carbon assessment. *iForest-Biogeoosci. For.* 6, 326.
- Holcomb, A., Mathis, S.V., Coomes, D.A., Keshav, S., 2023. Computational tools for assessing forest recovery with GEDI shots and forest change maps. *Sci. Remote Sens.* 8, 100106.
- Holcomb, A., Burns, P., Keshav, S., Coomes, D.A., 2024. Repeat GEDI footprints measure the effects of tropical forest disturbances. *Remote Sens. Environ.* 308, 114174.
- Huertas, C., Sabatier, D., Derroire, G., Ferry, B., Jackson, T.D., Pélessier, R., Vincent, G., 2022. Mapping tree mortality rate in a tropical moist forest using multi-temporal LiDAR. *Int. J. Appl. Earth Obs. Geoinf.* 109, 102780.
- Hunnable, H., Mayer, B., Kelly, A., Strong, J., Barata, P., 2024. Cambridge Permanence and Durability Voluntary Carbon Market Workshop: Resources and Summary. <https://www.cambridge.org/engage/coe/article-details/66c38d1ff3f4b052905d4317>.
- ICVCM, 2024. Core Carbon Principles, Assessment Framework and Assessment Procedure: Version 2. The Integrity Council for the Voluntary Carbon Market. <https://icvcm.org/the-core-carbon-principles/>.
- Isometric, 2024. Reforestation Protocol V1. <https://registry.isometric.com/protocol/reforestation/1.0>.
- Joshi, N., Mitchard, E.T.A., Brolly, M., Schumacher, J., Fernández-Landa, A., Johannsen, V.K., Marchamalo, M., Fensholt, R., 2017. Understanding 'saturation' of radar signals over forests. *Sci. Rep.* 7, 3505.
- Jucker, T., Asner, G.P., Dalponte, M., Brodrick, P.G., Philipson, C.D., Vaughn, N.R., Teh, Y.A., Brelsford, C., Burslem, D.F.R.P., Deere, N.J., Ewers, R.M., Kvasnica, J., Lewis, S.L., Malhi, Y., Milne, S., Nilus, R., Pfeifer, M., Phillips, O.L., Qie, L., Renneboog, N., Reynolds, G., Riutta, T., Strubbig, M.J., Svátek, M., Turner, E.C., Coomes, D.A., 2018. Estimating aboveground carbon density and its uncertainty in Borneo's structurally complex tropical forests using airborne laser scanning. *Biogeosciences* 15, 3811–3830.
- Jucker, T., Fischer, F.J., Chave, J., Coomes, D.A., Caspersen, J., Ali, A., Loubota Panzou, G.J., Feldpausch, T.R., Falster, D., Usoltsev, V.A., Adu-Bredu, S., Alves, L.F., Aminpour, M., Angoboy, I.B., Anten, N.P.R., Antin, C., Askari, Y., Muñoz, R., Ayyappan, N., Balvanera, P., Banin, L., Barbier, N., Battles, J.J., Bееckman, H., Bocko, Y.E., Bond-Lamberty, B., Bongers, F., Bowers, S., Brade, T., van Breugel, M., Chantrean, A., Chaudhary, R., Dai, J., Dalponte, M., Dimobe, K., Domec, J.-C., Doucet, J.-L., Duursma, R.A., Enríquez, M., van Ewijk, K.Y., Farfán-Rios, W., Fayolle, A., Forni, E., Forrester, D.L., Gilani, H., Godlee, J.L., Gourlet-Fleury, S., Haeni, M., Hall, J.S., He, J.-K., Hemp, A., Hernández-Stefanoni, J.L., Higgins, S.L., Holdaway, R.J., Hussain, K., Hutley, L.B., Ichie, T., Iida, Y., Jiang, H.-S., Joshi, P.R., Kaboli, H., Larsary, M.K., Kenzo, T., Kloeppel, B.D., Kohyama, T., Kunwar, S., Kuyah, S., Kvasnica, J., Lin, S., Lines, E.R., Liu, H., Lorimer, C., Loumeto, J.-J., Malhi, Y., Marshall, P.L., Mattsson, E., Matula, R., Meave, J.A., Mensah, S., Mi, X., Momo, S., Moncrieff, G.R., Mora, F., Nissanka, S.P., O'Hara, K.L., Pearce, S., Pelissier, R., Peri, P.L., Ploton, P., Poorter, L., Pour, M.J., Pourabaei, H., Dupuy-Rada, J.M., Ribeiro, S.C., Ryan, C., Sanaei, A., Sanger, J., Schlund, M., Sellan, G., Shenkin, A., Sonké, B., Sterck, F.J., Svátek, M., Takagi, K., Trugman, A.T., Ullah, F., Vadeboncoeur, M.A., Valipour, A., Vanderwel, M.C., Vovides, A.G., Wang, W., Wang, L.-Q., Wirth, C., Woods, M., Xiang, W., F. d. A. Ximenes, Y. Xu, T. Yamada, and M.-A. Zavalá, 2022. Tallo: A global tree allometry and crown architecture database. *Glob. Chang. Biol.* 28, 5254–5268.
