Carbon Direct | Meta

Remote Sensing for Forest Carbon

Barriers, opportunities, and a path forward

August 2025

Contents

Acronyms

AGB: above-ground biomass

AI: artificial intelligence

ARR: afforestation, reforestation, or revegetation

CDR: carbon dioxide removal

CHM: canopy height map

GEDI: Global Ecosystem Dynamics Investigation

IFM: improved forest management

IP: intellectual property

IPCC: Intergovernmental Panel on Climate Change

lidar: light detection and ranging

MMRV: measurement, monitoring, reporting, and verification

NAIP: National Agriculture Imagery Program (United States)

SAR: synthetic aperture radar

VCM: voluntary carbon market

VVBs: validation and verification bodies

Foreword

At Meta, our commitment to reach net-zero emissions across our value chain in 2030 is the north star in our work to address climate change and operate sustainably. To meet this goal, we are focused on working across our company, and with our suppliers, to reduce the emissions associated with operating a global business and building the physical infrastructure that brings our technologies and platforms to life. For any residual emissions, we rely on carbon removal projects as the final step to reach net zero.

Nature-based carbon removal via ecosystems like forests is one of the critical tools we can leverage to address the climate crisis. As we engage with the voluntary carbon market, we aim to increase the availability and quality of nature-based carbon credits. This both helps us to meet our net-zero goal and supports nature's vital role in mitigating climate change at scale in a crucial, near-term timeframe. Remote sensing technologies are one important tool that can improve the quality of carbon removal projects. These technologies, and their related datasets, can increase the transparency, accessibility, reliability, and scalability of measuring forest carbon sequestration. They may even increase the efficiency and speed at which new carbon removal projects are able to become verified and begin receiving revenue from issued carbon credits.

Barriers remain, however, to fully realizing the potential for and effectively applying these technologies in projects around the world.

We are conducting our own research utilizing satellite imagery, lidar data, and machine learning—which has produced an open-source dataset that estimates global tree canopy height at a high spatial resolution. Yet we acknowledge the challenges carbon project developers, registries, and others face when attempting to fully integrate and deploy tools like these

We are pleased to have collaborated with Carbon Direct to identify obstacles and opportunities to deploy remote sensing in forest carbon projects. We hope the findings in this report will help project developers and buyers address the barriers to applying these technologies, increase the certainty that new datasets can be adopted in the carbon market, and chart a path forward to unlocking the potential of remote sensing, artificial intelligence, and other new technologies for climate change mitigation. Our ability to apply new technologies to mitigating the effects of climate change will be pivotal to achieving this objective at the speed and efficiency it requires. We hope this report provides useful insights to unlock solutions to do so, and we look forward to continuing to partner with many of you in this effort.

Blair Swedeen
Global Head of Net Zero and Sustainability

Meta

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Anew

BeZero

Earthshot Labs

Ecosystem Restoration Standard

Ecotrust Forest Management (EFM)

Greenline Climate

Integradora de Comunidades Indígenas y Campesinas de Oaxaca (ICICO)

Isometric

Kijani

Mombak

National Indian Carbon Coalition

Open Forest Protocol

Ostrom Climate

Pachama

Sylvera

Symbiosis

Verra

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Executive summary

Forests play a critical role in regulating the Earth's climate. Protecting and restoring them is one of our most effective strategies to mitigate climate change. The Intergovernmental Panel on Climate Change (IPCC) recognizes forest carbon as one of the most viable pathways to achieving large-scale carbon dioxide removal (CDR).[1] Central to these efforts is the voluntary carbon market (VCM), which brings together buyers and sellers to finance forest carbon projects worldwide.

For the VCM to function successfully, we need to accurately quantify the impact of forest carbon projects through measurement, monitoring, reporting, and verification (MMRV). However, this remains challenging—and in some cases prohibitively expensive.

We are entering the digital age of forest management. Remote sensing technologies including sensors attached to satellite, aircraft, or drone platforms, are making MMRV more transparent, accessible, reliable, and scalable. Realizing the full potential of remote sensing will require overcoming barriers around data use and quality, industry standards, and technical capacity.

In this report, Carbon Direct and Meta aim to dissect these barriers and identify potential solutions. To do so, we conducted stakeholder research involving nearly 40 participants, including project developers, land owners, and registries. During interviews, stakeholders expressed an encouraging amount of consensus, including a desire to create an inclusive forest carbon MMRV consortium that would help to guide the industry's adoption and use of remote sensing. Establishing this consortium could be a critical first step toward allowing stakeholders to come together to adopt and implement the recommendations below.

To unlock remote sensing technology for forest carbon MMRV, we present seven recommendations:

1. **Define acceptable remote sensing data and workflows that allow flexibility as technologies evolve.** Right now, carbon registries, credit buyers, and verifiers have varying expectations and requirements, generating uncertainty. Lack of clear guidance makes it difficult for project developers to confidently adopt and integrate remote sensing methods.
2. **Clearly define where specific remote sensing datasets and models are geographically applicable.** Users need to know when and where they can trust model estimates. There is currently a lack of standardization and consensus on acceptable approaches for quantifying model uncertainty, reporting uncertainty, and determining where a calibrated model can be safely used. While evaluating new models as they develop will be an ongoing and iterative process, the applicability of current

1. Intergovernmental Panel on Climate Change (IPCC). 2023. Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. [accessed 2025 Jul 3]. https://www.cambridge.org/core/books/climate-change-2022-impacts-adaptation-and-vulnerability/161F238F406D530891AAAE1FC76651BD.

models must be understood before using them for credit issuance.

3. **Align on the role of uncertainty in credit issuance.** This will help buyers and registries account for natural variability in forest carbon estimates. There is ongoing skepticism among stakeholders regarding the accuracy and reliability of estimates of forest structure that are based on remote sensing. However, once model applicability is established, an appropriate degree of uncertainty can be accommodated in market mechanisms. We recommend that an inclusive forest carbon MMRV consortium facilitate a public-facing discussion among buyers, registries, scientific experts, and standard-setters to improve alignment on acceptable levels of uncertainty for carbon project applications.
4. **Standardize how data providers evaluate and report uncertainty** to facilitate comparison between and improve trust in remote sensing models and products. This requires that model uncertainties are well defined, and that avenues for market integration are clearly established. We recommend that domain experts, data providers, and registries collaborate on working toward more standardized methods for evaluating and reporting the reliability of remote sensing data products, for specific carbon project activities and regions.
5. **Create a global benchmarking dataset** with validated forest measurements to improve model testing and calibration, while being careful to respect the data sovereignty and privacy of parties providing measurements.[2] Dataset benchmarking can be reliably achieved when evaluation standards are clearly established. Both developers and registries noted that keeping pace with new remote sensing technologies and products is challenging. A publicly available, user-friendly benchmarking resource would help developers and registries assess the quality of new and existing datasets.
6. **Develop a centralized remote sensing data portal for forest carbon MMRV** to make high-quality data, models, and derived data products more accessible to VCM stakeholders. Following establishment of dataset benchmarks, infrastructure to house data can be created to facilitate reliable application of the data. This platform could host both open source and commercial models and data products. The portal would make data more accessible while allowing the sale of commercial data to incentivize investment in new data collection and model development.
7. **Apply new deep learning models** to create higher-resolution, more accurate, and more user-friendly remote sensing products that can better track forest carbon through time. This requires stakeholders to have a thorough understanding of model uncertainties, stable infrastructures, and well-defined standards for use. Deep learning architectures[3] have the potential to produce more accurate and geographically consistent estimates of forest structural attributes compared to classical machine learning methods.

2. Indigenous Peoples, including Tribal Nations and First Nations, have unique protocols around data sharing and sovereignty that should be respected when developing a global benchmarking dataset.

3. Meta's new canopy height model (Tolan et al. 2024) is an example of one such use of deep learning models to improve forest structural datasets.

Copernicus Sentinel-2 L2A data [2025-07-09]. Latitude = 53.75219 Longitude = -126.57166.

Remote sensing for forest carbon MMRV

Forests play a critical role in regulating the Earth's climate. Protecting and restoring them is one of our most effective strategies for achieving large-scale CDR.[4] Central to these efforts is the VCM, which brings together buyers and sellers to finance forest carbon projects worldwide.

Forest projects generate carbon credits for the VCM by demonstrating measurable climate benefits—examples include improved forest management (IFM) or afforestation, reforestation, or revegetation (ARR) activities. These projects have significant potential to drive sustainable forest practices and ecosystem restoration, but the field as a whole has been criticized for not consistently delivering on promised or claimed carbon accruals.[5] We must credibly report carbon accruals to strengthen the field's integrity, which demands rigorous and transparent MMRV.

While accurate MMRV for forest carbon projects is fundamental for credible credit issuance, the scale of many projects can make traditional MMRV approaches costly and challenging. Remote sensing tools have become integral to effective MMRV across large areas, but using these tools often requires technical, scientific, and statistical expertise. In order to better understand how to harness advances in remote sensing to drive transparency, scale, and equity in carbon markets, Meta asked Carbon Direct to conduct a study of the current state of remote sensing within the forest carbon space. This study aims to better understand what factors may drive more widespread uptake of remote sensing for forest carbon MMRV.
As part of this study, Carbon Direct and Meta conducted stakeholder research involving nearly 40 participants, including 19 interviews with forest carbon developers, registries, diligence providers, and data providers, as well as an in-person roundtable discussion.

In this report, we provide a brief history of remote sensing technology and discuss the value of remote sensing data within forest carbon MMRV frameworks. We describe current barriers to the uptake of these technologies and make recommendations for how the community could collectively drive more transparent, accessible, reliable, and scalable remote sensing in forest carbon project design and MMRV, drawing on our synthesis of stakeholder viewpoints. Based on these insights, we argue that a key step will be establishing a broad consensus on what defines a

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4. Intergovernmental Panel on Climate Change (IPCC). 2023. Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. [accessed 2025 Jul 3]. https://www.cambridge.org/core/books/climate-change-2022-impacts-adaptation-and-vulnerability/161F238F406D530891AAAE1FC76651BD.

5. West TAP, Wunder S, Sills EO, Börner J, Rifai SW, Neidermeier AN, Frey GP, Kontoleon A. 2023. Action needed to make carbon offsets from forest conservation work for climate change mitigation. Science. 381(6660):873–877. doi:10.1126/science.ade3535. [accessed 2025 Jul 3]. https://www.science.org/doi/10.1126/science.ade3535.

rigorous remote sensing dataset and methodological approach. Ultimately, we recommend creating an inclusive and diverse stakeholder consortium with the goal of addressing existing ambiguity in MMRV.

Background

To understand forest carbon sequestration, we need to measure forest structural attributes, such as tree size and tree density. Yet individually measuring every tree in a forest is impractical. The science of forest carbon measurement can be traced back to the establishment of large-scale, long-term forest monitoring plots associated with national forest inventory programs in the 1920s, such as the US Forest Service's Forest Inventory and Analysis Program.[6] Later, more research-oriented plots were established in the 1980s, such as the 50-hectare plot on Barro Colorado Island, Panama—one of the oldest and most intensively studied forest dynamics plots on Earth.[7] This 50-hectare plot is part of a global network of plots that have been used to study forest carbon dynamics for decades.[8] These plots allow researchers to track changes in tree growth, mortality, and recruitment over time, providing valuable data on changes in carbon stocks within forests.

Foresters use allometric equations and field-based measurements to estimate the amount of carbon stored in living trees (i.e., forest carbon stocks). Allometric equations rely on tree characteristics, such as diameter at breast height,[9] tree height, and tree species to estimate above-ground biomass (AGB) based on statistical relationships.[10] Although widely used, allometric equations have limitations. First, there is uncertainty around how well specific equations generalize to new contexts, and which forests they are appropriate for. Secondly, directly measuring individual trees is expensive and time consuming. Therefore, AGB estimates based on field-based measurements and allometric equations can only reliably provide carbon stock estimation for a small fraction of project areas.[11]

> Forest structural attributes are tree height, canopy structure (e.g., cover, layering, and gaps), tree density, crown size, above-ground biomass, and other variables that describe forests in three dimensions.

6. Forest Service, United States Department of Agriculture. 2023 Jan 13. Forest Inventory and Analysis. [accessed 2025 Jun 12]. https://research.fs.usda.gov/programs/fia.

7. Barro Colorado Island. 2017 Feb 6. ForestGEO. [accessed 2025 Jun 16]. https://forestgeo.si.edu/sites/neotropics/barro-colorado-island.

