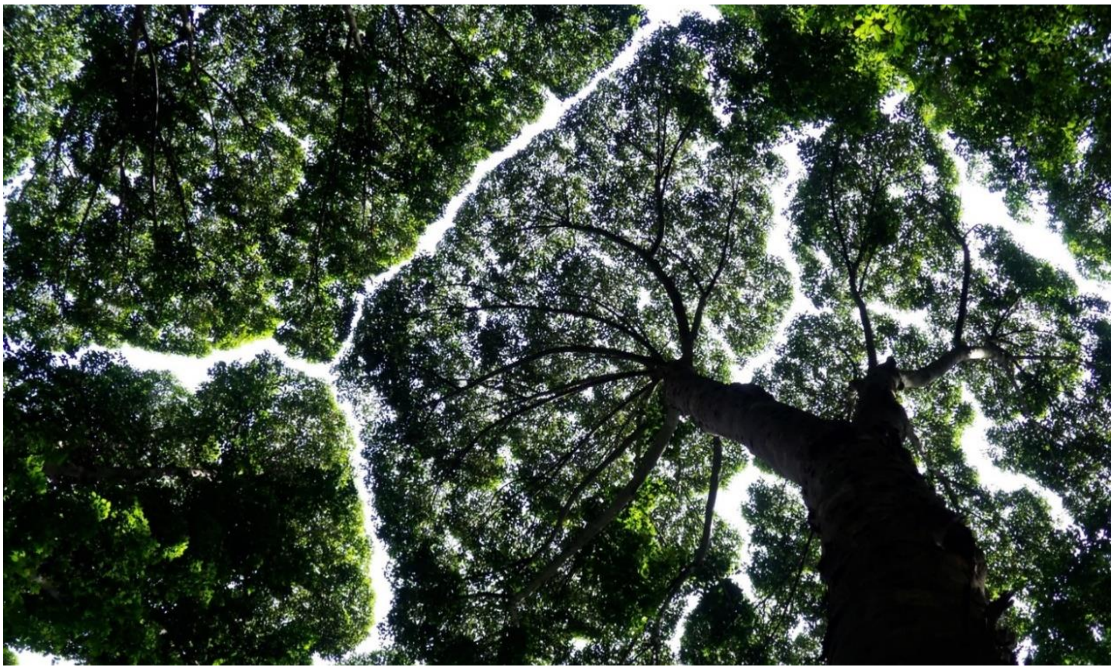
Assessment of Digital Measurement, Reporting, and Verification

A Snapshot of D-MRV in Decentralized Energy, Forestry, and Agriculture

White Paper
Zurich, 12 July 2022

Martin Soini, Anik Kohli, and Juerg Fuessler (INFRAS)



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Commissioned by
SustainCERT
Peter Konijn, Rodrigo Castro, Marion Verles

Project management
Juerg Fuessler

Written by
Martin Soini, Anik Kohli, and Juerg Fuessler (INFRAS)

INFRAS, Binzstrasse 23, 8045 Zurich
Tel. +41 44 205 95 95

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Content

Executive Summary

The digitalization of monitoring, reporting, and verification (MRV) is lagging behind. The MRV of climate change mitigation activities is an essential part of the project cycle in all relevant carbon standards, and particularly important to ensure the accuracy and credibility of carbon credits.

However, the costs and complexity of conventional MRV constitute a significant barrier to scaling up and accelerating climate action. The lack of automation leads to inefficiencies and hampers the rapid upscaling of certified carbon markets and the climate action they potentially enable. The primary stumbling blocks arising from conventional, non-digital processes are lower efficiency, scalability (due to lack of automation) as well as credibility, since manual processes are error prone.

Digital MRV (D-MRV) is still a nascent field. This paper provides a snapshot of the state of activities, actors, opportunities, and barriers in the digital MRV sector in two project types that are particularly important to current voluntary carbon markets:

- Technologies for decentralized energy provision (e.g. photovoltaic systems (PV) and clean cookstoves), as well as
- Carbon storage in forestry and agriculture.

The paper is primarily based on a series of interviews with commercial actors currently operating in the field of digital monitoring for carbon credit generation with the above project types. Additionally, it includes experience gained over four years with the Climate Ledger Initiative. The interviews were complemented with literature-based research to gain an understanding of the current approaches to digital monitoring for various applications. The maturity of the digital technologies considered in the different sectors ranges from early pilots to commercially established activities.

Assessment of D-MRV in different example technologies

An overview of the detailed assessment results of the considered technologies is provided in Section 2.3 (decentralized renewable energy and clean cookstoves, p.27) and Section 3.3 (forestry and agriculture, p. 44).