- Karnik, A., Kilbride, J., Goodbody, T., Ross, R., Ayrey, E., 2024. An Open-Access Database of Nature-Based Carbon Offset Project Boundaries.
- Kent, R., Lindsell, J.A., Laurin, G.V., Valentini, R., Coomes, D.A., 2015. Airborne LiDAR detects selectively logged tropical Forest even in an advanced stage of recovery. *Remote Sens.* 7, 8348–8367.
- Kim, S.-B., Ouellette, J.D., van Zyl, J.J., Johnson, J.T., 2016. Detection of inland open water surfaces using dual polarization L-band radar for the soil moisture active passive mission. *IEEE Trans. Geosci. Remote Sens.* 54, 3388–3399.
- Krause, P., Forbes, B., Barajas-Ritchie, A., Clark, M., Disney, M., Wilkes, P., Bentley, L.P., 2023. Using terrestrial laser scanning to evaluate non-destructive aboveground biomass allometries in diverse northern California forests. *Front. Remote Sens.* 4.
- Küng, L., Aeschlimann, S., Charalambous, C., McIlwaine, F., Young, J., Shannon, N., Strassel, K., Maesano, C.N., Kahsar, R., Pike, D., 2023. A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage. *Energy Environ. Sci.* 16, 4280–4304.
- Lakhani, N., 2024. Corporations Invested in Carbon Offsets that were 'Likely Junk', Analysis Says. *The Guardian*. <https://www.theguardian.com/environment/article/2024/may/30/corporate-carbon-offsets-credits>.
- Lewis, S.L., Wheeler, C.E., Mitchard, E.T., Koch, A., 2019. Restoring natural forests is the best way to remove atmospheric carbon. *Nature* 568 (7750), 25–28.
- Lindsell, J.A., Klop, E., 2013. Spatial and temporal variation of carbon stocks in a lowland tropical forest in West Africa. *For. Ecol. Manag.* 289, 10–17.
- Lui, G.V., Coomes, D.A., 2015. A comparison of novel optical remote sensing-based Technologies for Forest-Cover/change monitoring. *Remote Sens.* 7, 2781–2807.
- Ma, L., Hurr, G., Tang, H., Lamb, R., Lister, A., Chini, L., Dubayah, R., Armston, J., Campbell, E., Duncanson, L., Healey, S., O'Neil-Dunne, J., Ott, L., Poulter, B., Shen, Q., 2023. Spatial heterogeneity of global forest aboveground carbon stocks and fluxes constrained by spaceborne lidar data and mechanistic modeling. *Glob. Chang. Biol.* 29, 3378–3394.
- Magalhães, I.B., Pereira, A.S.A.D.P., Calijuri, M.L., Alves, S.D.C., Santos, V.J.D., Lorentz, J.F., 2020. Brazilian Cerrado and soy moratorium: effects on biome preservation and consequences on grain production. *Land Use Policy* 99, 105030.

- Malan, M., Carmenta, R., Gsottbauer, E., Hofman, P., Kontoleon, A., Swinfield, T., Voors, M., 2024. Evaluating the impacts of a large-scale voluntary REDD+ project in Sierra Leone. *Nat. Sustain.* 7, 120–129.
- Martin, A.R., Thomas, S.C., 2011. A reassessment of carbon content in tropical trees. *PLoS one* 6, 8.
- Matthews, H.D., Zickfeld, K., Dickau, M., MacIsaac, A.J., Mathesius, S., Ntongicimpaye, C.-M., Luers, A., 2022. Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario. *Commun. Earth Environ.* 3, 65.
- Matthews, H.D., Zickfeld, K., Koch, A., Luers, A., 2023. Accounting for the climate benefit of temporary carbon storage in nature. *Nat. Commun.* 14, 5485.