8. ForestGEO Sites. 2017 Feb 6. ForestGEO. [accessed 2025 Jun 16]. https://forestgeo.si.edu/sites-all.

9. "Diameter at breast height" refers to measuring the diameter of a tree at 1.37 meters above ground (average person's breast height).

10. AGB is often used as a proxy for forest carbon stocks due to its relative ease of estimation via remote sensing-based datasets and well-established conversion factors. While AGB does not capture the full carbon pool, it offers a practical basis for monitoring and can be complemented with models to estimate below-ground biomass and soil carbon for a more complete picture.

11. Advancements in terrestrial laser scanning systems are beginning to provide next-generation approaches for allometric modelling. These data offer millimeter-level characterization of tree structure that can help to reduce the over-generalization of allometric modeling and provide enhanced estimates of total volume at tree scale for AGB estimation.

Over the past two decades, advances in remote sensing datasets have allowed foresters to analyze sites remotely. This has helped to overcome numerous challenges in field-based data collection. Many remote sensing technologies (e.g., optical satellite imagery, radar)[12] can be used together with field measurements to generate spatially continuous modelled estimates of forest attributes across an entire area. More recently, lidar data[13] offer integration opportunities to improve the efficiency of direct measurement and field sampling. Some remote sensing datasets (e.g., the Landsat timeseries)[14] offer multiple observations through time, providing higher temporal resolution. These datasets provide a means to estimate changes in forest attributes through time, a critical requirement for multiple forest carbon MMRV applications.[15, 16]

> Spatially continuous modelling means that estimates of forest attributes are available across an entire area of interest, rather than just at isolated sample points.

Foresters and scientists are currently exploring how remote sensing data and traditional field measurements can be combined within machine learning and artificial intelligence (AI) workflows to optimize estimates of forest characteristics.[17, 18] This could improve the transparency, accessibility, reliability, and scalability of forest carbon MMRV (**figure 1**). Field-based measurements (e.g., manual tree measurement) remain fundamental to forest management and operations, but combining them with high-quality remote sensing data could enhance the cost-effectiveness of forest inventories by extending their insights to broader areas.

Remote sensing data and modeling approaches can help to support three key forest carbon project stages:

1. **Conducting project planning and feasibility:** Remote sensing approaches can be useful when identifying suitable project areas, and when dynamic baselines (see the *Registries and dynamic baselines* section of this report) and additionality analyses are being investigated.

12. Radar is an active remote sensing technology that emits radio waves and measures the signals reflected back from Earth's surface to estimate forest structural attributes like AGB.

13. Lidar emits laser pulses and measures the time delay and intensity of returns to estimate forest structural attributes like AGB.

14. Landsat satellites capture multispectral data, supporting applications such as land use monitoring, agriculture, forestry, water management, and climate change studies. The current satellites, Landsat 8 and Landsat 9, offer high-quality imagery across multiple spectral bands with a 16-day revisit time for each satellite.

15. Kennedy RE, Yang Z, Cohen WB. 2010. Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr — Temporal segmentation algorithms. Remote Sensing of Environment. 114(12):2897–2910. doi:10.1016/j.rse.2010.07.008. [accessed 2025 Jul 3]. https://www.sciencedirect.com/science/article/pii/S0034425710002245.

16. Coffield SR, Vo CD, Wang JA, Badgley G, Goulden ML, Cullenward D, Anderegg WRL, Randerson JT. 2022. Using remote sensing to quantify the additional climate benefits of California forest carbon offset projects. Global Change Biology. 28(22):6789–6806. doi:10.1111/gcb.16380. [accessed 2025 Jul 3]. https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.16380.

17. White JC, Coops NC, Wulder MA, Vastaranta M, Hilker T, Tompalski P. 2016. Remote Sensing Technologies for Enhancing Forest Inventories: A Review. Canadian Journal of Remote Sensing. 42(5):619–641. doi:10.1080/07038992.2016.1207484. [accessed 2025 Jul 3]. https://doi.org/10.1080/07038992.2016.1207484.

18. Common forest characteristics include timber volume, stand height, and diameter classes.

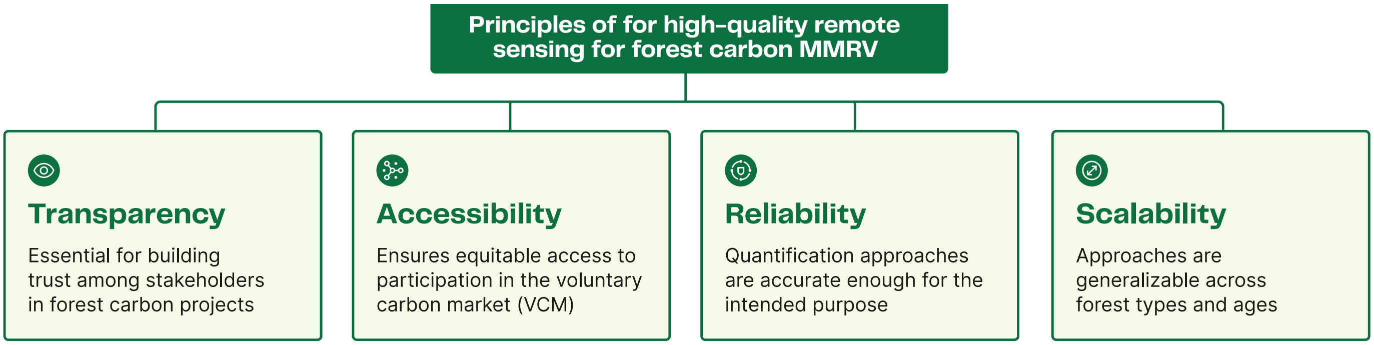


Figure 1. Principles of high-quality remote sensing for forest carbon MMRV. Source: Carbon Direct.

2. **Determining project area eligibility:** Remote sensing can help determine eligibility when historical land use and land cover is being assessed for compliance with registry standards.
3. **Monitoring project performance:** Remote sensing can be utilized for ongoing monitoring, to detect carbon reversals (release of carbon to the atmosphere), and to estimate performance for credit issuance through time.

At each of these stages, a project developer typically needs to know where forests are (e.g., using spatial information on forest cover) and how much carbon is present (e.g., AGB). Remote sensing-based products and modelling frameworks are capable of providing estimates of these critical forest attributes across broad spatial areas and through time with greater efficiency and at a lower cost than using more labor-intensive, traditional field-based methods.

However, understanding the reliability and practical applications of remote sensing data products can be a technical and opaque process. This can lead to either overestimating the abilities of remote sensing or blanket skepticism of it. If validated with field observations, remote sensing approaches have the potential to reliably monitor changes in carbon stocks over much larger areas, with much higher temporal resolution, than what is possible with field data alone. Yet the inherent variability, complexity, and idiosyncrasies of ecosystems—such as species composition, underlying soil types, phenological stage, health, and growth phases—pose real challenges for making broad inferences about forest structure. Consequently, all ecological inferences have an element of uncertainty (**box 1**). This is true of field-based measurement methods as well as remote sensing methods.

High-quality field data, used to train and validate models, is essential for generating reliable remote sensing products. Importantly, ground-truthing is not a one-time effort—ongoing, temporally representative field data collection is critical for capturing changes over time and ensuring that models remain accurate as forest conditions evolve. While field methods are resource-intensive and spatially constrained, robust remote sensing models can help extend the value of existing datasets, reduce the burden of collecting field data for under resourced project developers, and improve accessibility to the VCM by reducing the cost of MMRV.

Box 1. What is uncertainty in remote sensing for forest carbon MMRV and why does it matter?

Uncertainty refers to the range of possible errors in estimating forest structural attributes, like forest carbon stocks, due to limitations in sensors,[19] models, data resolution, or incomplete ground validation. Uncertainty arises from factors such as sensor noise, model assumptions, limited or non-representative training data, and the natural variability of ecosystems. All estimates of forest attributes, whether based on remote sensing data or field-based measurements, will carry some uncertainty. High levels of uncertainty can affect the credibility of emissions estimates, the volume of credit issuance, and market trust. Determining the level of uncertainty that is tolerable for a specific application is a decision-making process. Currently this process lacks broad consensus for best practices across industry stakeholders and experts. Further technical details on uncertainty are included in this report's *Appendix*.

Remote sensing-based data products like canopy height maps and AGB maps are derived from three primary underlying data sources, each with their own strengths and limitations:

1. **Surface reflectance data**[20] from passive optical sensors on satellites, such as Landsat or Sentinel-2,[21] are the most commonly used data for forest carbon project applications because they are freely available over broad temporal and spatial extents. Although they are useful for monitoring changes in land cover (e.g., conversion of forest to bare ground or agriculture), they cannot reliably measure forest structural attributes in most contexts and are prone to occlusion in humid regions because of persistent cloud cover.[22]
2. **Synthetic aperture radar (SAR) data,** such as data derived from the Sentinel-1[23] satellite or the recent launch of the European Space Agency Biomass mission,[24] can provide forest structure information. Unlike passive optical sensors, SAR sensors can operate in a wide range of weather conditions (e.g., cloud cover) and at night. This is particularly beneficial in regions with frequent

19. Variability among sensors and data resolutions can be addressed with advanced modeling approaches, but sensor-related uncertainty can also stem from sensors' detection limits which are harder to mitigate.

20. Surface reflectance data refers to the measurement of the fraction of incoming sunlight that a surface reflects at specific wavelengths. It is commonly used in remote sensing to analyze vegetation, soil, water, and land cover conditions.

21. Sentinel-2, a satellite designed to provide high-resolution optical imagery for land monitoring, is part of the Copernicus mission—the Earth observation component of the European Union's Space programme. It carries a multispectral instrument that captures data in 13 spectral bands, supporting applications like vegetation health assessment, soil and water monitoring, and disaster management.

22. Optical data products are limited to capturing only the outer layer of vegetation, as they rely on reflected sunlight, which cannot penetrate the canopy to reveal internal structural attributes. As a result, they cannot provide information on the vertical distribution of vegetation or internal canopy structure—key components of forest biomass. This limitation leads to difficulty distinguishing between medium- and high-biomass forests, a challenge commonly referred to as "signal saturation."

23. Sentinel-1 is part of the Copernicus mission—the Earth observation component of the European Union's Space programme. This satellite is focused on all-weather, day-and-night radar imaging. It carries a C-band SAR instrument that provides high-resolution data for applications such as land deformation monitoring, flood mapping, and maritime surveillance.

24. European Space Agency. c2025. Biomass Mission Overview | Earth Online. [accessed 2025 Jul 3]. https://earth.esa.int/eogateway/missions/biomass/description.

cloud cover, such as tropical rainforests and coastal regions. SAR data, like passive optical data, can saturate in forests with medium to high biomass, so it has not been entirely reliable for describing forest characteristics in dense tropical areas to date.[25] Due to sensor sensitivity constraints, it can also be challenging to use SAR data to monitor forest carbon in areas with very low forest cover.

3. **Lidar data,** which are produced using laser pulses capable of penetrating into dense forest canopies. This process, called laser scanning, overcomes the saturation issues seen with passive optical and SAR data and is often used in forest carbon projects. Laser scanning systems can be attached to ground-level terrestrial scanners, drones, aircraft, or satellites.[26] Lidar data provide highly accurate estimates of canopy height, forest density, structural variability, and terrain. Lidar sensors onboard aircraft (i.e., aerial lidar) give the most detailed structural measurements of forested landscapes of any widely used sensor. However, these data are expensive, leading to reduced spatial coverage and fewer (if any) repeated measurements. Furthermore, estimating forest biomass from lidar-derived canopy height measurements is usually not possible without accompanying field data (e.g., diameter at breast height measurements).