With **decentralized renewable energy** such as photovoltaics (PV), some companies are already well advanced in the use of digital MRV tools. For decentralized PV, for example, pay- as-you-go systems are increasingly implemented, requiring users to pay for energy before use based on (digital) energy meters. Such systems have brought a general advancement of digital tools for measuring and billing energy services. Using these systems for carbon MRV has many advantages: they are rather low cost, reduce the need for site visits, increase credibility as the unreliable manual transfer of meter readings is not necessary, are well accepted among current methodologies and standards, and have a generally high level of maturity and scalability. This is the easiest way for many actors to enter the field of digital MRV.

With **clean cookstoves**, where e.g. digital temperature sensors or power meters are used to track stove usage time, the cost benefits may be less obvious. We conclude that only the mass production of clean cookstoves with integrated sensors, and the related economies of scale, could bring down costs sufficiently to apply the sensors on a large scale. Cost reductions may also be achieved by equipping only a (random) sub-sample of stoves with sensors. Still, cost reductions may be limited, as determining the baseline (fuel type and quantity, efficiency, usage time) still require costly household surveys in most cases.

Concerning credibility, digital MRV for clean cookstoves may bring considerable benefits, because preliminary data indicates sensor-based measurement of usage times and frequency to be more reliable than conventional surveys. In addition, the transparent availability of key performance data on a digital dashboard makes these cookstoves attractive for (retail) consumers of carbon credits, as they can transparently track the performance of "their" projects over time. Also, the approach allows for direct payments to households (and particularly to women), and therefore strengthens SDG benefits.

Projects for carbon removal in forestry and agriculture represent another important contribution to carbon markets. Compared with technical energy systems, MRV in natural systems tends to be more complex and challenging. Conventional monitoring approaches in these areas are primarily based on extensive field data collection and approximate assumptions. Such simplifications include the use of rather generic "land use factors" and "tillage factors" to determine carbon stock changes due to project activities that may not be representative for the specific conditions of the activity in question. More advanced models are increasingly relevant for monitoring carbon removals. The field is developing rapidly. The following key approaches to digital MRV in forestry and agriculture are considered:

- **Ecosystem modeling for forestry biomass and soil organic carbon**: Many actors supporting or implementing nature-based carbon projects rely on comprehensive process-based and/or empirical modeling, or use machine learning approaches to obtain estimates of above and/or below-ground carbon stocks and their changes. Comprehensive data platforms aggregate a broad range of model input data from various sources, including field measurements, satellite imagery, LiDAR, and weather data.

- **In-situ measurement of soil carbon**: One of the actors interviewed commercializes recent research work on in-situ soil carbon measurement devices using inelastic neutron scattering and gamma spectroscopy to measure total soil carbon levels.

Digital approaches in both forestry and agriculture potentially allow for cost savings through high-volume sampling and the extensive use of model-based and data processing approaches, including machine learning and artificial intelligence, to reduce the need for (expensive, manual) in-situ field measurements for biomass or soil organic carbon content. However, up-front investments in modeling, technology, software, equipment, and skilled labor are usually considerable. In agriculture, data generation on soil organic carbon is often driven by purposes independent of carbon projects, notably to optimize farm management. With this, monetizing carbon is seen more as a co-benefit than the key driver paying for the intervention. This may weaken the additionality of the activity.

In general, the use of digital tools in forestry may provide for higher levels of accuracy e.g. in the calculated amount of carbon removed. Digital approaches rely on broader data sources to calculate biomass volumes and emission reductions. However, in the case of soil organic carbon and woody biomass calculations, approaches are more indirect than conventional approaches (typically laboratory testing and field measurements). Some actors claim the accuracy and precision of their results is superior to conventional approaches. It appears that these claims have not been independently validated at this stage. In other cases, the limited accuracy of remote sensing for estimating carbon is reported to be a barrier to the adoption of the approach by certain potential customer groups. Further, reliance on proprietary approaches and machine learning reduces transparency compared with conventional methodologies.

In effect, the emerging field of digital approaches to MRV in forestry and agriculture presents itself somewhat opaque and inconsistent. Many credibility claims from tech developers and innovative start-ups are difficult to assess today, as broad independent validation for a wide range of species and conditions seems lacking for many of the new approaches.

A similar picture is emerging for acceptability by standards. Major standards are planning to provide guidelines as well as digital tools fostering D-MRV in all sectors. However, it remains to be seen how fast they can develop the related technical and human capacity to fulfil their rule-setting role in these novel technological areas.

General findings

D-MRV approaches would allow for integrated digital systems encompassing monitoring, quantification, verification, and issuance processes, thereby enabling continuous certification and issuance. This would make earlier, continuous payment possible, shifting positive cash flows forward in time. This may increase attractiveness, particularly for projects with high up-front costs, where quick repayment is of the essence. Continuous certification and issuance are also attractive for (retail) credit buyers who can monitor the performance of "their" projects on user-friendly dashboards.