- McKinley, V.L., 2019. Effects of land use and restoration on soil microbial communities. In: Hurst, C.J. (Ed.), *Understanding Terrestrial Microbial Communities*. Springer International Publishing, Cham, pp. 173–242.
- McNicol, I.M., Ryan, C.M., Mitchard, E.T.A., 2018. Carbon losses from deforestation and widespread degradation offset by extensive growth in African woodlands. *Nat. Commun.* 9, 3045.
- Meyfroidt, P., Lambin, E.F., 2009. Forest transition in Vietnam and displacement of deforestation abroad. *Proc. Natl. Acad. Sci.* 106, 16139–16144.
- Meyfroidt, P., Börner, J., Garrett, R., Gardner, T., Godar, J., Kis-Katos, K., Soares-Filho, B. S., Wunder, S., 2020. Focus on leakage and spillovers: informing land-use governance in a tele-coupled world. *Environ. Res. Lett.* 15, 090202.
- Mitchard, E.T., Saatchi, S.S., Woodhouse, I.H., Nangendo, G., Ribeiro, N.S., Williams, M., Ryan, C.M., Lewis, S.L., Feldpausch, T.R., Meir, P., 2009. Using satellite radar backscatter to predict above-ground woody biomass: a consistent relationship across four different African landscapes. *Geophys. Res. Lett.* 36, L23401.
- Mitchard, E.T., Saatchi, S.S., Lewis, S., Feldpausch, T., Woodhouse, I.H., Sonké, B., Rowland, C., Meir, P., 2011. Measuring biomass changes due to woody encroachment and deforestation/degradation in a forest–savanna boundary region of Central Africa using multi-temporal L-band radar backscatter. *Remote Sens. Environ.* 115, 2861–2873.
- Mitchard, E.T.A., Carstairs, H., Cosenza, R., Saatchi, S.S., Funk, J., Nieto Quintano, P., Brade, T., McNicol, I.M., Meir, P., Collins, M.B., Nowak, E., 2023. Serious errors impair an assessment of forest carbon projects: A rebuttal of West et al. (2023). Available at: <https://arxiv.org/abs/2312.06793> [Accessed on:20/10/2025].
- Mohr, M., Pebesma, E., Dries, J., Lippens, S., Janssen, B., Thiex, D., Milcinski, G., Schumacher, B., Briese, C., Claus, M., Jacob, A., Sacramento, P., Griffiths, P., 2025. Federated and reusable processing of earth observation data. *Sci Data* 12, 194.
- Mugabowindekwe, M., Brandt, M., Chave, J., Reiner, F., Skole, D.L., Karirya, A., Igel, C., Hiernaux, P., Ciaia, P., Mertz, O., 2022. Nation-wide mapping of tree-level aboveground carbon stocks in Rwanda. *Nat. Clim. Chang.* 13, 91–97.
- Nerfa, L., Wilson, S.J., Reid, J.L., Rhemtulla, J., 2021. Practitioner views on the determinants of tropical forest restoration longevity. *Restor. Ecol.* 29 (3), e13345. <https://doi.org/10.1111/rec.13345>.
- Oliveira Fiorini, A.C., Mullally, C., Swisher, M., Putz, F.E., 2020. Forest cover effects of payments for ecosystem services: evidence from an impact evaluation in Brazil. *Ecol. Econ.* 169, 106522.
- Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C.E., Wulder, M.A., 2014. Good practices for estimating area and assessing accuracy of land change. *Remote Sens. Environ.* 148, 42–57.
- Ordway, E., Keller, M., Longo, M., Negron-Juarez, R., Feng, Y., Stouter, H., Rivera, I., Alencar, A., Bey, A., Braghieri, R., 2025. The PANGAEA Scoping Study Final Report. ORNL DAAC.
- Pandey, P.C., Koutsias, N., Petropoulos, G.P., Srivastava, P.K., Ben Dor, E., 2021. Land use/land cover in view of earth observation: data sources, input dimensions, and classifiers—A review of the state of the art. *Geocarto Int.* 36, 957–988.
- Pankhurst, L., 2025. Fewer Credits, More Credibility: jurisdictional Baselines in REDD+ Provide more Conservative, and Appropriate, Estimates of Avoided Deforestation. University of Bangor.