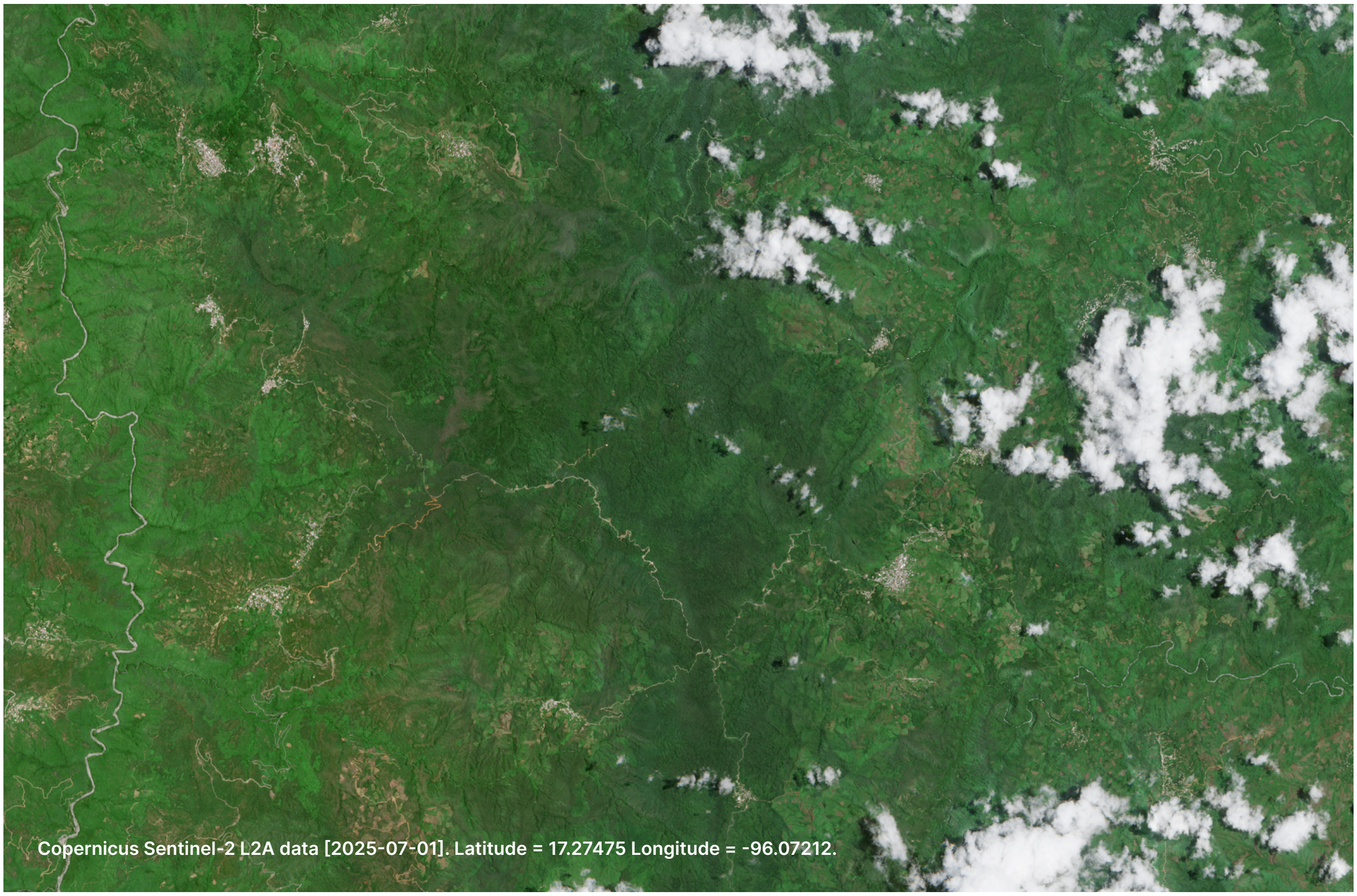
Data fusion techniques combine multiple remote sensing datasets with machine learning modeling to enhance data products.[27] Increasingly, a diverse range of remote sensing datasets are available. Data fusion promotes the strengths of individual datasets (e.g., repeated measurements and globally available optical imagery, or structural characterizations from aerial lidar) to produce data products with greater temporal resolution, spatial resolution, and increased spatial coverage. Data fusion can unlock advanced applications of remote sensing for project design, siting, and MMRV. Some data products must be purchased from commercial data providers, while others are freely available for public use.

> Machine learning is a way for computers to learn from data and make decisions or predictions without being directly programmed for every task.

25. However, the European Space Agency's recently launched Biomass mission may be able to overcome some of these prior shortcomings by operating at a longer wavelength (P-band).

26. NASA's Global Ecosystem Dynamics Investigation (GEDI) mission is a particularly influential example of spaceborne lidar data, which is freely available throughout many areas of the globe. These data are highly valuable for global and regional forest carbon estimates, but are sample-based (i.e., not spatially continuous, covering 4% of Earth's surface, and limited to +/- 52° latitude) and have a relatively coarse spatial resolution (i.e., 25 meters). These technical limitations mean that these data are unsuitable for measuring individual tree heights on their own, but they can still be used to calibrate higher-resolution canopy height models that are already trained.

27. Data providers have commonly used classical machine learning methods, such as sampling random forests, but deep learning architectures (e.g., convolutional neural networks, autoencoders, vision transformers) are increasingly used to unlock more advanced data products.



Copernicus Sentinel-2 L2A data [2025-07-01]. Latitude = 17.27475 Longitude = -96.07212.

Meta's Every Tree Counts initiative is an example of a data fusion approach that generates high-resolution global estimates of tree canopy height.[28] By integrating Maxar[29] imagery and aerial lidar data within a deep learning framework, Meta produced an open source, freely available model (hereafter referred to as "Meta's model") capable of predicting canopy height at submeter resolution worldwide.[30]

Meta's model produces canopy height maps at finer spatial resolution than prior maps, in part, because it uses high-resolution Maxar imagery, with a spatial resolution of ~0.6 meters, to make predictions. A key advantage of Meta's model is that it can be applied to multiple image sources (e.g., Airbus,[31] Maxar), which helps to increase its accessibility. Compared to other remote sensing data sources, Meta's model has the unique potential to optimize across key factors: spatial resolution, temporal resolution, and ability to provide insights into forest structure (**figure 2**). Meta's computer vision expertise, and significant computational resources contributed to the model's versatility and

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28. Tolan et al. 2023. Global Canopy Height. Google Earth Engine Apps. [accessed 2025 Jul 3]. https://meta-forest-monitoring-okw37.projects.earthengine.app/view/canopyheight.

29. Maxar Intelligence & Maxar Space Systems. c2025. Home. [accessed 2025 Jul 3]. https://www.maxar.com/.

30. Tolan J, Couprie C, Brandt J, Spore J, Tiecke T, Johns T, Nease P. 2024 Apr 22. Using Artificial Intelligence to Map the Earth's Forests. Meta Sustainability. [accessed 2025 Jul 3]. https://sustainability.atmeta.com/blog/2024/04/22/using-artificial-intelligence-to-map-the-earths-forests/.

31. Airbus. c2025. Satellite imagery | Earth observation satellites. [accessed 2025 Jul 3]. https://www.airbus.com/en/products-services/space/earth-observation/satellite-imagery.

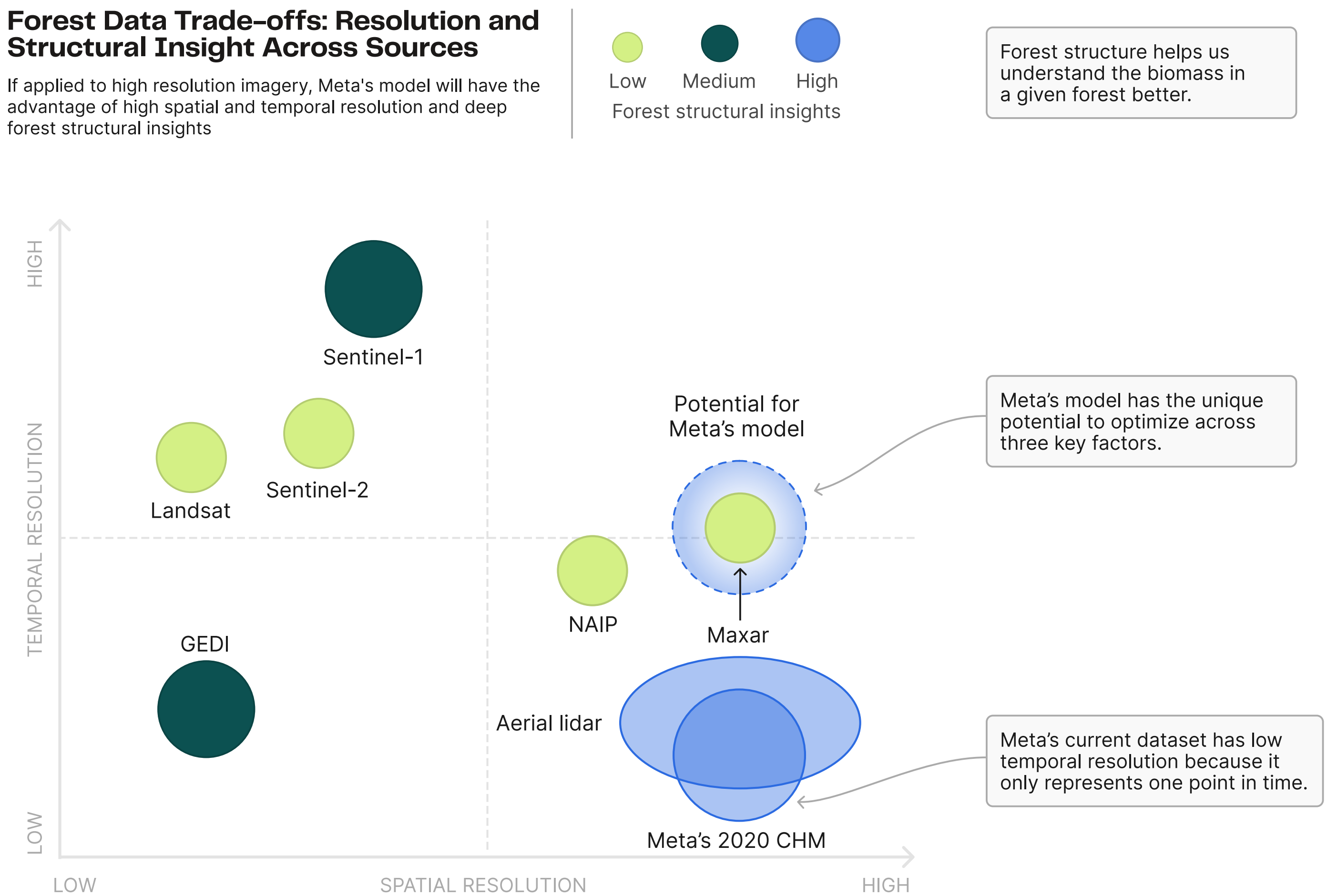


Figure 2. Remote sensing data sources vary in their spatial resolution (i.e., pixel size), temporal resolution (i.e., the frequency with which imagery available), and ability to provide insights into forest structure. Meta's model has the potential to optimize across these three factors. Note: CHM = canopy height map, GEDI = Global Ecosystem Dynamics Investigation, NAIP = National Agriculture Imagery Program (United States). Source: Carbon Direct.

training **(box 2)**. The model's estimates were based on millions of satellite images to help it learn spatial patterns on the landscape.

Meta's model recognizes features like tree crowns and shadows in images in much the same way as a human would interpret them. This allows the model to use spatial context (e.g., a long shadow is associated with a tall tree) to increase its accuracy in predicting canopy heights. When trained and validated with high-quality field data, deep learning approaches can improve predictive accuracy compared to traditional machine learning models and help address core challenges of data availability, resolution, and coverage. By reducing costs and enhancing methodological transparency, Meta's model aims to help pave the way for more reliable and accessible MMRV. We discuss how examples of these types of solutions are positioned to unlock more transparent, accessible, reliable, and scalable MMRV in the final section of this report.

Box 2. Training, validating, and calibrating remote sensing-based models

The process of building remote sensing-based models to estimate forest carbon attributes can be broken into three steps:

1. **Training:** First, scientists train the model by feeding it data for areas where both satellite imagery (or other input data) and field-based measurements are available and known.
2. **Validation:** Once the model is trained, scientists validate the model by testing it on data it has not seen before to see how well it performs, much like checking if a student really understands a lesson.
3. **Calibration:** Finally, scientists may calibrate a model by adjusting it to make its predictions line up even better with real-world measurements for a specific area or project.

Developers can expect the validation step to be especially important in scenarios where researchers are evaluating if a model that was trained in one forest type (e.g., temperate conifer forest) can be reliably applied to another forest type (e.g., tropical broadleaf forest). For example, Meta trained their model in forests in the United States where high-resolution satellite imagery and lidar-based measurements of canopy height were both known.[32] To evaluate how well their model performed in a tropical forest, Meta validated it in specific locations in Brazil, by quantifying model errors where canopy height was also known.