The consistent use of digital technologies in MRV at all levels of the project cycle would provide verifiers, standards, and researchers with a wealth of data. Access to such open data in a common repository could be used to improve methodologies, verification, and certification, increase the accuracy and credibility of emission reduction/removal quantification, and help to optimize crediting activities. It is only with maximum connectiveness and openness that the emerging D-MRV ecosystem will provide its full benefits and accessibility, notably including smaller market participants.

The present study provides a snapshot of the current developments in D-MRV with a focus on specific example technologies in energy, forestry, and agriculture. Further research is needed to gain a more comprehensive picture, including other project types and digital technologies in the voluntary carbon markets. Also, the validity of some of the more complex applications (notably forestry and agriculture) will need comprehensive testing and validation to become viable tools.

Major standards have started working groups on digital approaches. In addition, standards, certification bodies, project developers, industry associations, multilateral institutions, and tech entrepreneurs are involved in a flurry of activity to enable D-MRV and its concrete implementation. Although this proliferation of different projects may be a very fruitful approach, it will be crucial going forward to increasingly link and coordinate the digital initiatives to enable cheaper, better, and faster D-MRV.

For more CLI platform activities involving partners and stakeholders, and for more knowledge products on D-MRV – including a parallel CLI White Paper specifically on Principles for Digital Verification for SustainCERT (Climate Ledger Initiative, 2022) *– visit the Climate Ledger Initiative website:* https://climateledger.org/

1. Introduction

The digitalization of monitoring, reporting, and verification (MRV) is lagging behind

The monitoring, reporting, and verification (MRV) of the impacts of climate change mitigation activities is an essential part of the project cycle for all relevant carbon standards. It is particularly important to ensure the accuracy and credibility of carbon credits. However, the cost and complexity of conventional MRV constitute a significant barrier to accelerating climate action and accessing certified carbon markets. While digitalization has transformed many areas of the economy and society, such as social media, retail, finance, and manufacturing over the past decades, current MRV in carbon markets is often still based on reports, checklists, and spreadsheets sent around by email. Further, it may require comprehensive site visits where project implementation and meter readings are checked in situ. This conventional approach yields satisfactory results in some contexts. However, the reliance on manual interventions for data gathering and checks tends to be error-prone and expensive. Further, the need for manual data handling naturally reduces the credibility of results. Finally, with the recent rapid expansion of the climate tech sector, a broad range of digital tools such as enterprise-level greenhouse gas accounting software and remote sensing monitoring platforms have become available. When using such platforms to streamline carbon market projects, it is critical that not only data capture and processing but also verification are adapted to such digitally automated approaches. Such fully integrated digital systems may provide much-needed credibility and independence to the new generation of climate solutions providers.

Slow progress in the digitalization of MRV and the carbon market project cycle over the past 15 years may be due to rather moderate levels of market activity since 2012, as well as program standards failing to adopt digital approaches. This has been changing in recent years.

The Climate Ledger Initiative, SustainCERT, and the benefits of digital MRV

The use of digital innovations is emerging as key driver increasing the reliability, efficiency, and credibility of MRV activities. These technologies include the use of sensors, the internet of things, remote sensing, machine learning, advanced statistics on large datasets, and blockchain, but also smartphones or even simple mobile phone connections to collect and transmit data.

The Climate Ledger Initiative (CLI) has worked on identifying the potential of these digital MRV (D-MRV) approaches, together with its partners such as the EBRD, World Bank and leading carbon standards (see CLI Navigating Reports, EBRD).

The impact certification company SustainCERT aims to harness the power of digital technologies to lower the cost while improving the quality and frequency of reporting and verification. It has therefore commissioned this report from INFRAS and the CLI to contribute to the discussion and development of this important topic.

About this paper

Digital MRV is still a nascent field. This paper provides a snapshot of the state of activities, actors, opportunities, and barriers in the digital MRV space in two project types that are particularly important to current voluntary carbon markets:

- Technologies for **decentralized energy provision** (e.g. PV systems and cookstoves), as well as
- Carbon storage in **forestry and agriculture**.

The paper is primarily based on a series of interviews with commercial actors currently operating in the field of digital monitoring for carbon credit generation with the above project types (see Box 2 at the beginning of Section 2 and Box 3 at the beginning of Section 3). Many of these actors do not operate as project developers but rather provide monitoring solutions (hardware, software, and data) to clients. Maturity ranges from early pilots to established long-term operations. The interviews were complemented with literature reviews to gain an understanding of the current approaches to digital monitoring for various applications.

Based on the interviews, the earlier work of the CLI, and the limited literature the drivers, opportunities, and barriers for D-MRV were assessed. The analysis focuses on a set of specific criteria, which were determined to be crucial for the development of D-MRV (see Box 1).