- Phalan, B., Green, R.E., Dicks, L.V., Dotta, G., Feniuk, C., Lamb, A., Strassburg, B.B.N., Williams, D.R., Ermgassen, E.K.H.J.Z., Balmford, A., 2016. How can higher-yield farming help to spare nature? *Science* 351, 450–451.
- Plan Vivo, 2024. PV Climate Procedures Manual, V 3.6. Available at: <https://www.planvivo.org/Handlers/Download.ashx?IDMF=e29a4b33-70ef-48ef-a7b0-369837f525ca> [Accessed on: 20/10/2025].
- Planet Lab, 2024. Planet Forest Carbon Diligence Technical Specification, V1.1. Planet Lab. <https://planet.widen.net/s/rv77kqctqw/planet-userdocumentation-forestcarbon>.
- Poorter, L., Bongers, F., Aide, T.M., Zambrano, A.M.A., Balvanera, P., Becknell, J.M., Boukili, V., Brancalion, P.H., Broadbent, E.N., Chazdon, R.L., 2016. Biomass resilience of Neotropical secondary forests. *Nature* 530, 211–214.
- Procton, A., Calderón, C., Weatherer, L., 2024. State of the Voluntary Carbon Market 2024. <https://www.ecosystemmarketplace.com/publications/2024-state-of-the-voluntary-carbon-markets-sovm/>. Accessed 30/08/2025.
- Ramachandran, N., Saatchi, S., Tebaldini, S., d'Alessandro, M.M., Dikshit, O., 2023. Mapping tropical forest aboveground biomass using airborne SAR tomography. *Sci. Rep.* 13, 6233.
- Rau, E.-P., Gross, J., Coomes, D.A., Swinfield, T., Madhavapeddy, A., Balmford, A., Keshav, S., 2024. Mitigating risk of credit reversal in nature-based climate solutions by optimally anticipating carbon release. *Carbon Manag.* 15, 2390854.
- Reiche, J., Balling, J., Pickens, A.H., Masolele, R.N., Berger, A., Weisse, M.J., Mannarino, D., Gou, Y., Slagter, B., Donchyts, G., Carter, S., 2024. Integrating satellite-based forest disturbance alerts improves detection timeliness and confidence. *Environ. Res. Lett.* 19, 054011.
- Reid, J.L., Fagan, M.E., Lucas, J., Slaughter, J., Zahawi, R.A., 2019. The ephemerality of secondary forests in southern Costa Rica. *Conserv. Lett.* 12 (2), e12607. <https://doi.org/10.1111/conl.12607>.
- Reiner, F., Brandt, M., Tong, X., Skole, D., Karirya, A., Ciaia, P., Davies, A., Hiernaux, P., Chave, J., Mugabowindekwe, M., 2022. More than One Quarter of Africa's Tree Cover Found Outside Areas Previously Classified as Forest.
- Réjou-Méchain, M., Tanguy, A., Pioniot, C., Chave, J., Hérault, B., 2017. biomass: an R package for estimating above-ground biomass and its uncertainty in tropical forests. *Methods Ecol. Evol.* 8, 1163–1167.
- Rifai, S.W., West, T.A., Putz, F., 2015. “Carbon Cowboys” could inflate REDD+ payments through positive measurement bias. *Carbon Manag.* 6 (3–4), 151–158.
- Robinson, N., Drever, R., Gibbs, D., Lister, K., Esquivel-Muelbert, A., Heinrich, V., Ciaia, P., Silva-Junior, C., Liu, Z., Pugh, T., Satchi, S., Xu, Y., Cook-Patton, S., 2024. Protect Young Secondary Forests for Optimum Carbon Removal PREPRINT (Version 1).
- Rodrigues, M., 2023. Will Brazil's President Lula keep his climate promises? *Nature* 613, 420–421.
- RSPB, 2021. The Gola REDD Project. https://static1.squarespace.com/static/5d2c7fc6b94060e0001e56248/t/627cd5c8eb77d1e1693fab1/1652348403875/VCS+Description_1201_10Jan2021_submitted.pdf.
- Saatchi, S.S., Harris, N.L., Brown, S., Lefsky, M., Mitchard, E.T., Salas, W., Zutta, B.R., Buermann, W., Lewis, S.L., Hagen, S., 2011. Benchmark map of forest carbon stocks in tropical regions across three continents. *Proc. Natl. Acad. Sci.* 108, 9899–9904.
- Santoro, M., Cartus, O., 2023a. CCI BIOMASS Product User Guide v4. NERC EDS Centre for Environmental Data Analysis.