When the validation step reveals that a model trained in one location makes estimates that are consistently too high or too low (i.e., biased), scientists may calibrate these model instances.

Courses on these topics are available from NASA[33] and Coursera.[34]

32. Tolan J, Yang H-I, Nosarzewski B, Couairon G, Vo HV, Brandt J, Spore J, Majumdar S, Haziza D, Vamaraju J, et al. 2024. Very high resolution canopy height maps from RGB imagery using self-supervised vision transformer and convolutional decoder trained on aerial lidar. Remote Sensing of Environment. 300:113888. doi:10.1016/j.rse.2023.113888. [accessed 2025 Feb 19]. https://www.sciencedirect.com/science/article/pii/S003442572300439X.

33. NASA Applied Sciences. 2025. Applied Remote Sensing Training Program. [accessed 2025 Jul 3]. https://appliedsciences.nasa.gov/what-we-do/capacity-building/arset.

34. Coursera. c2025. Remote Sensing Image Acquisition, Analysis and Applications. [accessed 2025 Jul 3]. https://www.coursera.org/learn/remote-sensing.

Stakeholders

The VCM comprises a diverse range of stakeholders each with a concerted interest in how remote sensing data and modeling workflows are being integrated into project design and MMRV (table 1). Registries, in particular, are increasingly requiring that remote sensing data be used to support dynamic baselining.

Table 1. Key stakeholders with an interest in remote sensing for forest carbon project design, measurement, monitoring, reporting, and verification

Stakeholder	Description
Buyers	Carbon credit buyers (e.g., large corporations) use credits to offset emissions within their supply chain to help reach their climate goals. Buyers are not a monolith and often have their own quality criteria by which they evaluate project quality.
Data and analysis providers	Data and analysis providers, whether commercial or open-source, encompass private companies, academic labs, non-governmental organizations, and government agencies. These entities generate products on forest attributes (e.g., above-ground biomass, canopy height, or other structural metrics) using a mix of proprietary and publicly available methods. Some entities license robust, per-hectare data products derived from proprietary models, while others leverage in-house expertise and resources to deliver free, open data products, computational tools, and analysis pipelines. The boundary between commercial and open providers is fluid: most organizations can release both licensed and freely accessible outputs (e.g., Meta's canopy height map).
Domain experts	Domain experts possess expertise in a specific area such as remote sensing, machine learning, computer vision, and related fields that are advancing new technology and techniques. Domain experts can come from academia, government agencies, non-profit or local community organizations, and technology companies.
Project developers	Project developers are responsible for registering a carbon project with a registry and delivering credits. Among developers, technical capacity and resources for integrating remote sensing varies from highly sophisticated to very limited.
Registries and methodology working groups	Registries are the regulatory bodies that certify carbon projects and oversee credit issuance. They are responsible for ensuring that forest carbon projects comply with specific methodologies for project design and measurement, monitoring, reporting, and verification (MMRV). Registries often form working groups with domain experts to develop these methodologies. Some registries are starting to centralize digital MMRV in-house rather than ask developers to conduct the remote sensing analyses themselves.
Validation and verification bodies (VVBs)	VVBs are accredited third-party organizations that audit project methods to ensure that they comply with registry standards and methodologies.

Registries and dynamic baselines

Registries are increasingly recognizing that remote sensing data and modeling workflows can and should play a central role in advancing the transparency, reliability, and accessibility of MMRV. Some registries have consequently taken these approaches in-house, in the effort to standardize them and minimize potential project developer capacity constraints. Many registries' methodologies now require that project performance be estimated using remote sensing techniques, with methodologies that use a dynamic baseline being a core example.

> Dynamic baselines are an approach to forest carbon accounting that continuously updates estimates of carbon changes in the baseline scenario (i.e., what would have happened without the carbon project) using real-world data from comparable control areas.

Projects establish a dynamic baseline by selecting control plots located outside of a project's boundary to use as a basis of comparison when estimating the carbon stock changes within the project's boundary that are attributable to the project activity. When selecting control plots, remote sensing data can be used to maximize similarity of control plots to the project area (in terms of ecological and historical land management conditions). Calculating carbon stock changes based on a dynamic baseline typically involves monitoring changes to a remote sensing-based carbon stock estimate (commonly referred to as a "stocking index") at hundreds or thousands of locations through time. Stocking indices might refer to changes in AGB or vegetation height.[35] These serve as proxies for forest carbon, but project developers may use a number of stocking indices that vary in their suitability for this purpose.

Remote sensing data are therefore especially valuable for dynamic baseline approaches, as traditional field measurements are often too costly and logistically challenging to implement at landscape scales. Registries are continuing to recognize that project developers vary considerably in their technical and resource capacity for both field-based and remote sensing-based MMRV activities. This has prompted some registries to begin implementing remote sensing-based, "digital MMRV" approaches themselves (e.g., Isometric, Ecosystem Restoration Standard), which may portend a shift toward greater centralization of MMRV.

35. Souza CM, Roberts DA, Cochrane MA. 2005. Combining spectral and spatial information to map canopy damage from selective logging and forest fires. Remote Sensing of Environment. 98(2):329–343. doi:10.1016/j.rse.2005.07.013. [accessed 2025 May 1]. https://www.sciencedirect.com/science/article/pii/S0034425705002385.

Barriers to high-quality remote sensing for MMRV

There is considerable consensus among stakeholders regarding the potential for remote sensing data and models to enhance MMRV reliability and rigor. However, significant barriers are inhibiting the accessibility of these tools and their adoption. These barriers fall into three general themes: (1) governance and methodological alignment, (2) remote sensing data constraints, and (3) gaps in knowledge and infrastructure (**figure 3**).

Governance and methodological alignment

This theme focuses on the lack of clarity, consistency, and consensus around integrating remote sensing into forest carbon MMRV. Stakeholders clearly articulated a desire for institutional guidance and level-setting among developers, registries, and third parties on how to operationalize and assess remote sensing workflows and methodologies. Three main challenges fall under this theme, labeled A-C and described further below.

BARRIERS

Governance and methodological alignment

A. There is a lack of clarity, guidance, and consensus on what best practice looks like for MMRV.

B. Registries face difficulty balancing the need for methodological flexibility with the need to provide clear, actionable guidance in a quickly evolving field.

C. Validation and calibration is hindered by a lack of standardization and consensus on how to quantify and report uncertainty.

Remote sensing data constraints

D. Many data products with higher utility for MMRV are proprietary and costly to access.

E. Insufficient temporal and spatial resolution in datasets suitable for MMRV limits their ability to track forest dynamics, early regrowth, disturbance events, agroforestry projects, and forest structure in small parcels.

Knowledge and infrastructure gaps

F. Lack of expertise and computational resources among developers and registries is a considerable barrier to introducing remote sensing into MMRV.

G. There is skepticism regarding the accuracy and reliability of remote sensing-based estimates of forest structure.

H. A lack of suitable and project-specific validation and calibration data makes it difficult to know which data products are suitable for particular locations and applications.

Figure 3. Barriers to unlocking more transparent, accessible, reliable, and scalable remote sensing for forest carbon MMRV. These barriers fall into three main categories: governance and methodological agreement, remote sensing data constraints, and gaps in knowledge and infrastructure. Source: Carbon Direct

A. There is a lack of clarity, guidance, and consensus on what best practice looks like for MMRV. It is often unclear which data products and models represent best practice, making it difficult for project developers and buyers to navigate and implement high-quality, remote sensing-based, monitoring frameworks. In most cases, developers are responsible for implementing credible, conservative, and scientifically rigorous MMRV regardless of their technical remote sensing capacity.

Developers can be hesitant to adopt new remote sensing approaches for two reasons: (1) it is unclear which remote sensing approaches will be accepted by registries, validation and verification bodies (VVBs), and credit buyers; and (2) implementing remote sensing analytics involves significant cost, which means that developers need to feel assured that the investment is worthwhile. Developers are hesitant to invest resources in remote sensing for MMRV unless they have assurance that registries, VVBs, and credit buyers


Rainforest morning fog. Source: Adobe Stock.

will deem their MMRV approaches acceptable. Meanwhile, prospective corporate offtake partners are hesitant to invest in credit purchases without confirming that science-based MMRV are foundational to a project's credit generation.

Working groups like the Science for High Integrity Frameworks to Transform Carbon Markets[36] and the NASA Carbon Monitoring System[37, 38] are advancing highly valuable technical leadership in remote-sensing based MMRV. These groups offer positive starting points and could help in the effort to promote a broader consortium. This consortium would provide a forum for registries, buyers, developers, and other stakeholders to come together to prioritize standardization and guidance for the use of remote sensing datasets, workflows, and applications in forest carbon MMRV. Ultimately, clear and explicit explanations for how to integrate remote sensing into protocol requirements and carbon accounting practices would be helpful. Some existing examples include the American Carbon Registry (ACR), which is developing a framework on quantification of forest carbon using remote sensing, and Meta, which is working with Carbon Direct to release a guide for applying their canopy height map and underlying model to forest carbon projects. These are welcome contributions, but a broader industry effort is also needed.[39]

> "The decision is [to] go with something that doesn't have a broad consensus or do nothing."
>
> —Project developer, on choosing remote sensing data and workflows

B. Registries face difficulty balancing the need for methodological flexibility with the need to provide clear, actionable guidance in a quickly evolving field. Limited resources, lack of data transparency, and the rapid emergence of novel remote sensing datasets contribute to regulatory uncertainty and make rigorous scientific evaluation difficult. Registries expressed concerns about their technical and operational capacity to properly assess new and existing datasets, particularly at the pace that novel data products are being released.

Rigorously assessing new remote sensing models and datasets requires technical capacity, is time-intensive, and must be done in an idiosyncratic way for each dataset. While some registries are bringing remote sensing expertise and modeling in house,

36. Science for High Integrity Frameworks to Transform Carbon Markets (SHIFT-CM). 2024. Developing Good Practice Guidance for Natural Climate Solutions Research. [accessed 2025 Jul 2]. https://docs.google.com/document/d/1cuWO5dei1wZo3DFxW9dlOzxzmY4e8MBmMU2Lvro8YB4/edit?tab=t.0#heading=h.p3etfhp4d0g1.

37. Established in 2010, the NASA Carbon Monitoring System is a science initiative that supports the development of knowledge and prototyping capabilities across a range of systems, scales, and regions, with a focus on remote sensing applications for MMRV systems. Scientists funded by NASA's Carbon Monitoring System use remotely sensed data, computational tools, scientific expertise, and system-level capabilities available through the NASA Earth Science program.

38. NASA Carbon Monitoring System. nd. Home. [accessed 2025 Jun 18]. https://carbon.nasa.gov/cms/.

39. Carbon Direct and Meta. 2025. Integrating Meta's Canopy Height Map into Forest Carbon Methodologies: A Tactical Guidebook. https://www.carbon-direct.com/research-and-reports/meta-guidebook

> [T]hey get pitched something new every other week [. . .] it's just a barrage of information being thrown at them and they have no way to parse it."
>
> —Project developer, on registries and the rapid pace of remote sensing technology and data development

the reality is that most registries do not have the resources for this, which results in many remote sensing MMRV approaches remaining in a state of regulatory uncertainty. For example, aside from its use in ACR's IFM v2.1 methodology[40] as a matching variable for merchantability, Meta's global canopy height dataset lacks explicit approval from registries and VVBs for other applications.[41]

Lack of alignment on what constitutes a high-quality remote sensing framework for MMRV also stems from the fact that registries, corporate investors, and credit buyers each have their own criteria for evaluating high-quality CDR. Additionally, private data providers and registries are not always transparent about the methods they use to train and test models in order to protect intellectual property (IP), further complicating the ability of registries to provide clear guidelines. There is an opportunity to shift from competition to collaboration—enabling private actors to build trust in carbon markets by balancing IP protection with greater transparency. Some developers and diligence providers have noted that this can limit the use of new remote sensing datasets, because information on how the data were generated is often viewed as being fundamental for their scientific evaluation. These challenges highlight the need for an MMRV consortium where registries can work together, with support from the scientific community, to define clear criteria for high-quality remote sensing data and strike a better balance between IP protection and transparency.