- Santoro, M., Cartus, O., 2023b. ESA Biomass Climate Change Initiative (Biomass cci): Global Datasets of Forest above-Ground biomass for the Years 2010, 2017, 2018, 2019 and 2020, v4. NERC EDS Centre for Environmental Data Analysis.
- Santoro, M., Cartus, O., Carvalhais, N., Rozendaal, D., Avitabile, V., Araya, A., De Bruin, S., Herold, M., Quegan, S., Rodríguez-Veiga, P., 2021. The global forest above-ground biomass pool for 2010 estimated from high-resolution satellite observations. *Earth Syst. Sci. Data* 13, 3927–3950.
- Schleicher, J., Eklund, J., Barnes, M.D., Geldmann, J., Oldekop, J.A., Jones, J.P.G., 2020. Statistical matching for conservation science. *Conserv. Biol.* 34, 538–549.
- Schwartz, N.B., Aide, T.M., Graesser, J., Grau, H.R., Uriarte, M., 2020. Reversals of reforestation across Latin America limit climate mitigation potential of tropical forests. *Front. For. Glob. Change* 3, 85. <https://doi.org/10.3389/ffgc.2020.00085>.
- Seddon, N., Chausson, A., Berry, P., Girardin, C.A.J., Smith, A., Turner, B., 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philos. Trans. R. Soc. B Biol. Sci.* 375, 20190120.
- Sewell, A., van der Esch, S., Löwenhardt, H., 2020. Goals and Commitments for the Restoration Decade: A Global Overview of Countries' Restoration Commitments Under the Rio Conventions and Other Pledges. PBL Netherlands Environmental Assessment Agency.
- Seyller, C., Desbureaux, S., Ongolo, S., Karsenty, A., Simonet, G., Faure, J., Brimont, L., 2016. The ‘virtual economy’ of REDD+ projects: does private certification of REDD+ projects ensure their environmental integrity? *Int. For. Rev.* 18, 231–246.
- Seymour, F., 2020. INSIDER: 4 Reasons why a Jurisdictional Approach for REDD+ Crediting Is Superior to a Project-Based Approach. World Resources Institute. <https://www.wri.org/blog/2020/05/insider-4-reasons-why-jurisdictional-approach-redd-crediting-superior-project-based>.
- Seymour, F., Langer, P., 2021. Consideration of Nature-Based Solutions as Offsets in Corporate Climate Change Mitigation Strategies. World Resources Institute. <https://www.wri.org/research/consideration-nature-based-solutions-offsets-corporate-climate-change-mitigation>.
- Silva Junior, C.H.L., Pessoa, A.C.M., Carvalho, N.S., Reis, J.B.C., Anderson, L.O., Aragão, L.E.O.C., 2021. The Brazilian Amazon deforestation rate in 2020 is the greatest of the decade. *Nat. Ecol. Evol.* 5, 144–145.
- Siminski, A., Zambiasi, D.C., dos Santos, K.L., Fantini, A.C., 2021. Dynamics of natural regeneration: implications for landscape restoration in the Atlantic Forest, Brazil. *Front. For. Glob. Change* 4, 576908.
- Sims, M.J., Stanimirova, R., Raichuk, A., Neumann, M., Richter, J., Follett, F., MacCarthy, J., Lister, K., Randle, C., Sloat, L., Esipova, E., Jupiter, J., Stanton, C., Morris, D., Melhart Slay, C., Purves, D., Harris, N., 2025. Global drivers of forest loss at 1 km resolution. *Environ. Res. Lett.* 20, 074027.
- Slagter, B., Fesenmyer, K., Hethcoat, M., Belair, E., Ellis, P., Kleinschroth, F., Peña-Claros, M., Herold, M., Reiche, J., 2024. Monitoring road development in Congo Basin forests with multi-sensor satellite imagery and deep learning. *Remote Sens. Environ.* 315, 114380.
- Sloan, S., Talkhani, R.R., Huang, T., Engert, J., Laurance, W.F., 2024. Mapping remote roads using artificial intelligence and satellite imagery. *Remote Sens.* 16, 839.
- Souza, C.M., Shimbo, J.Z., Rosa, M.R., Parente, L.L., Alencar, A.A., Rudorff, B.F.T., Hasenack, H., Matsumoto, M., Ferreira, L.G., Souza-Filho, P.W.M., de Oliveira, S.W., Rocha, W.F., Fonseca, A.V., Marques, C.B., Diniz, C.G., Costa, D., Monteiro, D., Rosa, E.R., Vêlez-Martin, E., Weber, E.J., Lenti, F.E.B., Paternost, F.F., Pareyn, F.G. C., Siqueira, J.V., Viera, J.L., Neto, L.C.F., Saraiva, M.M., Sales, M.H., Salgado, M.P. G., Vasconcelos, R., Galano, S., Mesquita, V.V., Azevedo, T., 2020. Reconstructing three decades of land use and land cover changes in Brazilian biomes with Landsat archive and earth engine. *Remote Sens.* 12, 2735.
- Space Intelligence, 2024. Assess Carbon Stocks with CarbonMapper. <https://www.space-intelligence.com/carbonmapper-biomass-estimates/>. Accessed 30/08/2025.
- Sparovek, G., Reydon, B.P., Guedes Pinto, L.F., Faria, V., de Freitas, F.L.M., Azevedo-Ramos, C., Gardner, T., Hamamura, C., Rajão, R., Cerignoni, F., Siqueira, G.P., Carvalho, T., Alencar, A., Ribeiro, V., 2019. Who owns Brazilian lands? *Land Use Policy* 87, 104062.

- Spawn, S.A., Sullivan, C.C., Lark, T.J., Gibbs, H.K., 2020. Harmonized global maps of above and belowground biomass carbon density in the year 2010. *Sci. Data* 7, 112.
- Stanturf, J.A., Mansourian, S., 2020. Forest landscape restoration: state of play. *R. Soc. Open Sci.* 7, 201218.
- Streck, C., 2021. REDD+ and leakage: debunking myths and promoting integrated solutions. *Clim. Pol.* 21, 843–852.
- Swinfield, T.A.B.A., 2023. Cambridge Carbon Impact: Evaluating carbon credit claims and co-benefits. University of Cambridge. <https://doi.org/10.33774/coe-2023-bl26j>.
- Swinfield, T., Shrikant, S., Bull, J.W., Madhavapeddy, A., S. O. S. E. zu Ermgassen., 2024. Nature-Based Credit Markets at a Crossroads. *Nature Sustainability*.
- Swinfield, T., Williams, Abby, Coomes, David, Dales, Michael, Ferris, Patrick, Guizar-Coutiño, Alejandro, Hartup, James, Holland, Jody, Jaffer, Sadiq, Jones, Julia P.G., Lam, Miranda O.K., Keshav, Srinivasan, Madhavapeddy, Anil, Toye-Scott, Eleanor, West, Thales A.P., Balmford, A., 2025. Understanding the Mechanisms for Over-Crediting in REDD+ In Press.
- Sylvera, T., 2023. Defining Carbon Credit Quality in the Voluntary Carbon Markets. <https://www.sylvera.com/reports/defining-carbon-credit-quality-in-vcms>. Accessed 30.08.2025.
- Symbiosis Coalition, 2025. Symbiosis Coalition: Nature-Based Carbon Removals. <https://www.symbiosiscoalition.org/>. Accessed: 30/08/2025.
- Tang, H., Dubayah, R., 2017. Light-driven growth in Amazon evergreen forests explained by seasonal variations of vertical canopy structure. *Proc. Natl. Acad. Sci.* 114, 2640–2644.
- Thorlakson, T., Neufeldt, H., 2012. Reducing subsistence farmers' vulnerability to climate change: evaluating the potential contributions of agroforestry in western Kenya. *Agric. Food Secur.* 1, 15.
- Tong, X., Brandt, M., Yue, Y., Ciais, P., Rudbeck Jepsen, M., Penuelas, J., Wigner, J.-P., Xiao, X., Song, X.-P., Horion, S., Rasmussen, K., Saatchi, S., Fan, L., Wang, K., Zhang, B., Chen, Z., Wang, Y., Li, X., Fensholt, R., 2020. Forest management in southern China generates short term extensive carbon sequestration. *Nat. Commun.* 11, 129.
- Tosteson, J., Mitchard, E.T.A., Pauly, M., 2024. REDD+ Baselines Revisited: A 20 Year Global Analysis of Carbon Crediting from Avoided Deforestation. <https://everland.earth/news/new-research-crediting-from-redd-projects-systematically-robust/>.
- Trencher, G., Nick, S., Carlson, J., Johnson, M., 2024. Demand for low-quality offsets by major companies undermines climate integrity of the voluntary carbon market. *Nat. Commun.* 15, 6863.