C. Validation and calibration is hindered by a lack of standardization and consensus on how to quantify and report uncertainty. Without data specific to the project, or at least the project's forest type, developers must rely on existing uncertainty estimates that may or may not be appropriate for the project context. The data that are available for local calibration and validation of AGB, often referred to as "ground-truth data," usually come from forest inventory plots that are measured in the field. AGB estimates derived from forest inventory plots are based on allometric equations, which have their own uncertainties and systematic biases,

40. American Carbon Registry [ACR]. 2024. Improved Forest Management On Non-Federal U.S. Forestlands, Version 2.1. [accessed 2025 Jul 2]. https://acrcarbon.org/wp-content/uploads/2022/07/ACR-Methodology-IFM-on-Non-Federal-US-Forestlands-v2_1-20240701.pdf.

41. At the time of this writing, ACR is close to releasing a more comprehensive framework to guide the use of remote sensing for their methodologies.

making them a suboptimal source of truth.[42, 43] Furthermore, the geographic distribution of these datasets are skewed toward the Global North, while large data gaps exist in the Global South, further contributing to inequities in carbon market access and influence. This is problematic given that a considerable proportion of forest carbon projects take place in the Global South, where emission abatement costs are generally lowest.[44] Investing in MMRV systems in the Global South is a critical need because projects in these regions face persistent data challenges. Data are often difficult to access and unstandardized, making calibration and validation efforts labor-intensive and idiosyncratic. This presents a significant barrier for many landowners and developers. Through the consortium we propose, initiatives to improve data availability and capacity building could enable more equitable participation in carbon markets. Further technical details on this barrier are included in this report's *Appendix*.

Remote sensing data constraints

This theme focuses on technical data limitations including availability, spatial and temporal resolution, and cost. Two main challenges fall under this theme, labeled D-E and described further below.

D. Many data products with higher utility for MMRV are proprietary and costly to access.

A majority of project developers noted that they would like to integrate remote sensing biomass datasets into MMRV approaches, but that these datasets are prohibitively expensive at the required spatial extents, or are not easily modified for evaluating AGB estimates over space and time. Biomass products are generally purchased on a per-area basis and the vast majority of developers we spoke to emphasized that purchasing these data is not economically viable for their required areas and temporal frequency. As more registries require some degree of dynamic baselining (which are likely to evolve alongside datasets and analytical frameworks) developers will need to monitor greater spatial extents (see the *Registries and dynamic baselines* section of this report). Similar to biomass products, the cost of purchasing high-resolution remote sensing imagery is prohibitive for many developers. They expressed an interest in more affordable and centralized models to reduce financial strain. Some newer registries have pushed for more centralized, digital MMRV. This is partly motivated by the cost and technical capacity burdens smaller project developers face as well as by the lack of clear, scientific consensus on which datasets are appropriate for specific projects and purposes.

42. Malhi Y, Phillips OL, Chave J, Condit R, Aguilar S, Hernandez A, Lao S, Perez R. 2004. Error propagation and scaling for tropical forest biomass estimates. Philosophical Transactions of the Royal Society of London Series B: Biological Sciences. 359(1443):409–420. doi:10.1098/rstb.2003.1425. [accessed 2025 Mar 25]. https://royalsocietypublishing.org/doi/abs/10.1098/rstb.2003.1425.

43. Demol M, Aguilar-Amuchastegui N, Bernotaite G, Disney M, Duncanson L, Elmendorp E, Espejo A, Furey A, Hancock S, Hansen J, et al. 2024. Multi-scale lidar measurements suggest miombo woodlands contain substantially more carbon than thought. Commun Earth Environ. 5(1):1–11. doi:10.1038/s43247-024-01448-x. [accessed 2025 Apr 25]. https://www.nature.com/articles/s43247-024-01448-x.

44. Karnik A, Kilbride JB, Goodbody TRH, Ross R, Ayrey E. 2025. An open-access database of nature-based carbon offset project boundaries. Sci Data. 12(1):581. doi:10.1038/s41597-025-04868-2. [accessed 2025 Apr 24]. https://www.nature.com/articles/s41597-025-04868-2.

E. Insufficient temporal and spatial resolution in datasets suitable for MMRV limits their ability to track forest dynamics, early regrowth, disturbance events, agroforestry projects, and forest structure in small parcels. Remote sensing products generated at annual or sub-annual timesteps are critical for developers and registries to effectively detect changes over time. However, aerial lidar and many other high-resolution remote sensing sources (e.g., aerial imagery) are often available for only a single point in time, have multi-year gaps between updates, or are prohibitively expensive to acquire. Alignment among standards and other key market actors could create the demand signal needed for these products to be generated at more optimal timesteps.

Datasets with high spatial and temporal resolution are important for monitoring agroforestry projects, forest degradation, and selective harvesting regimes.[45] Some IFM project developers have identified potential in high-resolution remote sensing data for monitoring subtle signs of forest degradation, like selective logging at project edges. However, they remain uncertain as to whether current tools are capable of reliably detecting such nuanced structural changes. More targeted approaches, such as regional aerial lidar campaigns or drone acquisition, may be required to track these changes, but these methods are logistically complex and expensive. Even globally available remote sensing data with adequate temporal frequency often falls short in capturing key forest structure attributes, such as AGB and canopy height, which are essential for implementing robust MMRV approaches.

Knowledge and infrastructure gaps

This theme focuses on the challenges surrounding practical implementation of remote sensing including stakeholders' technical experience, lack of computational resources, and limited capacity to acquire or source suitable validation data. Three main challenges fall under this theme, labeled F–H and described further below.

F. Lack of expertise and computational resources among developers and registries is a considerable barrier to introducing remote sensing into MMRV. While some larger developers maintain in-house teams, smaller and non-profit project developers often lack the resources and technical capacity to ingest, process, and analyze remote sensing data. This is especially true for large project areas and high-resolution datasets. Both developers and registries noted that keeping pace with new remote sensing technologies and products is challenging. Developers stated that turnkey, user-friendly remote sensing tools and up-to-date technical transfer resources would go a long way in promoting best practices. While building internal capacity on projects is seen as important, outsourcing remains common due to resource constraints. However, project developers working with Indigenous communities and Tribal nations raised concerns about data sovereignty and the need to fully vet any third-party remote sensing providers.

G. There is skepticism regarding the accuracy and reliability of remote sensing-based estimates of forest structure. Some of this skepticism is driven

45. Heterogeneous planting designs are particularly difficult to classify and characterize using standard land cover approaches.

by poor corroboration between analogous forest structure datasets and field measurements. Some developers noted that large errors in estimating canopy height hinder their ability to monitor changes in canopy cover, making it challenging to track forest disturbance and regrowth. Uncertainty estimates reported in the scientific literature support these concerns.[46] Developers, particularly those working on ARR projects, noted that existing biomass remote sensing products were especially insufficient for early-stage, regenerating forests. This is problematic because inaccurate quantification of carbon stocks within the first monitoring period and issuance event can result in considerable lost revenues for project developers.

> "A lot of these models [. . .] perform much better at very high levels of biomass [. . .] so that at low stocking values you see [. . .] erroneous results and those are the actual moments that matter the most for a reforestation project that is trying to get to market as quickly as possible with accurate numbers of credits."
>
> —Project developer, on using remote sensing datasets for early-stage regeneration assessment and crediting

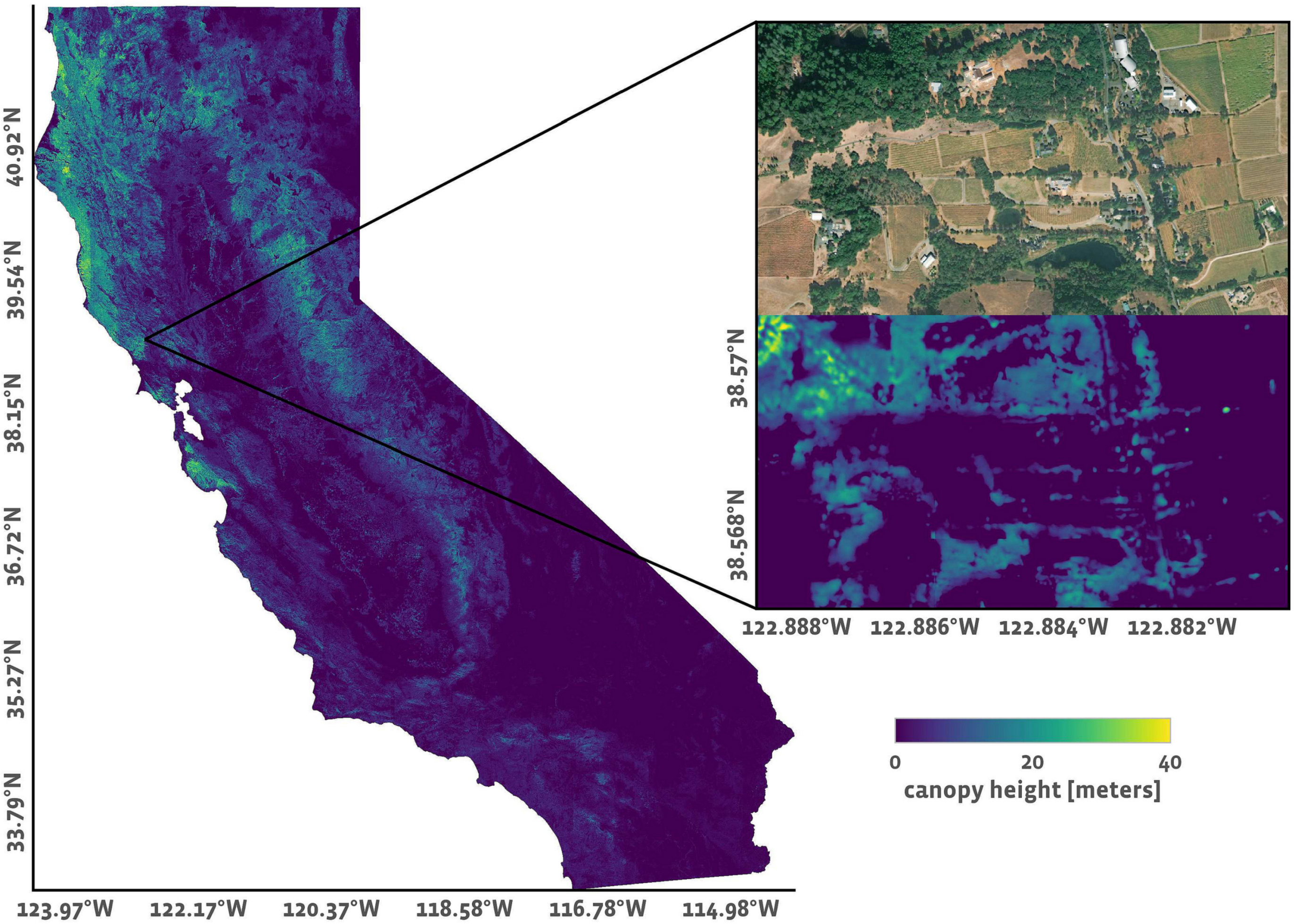
H. A lack of suitable and project-specific validation and calibration data makes it difficult to know which data products are suitable for particular locations and applications. The developers of remote sensing models and data products need access to more high-quality ground truth data that capture variation in forest structure across forest types and management regimes (including privately managed forests). Even where global models and datasets have been validated, stakeholders still require guidance on how to determine where a model or dataset can be applied, if previously reported model uncertainty estimates apply to their project area, and how they should go about producing uncertainty estimates that are specific to their project.[47] Determining where and when a model is appropriate is essential for deciding if a model can be used as is, or if additional validation or calibration is needed.

Unfortunately, there's no broad consensus in academia or the forest carbon project community on how to define the geographic area that an uncertainty estimate covers. This leads to a lack of clarity around which datasets are appropriate for

46. Lang N, Jetz W, Schindler K, Wegner JD. 2023. A high-resolution canopy height model of the Earth. Nat Ecol Evol. 7(11):1778–1789. doi:10.1038/s41559-023-02206-6. [accessed 2025 Jul 14]. https://www.nature.com/articles/s41559-023-02206-6.

47. Duncanson L, Hunka N, Jucker T, Armston J, Harris N, Fatoyinbo L, Williams CA, Atkins JW, Raczka B, Serbin S, et al. 2025. Spatial resolution for forest carbon maps. Science. 387(6732):370–371. doi:10.1126/science.adt6811. [accessed 2025 Apr 24]. https://www.science.org/doi/10.1126/science.adt6811.

specific projects and purposes. Some developers take it upon themselves to validate and calibrate global models with field data from their project areas. This lets them create uncertainty estimates tailored to each project, but their methods are often unique and not transparent. Further, many developers lack the resources or expertise to do this. It is hard for the industry to quickly evaluate the robustness of uncertainty estimates across diverse datasets and use cases.



Canopy height map for the state of California, inset showing zoomed in region with input RGB imagery. Source: Tolan J, et al. 2024. Very high resolution canopy height maps from RGB imagery using self-supervised vision transformer and convolutional decoder trained on aerial lidar. https://doi.org/10.1016/j.rse.2023.113888. Licensed under CC BY 4.0.

Building a community: Recommendations and pathways forward

Our interviews and analysis found a common wish among stakeholders—a forest carbon MMRV consortium should be built and tasked with pioneering actionable and industry-wide standards for remote-sensing and MMRV. Forming such a consortium could be a critical step in aligning forest carbon MMRV practices and improving the integrity of the VCM. It should be inclusive and diverse, support both technology transfer and capacity building, and clearly articulate roles and responsibilities (such as those suggested in **table 2**). By systematically linking MMRV science and technology with approval bodies (registries and VVBs), the consortium could help create a more consistent cycle of learning, evaluation, and adoption. Representatives of these stakeholders would each be critical in the creation of a forest carbon MMRV consortium tasked with establishing consensus, developing standards, and enacting recommendations (**figure 4**).

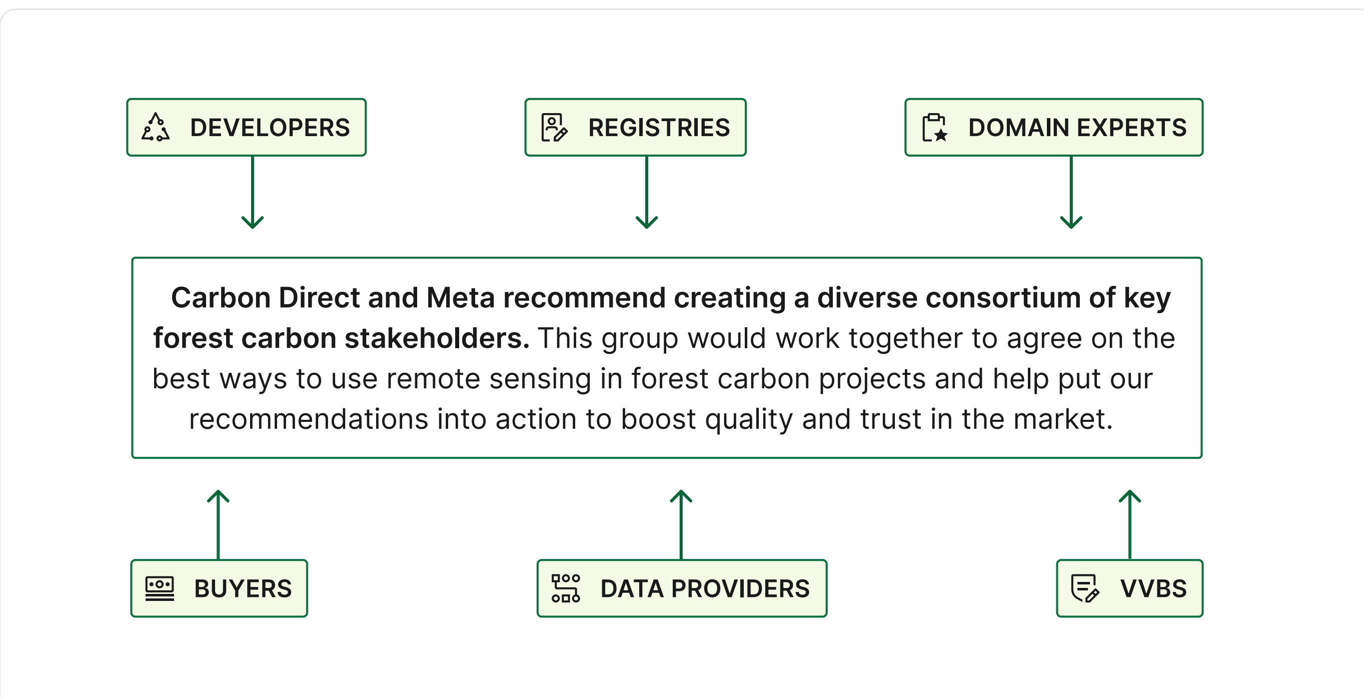


Figure 4. Multi-stakeholder consortium concept for implementing remote sensing guidance in forest carbon projects. Source: Carbon Direct.

Table 2. Recommendations for unlocking more transparent, accessible, reliable, and scalable remote sensing for MMRV of forest carbon projects, with relevant stakeholder

	Stakeholder					
Recommendation	**Buyers**	**Domain experts**	**Data and analysis providers**	**Project developers**	**Registries**	**VVBs**
Define acceptable remote sensing data and workflows that allow flexibility as technologies evolve.	✓	✓	✓	✓	✓✓	✓
Clearly define where specific remote sensing datasets and models are geographically applicable.		✓✓			✓	
Align on the role of uncertainty in credit issuance.	✓				✓✓	
Standardize how data providers evaluate and report uncertainty.		✓			✓✓	
Create a global benchmarking dataset.			✓✓			
Develop a centralized remote sensing data portal for forest carbon MMRV.		✓✓	✓	✓		
Apply new deep learning models to unlock new remote sensing applications.		✓✓	✓			

Note: All stakeholder opinions should be considered for all opportunities, but each requires a lead actor and some core participants. Recommended lead actor(s) are indicated with a double check mark, and stakeholders who should be heavily involved are indicated with a single check mark. Registries are likely to require technical advisory bodies that include domain experts to effectively implement recommendations.

We envision that this consortium would serve as a trusted forum for establishing consensus about which, and how, remote sensing tools should be used; enabling co-development of technical standards that industry players can rely on; and translating consensus-driven recommendations into practice. By fostering cross-sector collaboration, this consortium could drive consistent, science-based advancement while ensuring the system remains inclusive, adaptive, and grounded in real-world needs.

Based on the barriers we identified above, we propose seven recommendations that a consortium could prioritize to unlock more transparent, accessible, reliable, and scalable remote sensing for forest carbon MMRV (figure 5).

BARRIERS

Governance and methodological alignment

A. There is a lack of clarity, guidance, and consensus on what best practice looks like for MMRV.

B. Registries face difficulty balancing the need for methodological flexibility with the need to provide clear, actionable guidance in a quickly evolving field.

C. Validation and calibration is hindered by a lack of standardization and consensus on how to quantify and report uncertainty.

Remote sensing data constraints

D. Many data products with higher utility for MMRV are proprietary and costly to access.

E. Insufficient temporal and spatial resolution in datasets suitable for MMRV limits their ability to track forest dynamics, early regrowth, disturbance events, agroforestry projects, and forest structure in small parcels.

Knowledge and infrastructure gaps

F. Lack of expertise and computational resources among developers and registries is a considerable barrier to introducing remote sensing into MMRV.

G. There is skepticism regarding the accuracy and reliability of remote sensing-based estimates of forest structure.

H. A lack of suitable and project-specific validation and calibration data makes it difficult to know which data products are suitable for particular locations and applications.

RECOMMENDATIONS

1. Define acceptable remote sensing data and workflows that allow flexibility as technologies evolve. (A, B)
2. Clearly define where specific remote sensing datasets and models are geographically applicable. (D)
3. Align on the role of uncertainty in credit issuance. (G)
4. Standardize how data providers evaluate and report uncertainty. (B, G)
5. Create a global benchmarking dataset. (F)
6. Develop a centralized remote sensing data portal for forest carbon MMRV. (E, H)
7. Apply new deep learning models to unlock new remote sensing applications. (C)

Figure 5. Recommendations for unlocking more transparent, accessible, reliable, and scalable remote sensing for forest carbon MMRV. Letters correspond to barriers described in the previous section. Source: Carbon Direct.

RECOMMENDATION 1: Define acceptable remote sensing data and workflows that allow flexibility as technologies evolve. This should be done while avoiding the pitfalls of standardization and centralization (**box 3**). An important step to unlock reliable and accessible remote sensing in carbon projects is to develop consensus and standardization among registries, project developers, VVBs, and domain experts on which remote sensing data products are acceptable for specific carbon project applications. Registries could be well positioned to lead the development of robust digital MMRV frameworks, helping to allocate resources and accelerate project evaluation for buyers. This should be done with significant guidance from domain experts, particularly when parsing how relevant the latest science is to the VCM. However, determining exactly what should be standardized, and what, if anything, should be centralized, is nuanced and will require careful collaboration among stakeholders to avoid potential pitfalls (**box 3**).

RECOMMENDATION 2: Clearly define where specific remote sensing datasets and models are geographically applicable. Building on **Recommendation 1**, once consensus on broad workflows for remote sensing data is reached, we must determine the geographic applicability of specific datasets. Estimation uncertainty varies over space and time. It also changes depending on geographic location and the forest type being analyzed. Even when datasets are validated and uncertainty is reported, there can still be questions

Box 3. Pitfalls to avoid when working toward consensus and standardization of acceptable remote sensing datasets and methods for forest carbon project MMRV

1. **Being overly prescriptive about acceptable datasets or analytical approaches:** The field of remote sensing is evolving rapidly, so some flexibility is required to stay in sync with the latest science. Different remote sensing approaches may be suitable for different project types (e.g., IFM versus ARR) and regions (e.g., tropical versus temperate forests). There is no single approach that will work best everywhere.
2. **Overwriting place-based traditional knowledge and local data:** Solutions must be collaborative, inclusive, context-sensitive, and designed to empower local stakeholders, not replace them. Where applicable, local and regional data should be prioritized to inform project baselines and modeling.
3. **Losing transparency as a result of centralization:** Any form of centralization must be made accessible and transparent to enable regular and robust third-party technical reviews of standards as they evolve with the latest science.
4. **Asking for full transparency and open access where it is not economically feasible:** Commercial data and analytics providers will continue to create intellectual property that needs to be protected to help incentivize data collection, innovation, and competition.

about where a dataset can be appropriately used. We recommend that domain experts work with registries to reach consensus on how to determine and report the acceptable spatial, geographic, and ecological boundaries (i.e., the inference space) of where a model or data product can be used. Most remote sensing models are already trained and validated using some form of ground-truth data, but ground-truthing exercises are often limited in geographic scope. The overarching goal for alignment and standardization should be to make the uncertainty estimates of datasets easier to interpret and relevant to decision-making for specific project areas and project sizes.

RECOMMENDATION 3: Align on the role of uncertainty in credit issuance. Once model limitations are clearly defined (**Recommendation 2**), this step can help translate uncertainty into practical terms for the market. We recommend that the consortium facilitate a public-facing discussion among buyers, registries, scientific experts, and standard-setters (e.g., the Integrity Council for the Voluntary Carbon Market,[48] International Carbon Reduction and Offset Alliance)[49] to improve alignment on acceptable levels of uncertainty for carbon project applications. This could also facilitate an understanding of how uncertainty might affect willingness to pay. Nature's inherent variability will always contribute to uncertainty in estimates of forest carbon project performance. There is a need to build consensus on how much accuracy and precision is considered enough. We could use the errors associated with field-based methods as a starting point (field-based methods have higher levels of error than many may realize).

RECOMMENDATION 4: Standardize how data providers evaluate and report uncertainty. This recommendation requires that model uncertainties are well defined (**Recommendation 2**), and that avenues for market integration are clearly established (**Recommendation 3**). Rather than certifying specific datasets, we recommend that domain experts, data providers, and registries collaborate on working toward more standardized methods for evaluating and reporting the reliability of remote sensing data products for specific carbon project activities and regions. This may require some innovation in how private registries and companies can retain their IP while also making parts of their model approaches and validation process transparent. A key element of this standardization process will be aligning on what types of data can be used for generating uncertainty estimates. A robust form of ground-truth data could come from the combination of terrestrial[50] and aerial lidar[51] which can create more accurate

48. The Integrity Council for the Voluntary Carbon Market [ICVCM]. c2025. Leading the way to a high integrity Voluntary Carbon Market. [accessed 2025 Jun 20]. https://icvcm.org/.

49. International Carbon Offset and Reduction Alliance [ICROA]. c2025. Accrediting Best Practice in Carbon Offsetting. [accessed 2025 Jun 20]. https://icroa.org/.