- Turton, A.E., Augustin, N.H., Mitchard, E.T.A., 2022. Improving estimates and change detection of Forest above-ground biomass using statistical methods. *Remote Sens* 14, 4911.
- UKCOP26, 2021. Glasgow Leaders' Declaration on Forests and Land Use. Accessed on: 20/02/2024. <https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use/>.
- UNFCCC/CDM, 2015. AR-TOOL14: Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities, V4.2. United Nations Framework Convention on Climate Change. <https://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-14-v4.2.pdf>.
- Vaglio Laurin, G., Liesenberg, V., Chen, Q., Guerriero, L., Del Frate, F., Bartolini, A., Coomes, D., Wilebore, B., Lindsell, J., Valentini, R., 2013. Optical and SAR sensor synergies for forest and land cover mapping in a tropical site in West Africa. *Int. J. Appl. Earth Obs. Geoinf.* 21, 7–16.
- Vaglio Laurin, G., Chan, J.C.-W., Chen, Q., Lindsell, J.A., Coomes, D.A., Guerriero, L., Frate, F.D., Miglietta, F., Valentini, R., 2014a. Biodiversity mapping in a tropical West African Forest with airborne hyperspectral data. *PLoS One* 9, e97910.
- Vaglio Laurin, G., Chen, Q., Lindsell, J.A., Coomes, D.A., Frate, F.D., Guerriero, L., Pirotti, F., Valentini, R., 2014b. Above ground biomass estimation in an African tropical forest with lidar and hyperspectral data. *ISPRS J. Photogramm. Remote Sens.* 89, 49–58.
- van Ittersum, M.K., van Bussel, L.G.J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., Claessens, L., de Groot, H., Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., van Oort, P.A.J., van Loon, M.P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J.H.J.R., Ouattara, K., Tesfaye, K., Cassman, K.G., 2016. Can sub-Saharan Africa feed itself? *Proc. Natl. Acad. Sci.* 113, 14964–14969.
- Vancutsem, C., Achard, F., Pekel, J.-F., Vieilledent, G., Carboni, S., Simonetti, D., Gallego, J., Aragão, L.E.O.C., Nasi, R., 2021. Long-term (1990–2019) monitoring of forest cover changes in the humid tropics. *Sci. Adv.* 7, eabe1603.
- VCS, 2014. VM0009: Methodology for Avoided Ecosystem Conversion V3.0. Verra. <https://verra.org/methodologies/vm0009-methodology-for-avoided-ecosystem-conversion-v3-0/>.
- VCS, 2015. VT0005: Tool for Measuring Aboveground Live Forest Biomass Using Remote Sensing. Verra. <https://verra.org/wp-content/uploads/imported/methodologies/VT0005-Tool-for-measuring-ALBF-using-remote-sensing-v1.0.pdf>.
- VCS, 2020. VMD0017: Estimation of Uncertainty for REDD+ Project Activities (X-UNC) V2.2. Verra. <https://verra.org/methodologies/vmd0017-estimation-of-uncertainty-for-redd-project-activities-x-unc-v2-2/>.
- VCS, 2023a. VM0007: REDD+ Methodology Framework V1.7. Verra. <https://verra.org/methodologies/vm0007-redd-methodology-framework-redd-mf-v1-7/>.
- VCS, 2023b. VM0047: Afforestation, Reforestation and Revegetation, V1.0. Verra. <https://verra.org/methodologies/vm0047-afforestation-reforestation-and-revegetation-v1-0/>.
- VCS, 2023c. VM0048: Reducing Emissions from Deforestation and Forest Degradation V1.0. Verra. <https://verra.org/methodologies/vm0048-reducing-emissions-from-deforestation-and-forest-degradation-v1-0/>.
- VCS, 2023d. VMD0001: Estimation Of Carbon Stocks In The Above- And Belowground Biomass In Live Tree And Non-Tree Pools (CP-AB), V1.2. Verra. <https://verra.org/methodologies/vmd0001-estimation-of-carbon-stocks-in-the-above-and-belowground-biomass-in-live-tree-and-non-tree-pools-cp-ab-v1-1/>.
- VCS, 2024. VMD0055 Estimation of Emission Reductions from Avoiding Unplanned Deforestation, V1.1. Verra. <https://verra.org/methodologies/vmd0055-estimation-of-emission-reductions-from-avoiding-unplanned-deforestation-v1-1/>.