50. Yang W, Wilkes P, Vicari MB, Hand K, Calders K, Disney M. 2024. Treegraph: tree architecture from terrestrial laser scanning point clouds. Remote Sensing in Ecology and Conservation. 10(6):755–774. doi:10.1002/rse2.399. [accessed 2025 Apr 25]. https://onlinelibrary.wiley.com/doi/abs/10.1002/rse2.399.

51. Rodda SR, Fararoda R, Gopalakrishnan R, Jha N, Réjou-Méchain M, Couteron P, Barbier N, Alfonso A, Bako O, Bassama P, et al. 2024. LiDAR-based reference aboveground biomass maps for tropical forests of South Asia and Central Africa. Sci Data. 11(1):334. doi:10.1038/s41597-024-03162-x. [accessed 2025 Apr 25]. https://www.nature.com/articles/s41597-024-03162-x.

estimates of AGB than allometric equations applied to field inventory plots.[52] Another key element of this effort will be working with domain experts to outline standardized evaluation metrics. For example, domain experts should work with registries to confirm what the most appropriate error metric is (e.g., mean absolute error, 90% confidence interval, etc.), on what spatial scales uncertainty should be calculated, and how data providers should report model uncertainty. Aligning on answers to these questions will help clarify model applications and limitations.[53]

RECOMMENDATION 5: Create a global benchmarking dataset. With evaluation standards clearly established (**Recommendation 4**), dataset benchmarking can be reliably achieved. Domain experts and data providers should lead the effort of developing a standardized, global benchmarking dataset that includes benchmarks that are specific to regions, or at least to forest types. This benchmarking dataset would contain ground-based estimates of AGB and canopy height from intensively sampled sites that, at a minimum, cover all of the forest types where forest carbon projects are implemented. Efforts to incentivize data collection and sharing (e.g., through buyer contracts) should be prioritized in the Global South, where there are currently large data gaps and where baseline project costs are generally lower. As the dataset matures, it should include more detailed coverage within specific forest types. Although this dataset could be used to train, validate, and calibrate remote sensing-based models, its primary purpose would be to standardize the validation of a models' ability to predict AGB and canopy height in different areas of the globe. Crucially, this would provide a standardized means to develop uncertainty estimates for a wide range of data products. The benchmarking dataset would enable a project developer to quickly see each potential data product's performance in their forest type. Rather than standardizing the data products themselves it would standardize the means of evaluating a diverse and evolving array of data products and models.

The industry must determine who is responsible for maintaining and standardizing this benchmarking dataset. The question of who will provide these data and how data collection efforts will be funded is yet to be answered, though examples of remote sensing benchmarking datasets are becoming more common.[54] Data collected by developers could be used for this purpose without necessarily requiring data providers to make their data 100% transparently and freely available, because this wouldn't incentivize spending large amounts of time and money on ground-truth data collection. A coordinated and collaborative effort to collect ground-truth data—specifically to enable more transparent, accessible, reliable, and scalable remote sensing for carbon project MMRV—would be a standout opportunity for philanthropic support, helping to make as much of the resulting benchmarking dataset as possible

52. Demol M, Aguilar-Amuchastegui N, Bernotaite G, Disney M, Duncanson L, Elmendorp E, Espejo A, Furey A, Hancock S, Hansen J, et al. 2024. Multi-scale lidar measurements suggest miombo woodlands contain substantially more carbon than thought. Commun Earth Environ. 5(1):1–11. doi:10.1038/s43247-024-01448-x. [accessed 2025 Apr 25]. https://www.nature.com/articles/s43247-024-01448-x.

53. National Aeronautics and Space Administration [NASA]. 2021. Land Product Validation Subgroup (Working Group on Calibration and Validation C on EOS. Aboveground Woody Biomass Product Validation Good Practices Protocol. doi:10.5067/DOC/CEOSWGCV/LPV/AGB.001. [accessed 2025 Jun 4]. http://lpvs.gsfc.nasa.gov/documents.html.

54. Puliti S, Lines ER, Müllerová J, Frey J, Schindler Z, Straker A, Allen MJ, Winiwarter L, Rehush N, Hristova H, et al. 2025. Benchmarking tree species classification from proximally sensed laser scanning data: Introducing the FOR-species20K dataset. Methods in Ecology and Evolution. 16(4):801–818. doi:10.1111/2041-210X.14503. [accessed 2025 Apr 25]. https://onlinelibrary.wiley.com/doi/abs/10.1111/2041-210X.14503.

available as a public good. A coordinated effort is likely to help create more reliable and transparent products, improve conformance with ESG goals and corporate social responsibility, and develop a new normal for validation of nature-based projects. Data collection efforts could also be funded by the price premium that more rigorously validated and calibrated models would command, which also links well with **Recommendation 3**. An ensemble of data sources and quantification approaches in each benchmarking region could be used to help determine the truth. Some registries have already evaluated multiple data providers and have suggested that an ensemble approach could be useful for estimating AGB.

Data that are included in the benchmarking dataset should be collected in a way that is conducive to validating remote sensing data. Most of the ground-truth data currently used for this purpose was not collected for the explicit purpose of validating remote sensing models and data products. Field plots need to be large enough to match with pixels after accounting for positional error. Secondly, field data used as ground-truth data should not be subject to systematic biases, such as the tendency of many allometric models to systematically underpredict the AGB of large trees.[55] Some researchers are already using methods such as integrating terrestrial lidar with aerial lidar which can produce AGB maps with low uncertainty.[56] These methods are being applied to sampling designs for the explicit purpose of scaling up inferences and validating remote sensing models. They likely provide greater certainty than using traditional field plots and allometric equations. Nevertheless, determining the most appropriate source of truth for model training and validation is still a topic of academic debate and will likely change in the future. Therefore, some flexibility in benchmarking standards and data sources is required, with an emphasis on developing approaches that reduce estimated uncertainties over space and time.

In addition to avoiding the pitfalls of standardization and centralization discussed in **box 3**, there are two additional important considerations for the development of a global benchmarking dataset. First, any global benchmarking effort must be compatible across the registries. During the Meta-hosted workshop conducted as part of this analysis, one registry expressed that they would use this information to help with decision-making, but it wouldn't replace their methods. While a benchmarking dataset would be most useful if registries accepted and interpreted the data consistently, a reality of the industry is that registries differentiate themselves by developing their own standards. Providing variable offerings is important and promotes competition. However, if a lack of alignment on dataset standardization and centralization persists, it will likely continue to foster challenges with data applicability, efficacy, uncertainty, and transparency. Mitigating these challenges will require that registries collaborate and align on benchmarking needs. Second, a global benchmarking dataset must account for constraints that are specific to individual projects, registries, and applications.

55. Demol M, Aguilar-Amuchastegui N, Bernotaite G, Disney M, Duncanson L, Elmendorp E, Espejo A, Furey A, Hancock S, Hansen J, et al. 2024. Multi-scale lidar measurements suggest miombo woodlands contain substantially more carbon than thought. Commun Earth Environ. 5(1):1–11. doi:10.1038/s43247-024-01448-x. [accessed 2025 Apr 25]. https://www.nature.com/articles/s43247-024-01448-x.

56. Demol M, et al., Multi-scale lidar measurements.

RECOMMENDATION 6: Develop a centralized remote sensing data portal for forest carbon MMRV. Following establishment of dataset benchmarks (**Recommendation 5**), an infrastructure to house data can be created to facilitate reliable application of the data. Data providers should lead the effort of developing a centralized data portal where MMRV-relevant, high-resolution imagery and data products are made available to developers, registries, and other stakeholders. Building on **Recommendations 1, 2, and 4,** datasets on the portal would meet agreed-upon quality criteria that are determined with consistent approaches, and data providers would report uncertainty in a standardized way. The portal could host both open source and licensable models and data products. This would allow data to become more accessible while also allowing for the sale of commercial data, which would incentivize investment in new data collection and model development. If the portal also includes a mechanism to signal demand, higher-resolution data (spatial and temporal) could be made available in specific areas and time periods of interest. This portal could integrate with or build on existing data portals such as the Google Earth Engine Data Catalog[57] or ESA Earth Online.[58]

The recommended data portal must be designed so that registries that are trying to bring digital MMRV in house (e.g., Isometric, Ecosystem Restoration Standard) could integrate with it. Registries could perhaps build on top of the data portal and use it as a starting point for determining their own metrics of quality (**Recommendation 4**). Further technical details on the proposed portal design are included in this report's *Appendix*.

RECOMMENDATION 7: Apply new deep learning models to unlock new remote sensing applications. This recommendation relies on all previous recommendations, as it requires a thorough understanding of model uncertainties, establishment of stable infrastructures, and well-defined standards for use. Domain experts and data providers should leverage deep learning and computer vision models to produce more reliable forest structure data products with lower uncertainty and higher spatial and temporal resolution. Deep learning architectures (e.g., vision transformers),[59] such as those used by Meta's model (**box 4**), have the potential to produce more accurate and geographically consistent estimates of forest structural attributes compared to classical machine learning methods (e.g., random forests, support vector machines). Generally, even the most technically competent and well-resourced developers and registries do not work with deep learning and computer visions models. Therefore, a critical step toward the adoption of these models for forest carbon project development will be implementing them as easy-to-use features of a data portal (**Recommendation 6**). We recommend providing these layers at multiple spatial and temporal resolutions so that the user can match the resolution to their needs and computational resources. Users could work with lower-resolution data when high-resolution detail is unnecessary and computational resources are limited.

57. Google for Developers. nd. Earth Engine Data Catalog. [accessed 2025 Jun 4]. https://developers.google.com/earth-engine/datasets.

58. European Space Agency. nd. Data - Earth Online. [accessed 2025 Jun 4]. https://earth.esa.int/eogateway/catalog.

59. Vision transformers have the advantage of providing more spatially coherent maps of canopy height or carbon stocks compared to the patchier per-pixel classification approaches that are not spatially aware. They also have the exciting potential to leverage relatively accessible and temporally rich optical imagery to create time series of forest structural attributes like AGB and canopy height that are more challenging to derive.

Box 4. Applying Meta's model to carbon project design and MMRV

Meta's model is well-positioned to unlock new applications for forest carbon MMRV. The model uses a vision transformer that leverages spatial context from high-resolution imagery to make predictions about forest structure. This approach can reduce the tendency of canopy height models to not capture tall canopies . In the companion piece to this paper,[60] we discuss how Meta's model can be used in three common methodologies. Here, we call out some particularly novel and exciting current and future applications:

- **Monitoring agroforestry projects:** Submeter canopy height data could facilitate tree counting in agroforestry plots that use census-based methods for monitoring project performance and reversals.
- **Counting individual trees in sparsely forested ecosystems:** The ability to count individual trees could facilitate the quantification of natural regeneration baselines and project performance in sparsely forested areas such as Sahelian savannas, Miombo woodlands, and Brazilian Cerrado.
- **Identifying old-growth forest and other areas of conservation priority:** Many attributes of old-growth forests, such as very tall trees, canopy gaps, and understory complexity, are detectable with high-resolution canopy height data.
- **Quantifying biodiversity benefits:** Structural heterogeneity is often an indicator of biodiversity and can be used to create benchmarks in reference ecosystems or to quantitatively set forest structure goals. Different species of concern have specific forest structure requirements. Meta's model is well positioned to be used as a tool in identifying specific forest areas with high conservation value and tracking progress toward restoring specific habitats.
- **Quantifying changes in forest degradation:** Not all logging takes the form of easily detectable clear cuts. Selective logging can cause forest degradation that is difficult to detect using widely available data with a spatial resolution of 10–30 meters. Meta's model is well positioned to be used as a tool to detect increases in forest degradation. It can also be used to detect the inverse, or "reverse leakage," which may occur as a co-benefit of forest carbon projects that provide employment opportunities that disincentivize logging.
- **Monitoring reversals and attribution:** Reversals are currently monitored using optical imagery or human interpretation of high-resolution imagery. However, these methods can be unreliable in places where forest regrowth is difficult to detect and distinguishing between new growth and intact (undisturbed tree canopies) is challenging for both models and humans. Meta's model is well-positioned to be used as a tool to quantify the areal extent and expected relative carbon intensity of disturbances. Most interestingly, because it can incorporate spatial context and recognize characteristic spatial patterns of disturbance, it is a more sophisticated tool for use in attributing disturbance to specific agents (e.g., pest outbreak, fire logging).
- **Providing an input variable for estimating AGB:** Canopy height is a strong predictor of AGB and provides a key structural variable that complements spectral information. By integrating spatially explicit, high-resolution canopy height data with satellite imagery, climate data, or field-based allometric models, more accurate and spatially consistent AGB predictions are possible.