- Verra, 2024. Verra Launches ABACUS Label for Ecosystem Restoration and Reforestation Credits. <https://verra.org/verra-launches-abacus-label-for-ecosystem-restoration-and-reforestation-credits/>.
- Verra (Ed.), 2025. Allocated Deforestation Risk Maps: Timetable. Verra. <https://verra.org/methodologies-main/allocated-deforestation-risk-maps-timetable>.
- Villoria, N., Garrett, R., Gollnow, F., Carlson, K., 2022. Leakage does not fully offset soy supply-chain efforts to reduce deforestation in Brazil. *Nat. Commun.* 13, 5476.
- von Essen, M., Lambin, E.F., 2021. Jurisdictional approaches to sustainable resource use. *Front. Ecol. Environ.* 19, 159–167.
- Wang, Y., Sun, Y., Cao, X., Wang, Y., Zhang, W., Cheng, X., 2023. A review of regional and global scale land use/land cover (LULC) mapping products generated from satellite remote sensing. *ISPRS J. Photogramm. Remote Sens.* 206, 311–334.
- Wang, L., Long, T., Jiang, W., Adam, E., Wen, C., Jiao, W., He, G., 2025. Economic well-being assessment: a review of traditional and remote sensing approaches. *Int. J. Digit. Earth* 18, 2504137.
- West, T.A.P., Börner, J., Sills, E.O., Kontoleon, A., 2020. Overstated carbon emission reductions from voluntary REDD+ projects in the Brazilian Amazon. *Proc. Natl. Acad. Sci.* 117, 24188–24194.
- West, T.A.P., Wunder, S., Sills, E.O., Börner, J., Rifai, S.W., Neidermeier, A.N., Frey, G.P., Kontoleon, A., 2023. Action needed to make carbon offsets from forest conservation work for climate change mitigation. *Science* 381, 873–877.
- Wheeler, C.E., Omeja, P.A., Chapman, C.A., Glipin, M., Tumwesigye, C., Lewis, S.L., 2016. Carbon sequestration and biodiversity following 18 years of active tropical forest restoration. *For. Ecol. Manag.* 373, 44–55.
- Wilebore, B., Coomes, D., 2016. Combining spatial data with survey data improves predictions of boundaries between settlements. *Appl. Geogr.* 77, 1–7.
- Williams, B.A., Beyer, H.L., Fagan, M.E., Chazdon, R.L., Schmoeller, M., Sprenkle-Hyppolite, S., Griscom, B.W., Watson, J.E., Tedesco, A.M., Gonzalez-Roglich, M., 2024. Global potential for natural regeneration in deforested tropical regions. *Nature* 636, 131–137.
- Woittiez, L.S., van Wijk, M.T., Slingerland, M., van Noordwijk, M., Giller, K.E., 2017. Yield gaps in oil palm: a quantitative review of contributing factors. *Eur. J. Agron.* 83, 57–77.
- World Bank, 2023. State and Trends of Carbon Pricing 2023. World Bank, Washington, DC. <https://openknowledge.worldbank.org/entities/publication/58f2a409-9bb7-4ee6-899d-be47835c838f>.
- Xie, Y., Sha, Z., Yu, M., 2008. Remote sensing imagery in vegetation mapping: a review. *J. Plant Ecol.* 1, 9–23.
- Xu, L., Saatchi, S.S., Yang, Y., Yu, Y., Pongratz, J., Bloom, A.A., Bowman, K., Worden, J., Liu, J., Yin, Y., Domke, G., McRoberts, R.E., Woodall, C., Nabuurs, G.-J., de-Miguel, S., Keller, M., Harris, N., Maxwell, S., Schimel, D., 2021. Changes in global terrestrial live biomass over the 21st century. *Sci. Adv.* 7, eabe9829.
- Xu, W., Cheng, Y., Luo, M., Mai, X., Wang, W., Zhang, W., Wang, Y., 2025. Progress and limitations in Forest carbon stock estimation using remote sensing technologies: a comprehensive review. *Forests* 16, 449.
- Zanne, A.E., Lopez-Gonzalez, G., Coomes, D.A., Ilic, J., Jansen, S., Lewis, S.L., Miller, R. B., Swenson, N.G., Wiemann, M.C., Chave, J., 2009. Global Wood Density Database. Dryad. <http://hdl.handle.net/10255/dryad.235>.