60. Carbon Direct and Meta. 2025. Integrating Meta's Canopy Height Map into Forest Carbon Methodologies: A Tactical Guidebook. https://www.carbon-direct.com/research-and-reports/meta-guidebook

Conclusion

We are in the digital age of forest monitoring. Remote sensing presents a transformative opportunity to enhance the transparency, accessibility, reliability, and scalability of forest carbon MMRV. However, realizing its full potential requires overcoming significant governance, technical, and infrastructure barriers.

The MMRV community needs, and is indeed motivated to:

- **Establish a broad consensus to moving this technology forward.** However, this effort will require a balanced approach, as it must be flexible enough to keep pace with rapid technological advances.
- **Clarify standards and quantify uncertainty to build stakeholder confidence** in remote sensing for forest carbon MMRV. This would enhance the integrity of the VCM.
- **Invest in benchmarking datasets, centralized data portals, and user-friendly tools** to help democratize access to high-quality remote sensing products.

The emergence of deep learning models, such as Meta's, underscores the potential for remote sensing to deliver higher-resolution, more accurate insights for a range of forest carbon applications. Building a robust, inclusive MMRV consortium that represents diverse stakeholder perspectives will be essential to operationalizing this potential. Ultimately, aligning governance, technical innovation, and capacity building will make remote sensing technology easier to access and use, bolstering the credibility of the VCM.


Copernicus Sentinel-2 L2A data [2025-07-08]. Latitude = -10.74684 Longitude = -63.58246.

Glossary

Allometric equation: A mathematical model relating easily measured tree dimensions (e.g., diameter, height) to variables that are harder to measure (e.g., biomass). These equations are specific to particular species or sites and are critical for estimating forest carbon stocks.

Calibration: The process of aligning the predictions of a model with observed, ground-truth measurements to ensure that the model's outputs are as accurate as possible for the context in which it is calibrated.

Carbon project methodology: A standardized, science-based framework that defines how a carbon project should be designed, implemented, monitored, and verified to quantify the greenhouse gas reductions or removals it claims to generate.

Data product: Processed dataset in a standardized format (e.g., GeoTIFF, NetCDF), often including metadata, that may be derived from remotely sensed data or a combination of remotely sensed data, field data, and modeling.

Forest structural attributes: Variables that describe different dimensions of forest structure including above-ground biomass, tree canopy height, and tree density. These attributes are used to find suitable areas for forest carbon projects, to monitor disturbances, and to estimate project performance. Above-ground biomass can be used to estimate forest carbon stocks.

Forest type: A classification of forests based on dominant tree species, composition, and environmental conditions (e.g., tropical rainforest, temperate deciduous forest). Types are defined by factors like canopy structure, leaf longevity, and climate.

Ground truthing: The process of validating a remote sensing inference with field observations that are assumed to be the source of truth.

Machine learning: A subset of artificial intelligence that allows computers to learn from data and improve their performance over time without being explicitly programmed for every outcome. Instead of following fixed rules, machine learning algorithms identify patterns and relationships in data to make predictions, classify information, or detect anomalies. This approach is particularly valuable in complex or data-rich environments—like remote sensing—where traditional rule-based programming may be insufficient or inefficient.

Model: A mathematical or computational structure that represents the relationships between inputs and outputs based on underlying patterns in data. Models can range from simple formulations, like regression models that fit linear or nonlinear relationships between variables, to highly complex architectures such as deep learning models and vision transformers that learn hierarchical and abstract representations from large-scale datasets.

Remote sensing: The science of acquiring information about Earth's surface or other objects without physical contact, using sensor technologies on satellites, aircraft, or drones. It includes passive (e.g., reflected sunlight) and active (e.g., radar, lidar) methods to detect surface properties.

Reversal: The unintentional or intentional release of previously sequestered carbon (e.g., via logging, fire, or other disturbance).

Spatial and temporal resolution: Spatial resolution is the ground area represented by one pixel (e.g., 30 meters for Landsat). Finer spatial resolution captures smaller features. Temporal resolution is the frequency of data acquisition (e.g., daily for MODIS). High temporal resolution tracks dynamic changes.

Validation: Assessing model performance by comparing model estimates with independent ground-truth data.

Appendix

Data portal design (Recommendation 6)

While most data providers already understand the value of transparently describing the limitations of their models and datasets, working toward greater standardization and centralization will help providers communicate these limitations in more consistent language. This will help users navigate and compare models and their limitations more effectively and ultimately increase usage. The portal should document regionally specific uncertainty estimates for data products (**Recommendation 4**) in a standardized and accessible way, which would be enabled by integrating a global benchmarking dataset (**Recommendation 5**) with this portal. The portal could indicate which datasets were approved by specific registries (where possible) and provide clear guidance on conservatism. Critically, the user interface for the portal needs to be as simple as possible and global in scope to accommodate a wide range of technical capacities in working with models and spatial data.

The proposed data portal could lower the cost and increase the accessibility of digital MMRV for developers with fewer resources in multiple ways. First, a centralized and accessible portal for datasets will be particularly helpful for smaller developers who lack in-house expertise to effectively acquire, analyze, and use remote sensing data themselves (e.g., through Google Earth Engine). Secondly, it can be expensive for project developers to get through the project feasibility stage. While it may take time for registries to accept or certify the use of specific data products on a centralized data portal, these datasets could be used as a feasibility sandbox for determining project feasibility and eligibility in the interim. This would help buyers and investors evaluate the potential of early-stage projects from under resourced project developers more quickly and cheaply. When making these evaluations, buyers care about understanding not just the credibility of a project but also the potential for credit issuances through time. Buyers need ways to compare what a good credit yield looks like across projects, streamline this assessment, and justify if and why one project is better than another. While carbon credit agencies could provide such information, a feasibility sandbox integrated with open-source data could standardize technical diligence approaches and improve confidence among buyers. One developer noted that any feasibility analysis of a project should strive to use the same methods as those that will ultimately be used for crediting, to avoid large jumps in the projected internal rate of return. A centralized data portal for assessing feasibility and, ultimately, credit issuance would satisfy this need.

A centralized data portal would also enable the broader use of advanced, open-source models, such as Meta's model, where they could be applied to free or paid high-resolution imagery, depending on the needs and budget of the user. This would also reduce the technical barrier of working with open-source models by automating the complex steps of finding and preparing suitable data for the models to ingest and quantifying uncertainty in the resulting predictions. The portal could host a wide variety of models, especially ones that are relatively agnostic to input data.

Autumn forest trails. Source: Adobe Stock.

A data portal or product hub should still allow project developers to use their own validation data, when it is available, to test the performance of regional or global models in their specific project area. Many project developers already use their own field data to validate potential data products and appreciate being able to do so. A data portal could allow developers to upload project-specific validation data and the platform could provide an automated, project-specific calibration and uncertainty quantification methodology (**Recommendation 4**) that is pre-approved by registries. This would help alleviate the technical burden of determining if global datasets are acceptable for project-specific use cases. It could reduce the need for third-party verification, or make third-party verification more affordable and less idiosyncratic.

Uncertainty deductions for credit calculations (Box 1 and Barrier C)

Although uncertainty deductions for credit calculations are becoming more common across project types and methodologies it would be helpful to have stakeholders align on where in the distribution of carbon stock estimates (**figure 6**) we think is a conservative place to set credit issuance. There will be limits to how much standardization can occur for this. Buyers are not a monolith and have differing interests, values, and capacities to pay. Additionally, approaches for quantifying uncertainty vary across models.

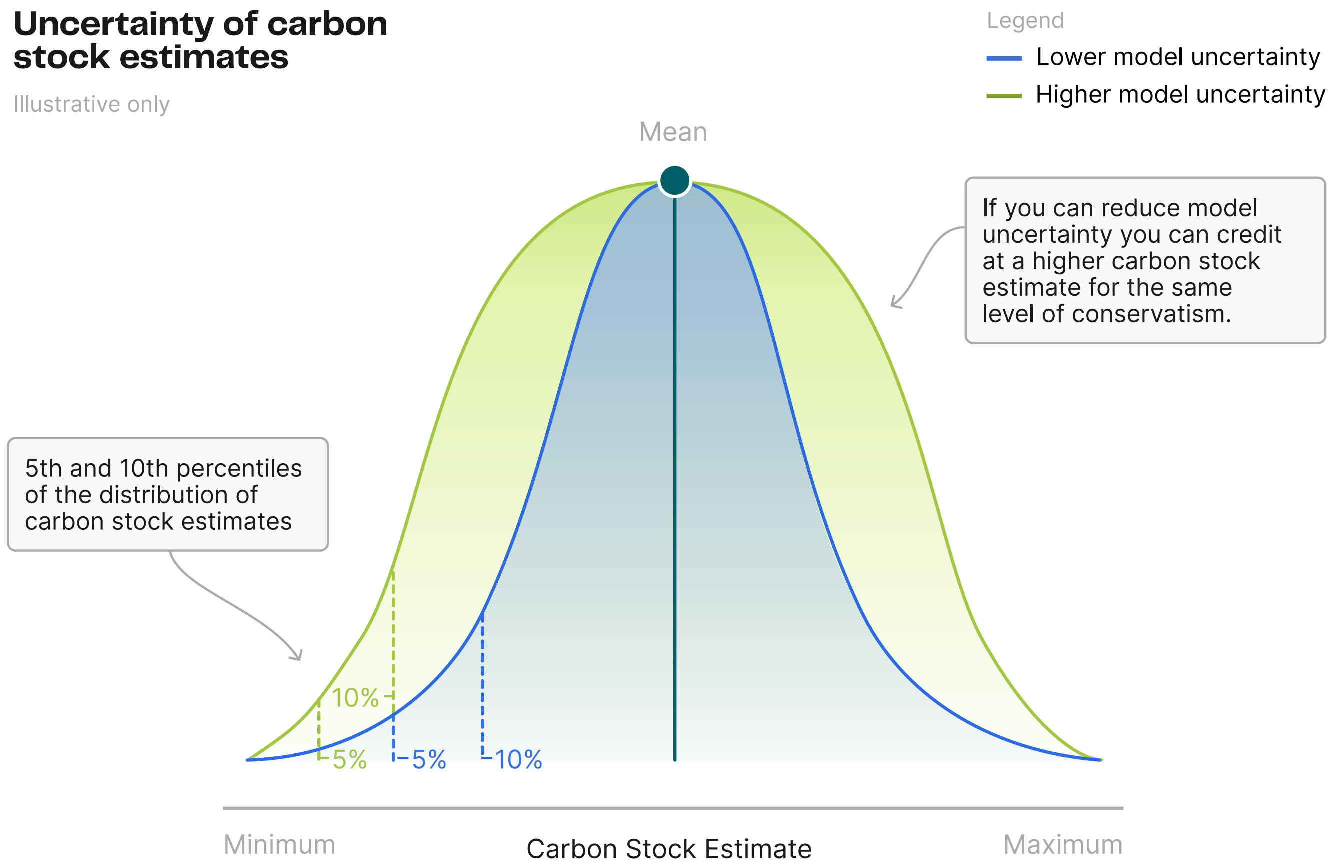


Figure 6. Carbon stock estimates are always associated with uncertainty. As uncertainty decreases, the distribution of estimates becomes tighter. In other words, the true value is more likely to be found in a narrower range of estimates. Credits can theoretically be issued based on estimates at any point in a distribution of estimates, but issuances derived further to the left of the distribution will be more conservative, while issuances to the right will be less conservative. For example, issuances based on the 10th percentile in the distribution of estimates will be more conservative than issuances based on the mean estimate. This concept could be used as a starting point for aligning the market on where in the distribution of estimates issuances should be based, and if and how prices should vary depending on conservatism (i.e., the percentiles of the distribution of estimates). Source: Carbon Direct.

Credits

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About Carbon Direct

Carbon Direct Inc. helps organizations go from climate goal to climate action. We combine technology with deep expertise in climate science, policy, and carbon markets to deliver carbon emission footprints, actionable reduction strategies, and high-quality carbon dioxide removal. With Carbon Direct, clients can set and equitably deliver on their climate commitments, streamline compliance, and manage risk through transparency and scientific credibility. Our expertise is trusted by global climate leaders including Microsoft, American Express, and Alaska Airlines, as well as by the World Economic Forum, which selected Carbon Direct as an Implementation Partner for the First Movers Coalition. To learn more, visit www.carbon-direct.com.

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