Box 1: Criteria for the analysis of digital MRV solutions

The analysis of D-MRV solutions for decentralized energy provision (Section 2) and forestry/agriculture (Section 3) considers the following criteria:

- **Costs**: D-MRV implementation may entail additional initial costs but at the same time allow for cost savings since digital approaches are generally more efficient.
- **Credibility**: Advanced monitoring and modeling promise to deliver more accurate and transparent results. However, novel approaches such as sophisticated machine learning to determine nature-based carbon stocks can be black boxes by design. Credibility is therefore potentially subject to a trade-off.
- **Applicability with current standards**: Differences with respect to conventional methodologies cause potential acceptance barriers in terms of carbon credit certification. Therefore, limitations in this regard need to be considered.
- **Maturity and scalability**: Current D-MRV approaches have different levels of maturity and—due to various barriers—different potentials to reach large scale.

This paper is structured as follows: First, an assessment of D-MRV examples is presented, related to off-grid energy technologies in photovoltaic systems and efficient cookstoves (Section 2), as well as in forestry and agriculture (Section 3). Section 4 provides more general considerations, including on the scope of D-MRV activities, their origins, and their connectiveness. Finally, Section 5 summarizes preliminary findings.

2. Digital MRV for decentralized energy provision

Carbon market projects related to energy provision and efficiency are highly diverse. The focus of Section 2 is on the decentralized provision of renewable power and clean cookstoves. These project types are considered representative, allowing for an assessment of the issues typical of D-MRV in the decentralized energy sector. It is complemented by Section 3, which looks at D MRV in forestry and agriculture. In their conventional implementation, these two energy project classes suffer from various barriers, which may be overcome with digitalization:

- *Low efficiency in the MRV of projects based on small-scale systems*: According to the actors interviewed, decentralized energy-based carbon projects are economically challenging, as the small scale of operated systems (e.g. single PV panels, single cookstoves) results in considerable transaction costs. However, small-scale systems are desirable due to their higher positive SDG impacts for local communities. This contrasts with large systems such as hydropower dams or wind farms with fewer contact points and therefore lower positive social impacts.
- *Accuracy of conventional monitoring approaches is often limited*: Clean cookstove projects for carbon abatement are common, yet monitoring is largely based on user surveys with sometimes limited accuracy and reliability. A study from 2016 shows conventional MRV to lack accuracy when compared with sensor-based assessments of stove usage (Ramanathan, et al., 2017). Therefore, more automated and robust systems promise improved accuracy and credibility.

The use cases and interviewed actors are described in Box 2.

Box 2: Use cases analyzed in Section 2
Decentralized energy projects are being implemented or supported by actors who typically have a strong background in pay-as-you-go energy provision. In all considered cases, the emphasis is on integrated digital platforms for flexible and efficient data management: ▪ **Bboxx** addresses energy poverty through the provision of pay-as-you-go energy services in a vertically integrated manner: The full value chain from the installation of home solar systems to software for payment management is covered. The establishment of projects for carbon markets is a work in progress. https://www.bboxx.com/

Box 2: Use cases analyzed in Section 2

- **The D-REC initiative by South Pole** aims to create Distributed Renewable Energy Certificates (D-REC) as a novel form of Renewable Energy Certificate (REC) that might be internationally recognized. In the wake of this approach, a pipeline for digital carbon credit generation programs is being implemented. In these efforts D-REC defines itself as the link between developers and issuing bodies.
  www.southpole.com/clients/d-rec-initiative
- **Inclusive Energy** operates as a hardware/software provider offering solutions to track and monetize carbon revenues from solar home solar systems and biogas digesters. Its measurement hardware is operated by project developers and feeds data into the Inclusive Energy data platform. While the pay-as-you-go business model covers photovoltaics and biogas, carbon credit generation is limited to the latter so far.
  https://inclusive.energy/

The development of digital **clean cookstove** monitoring has picked up pace in recent years. However, the corresponding projects are limited to a relatively small scale so far. Two examples from the portfolio of CLI-supported use cases are presented below:

- **FairClimateFund** is a social enterprise implementing (amongst others) large-scale clean cooking projects for carbon credit generation. As part of a pilot project in India supported by the CLI, 100 cookstoves were equipped with temperature sensors to directly digitize activity data.
  www.fairclimatefund.nl/en/learn-more/news/digital-cookstoves-in-india
  climateledger.org/en/Use-Cases/Cooking-as-a-business.72.html
- **EED Advisory (OpenHAP project)** is not directly involved in carbon credit generation. However, a recent research project for CLI on indoor air pollution measurement and activity tracking for cookstoves touches on many of the topics that are also relevant for MRV in the carbon credit context.
  climateledger.org/en/Use-Cases/OpenHAP.66.html

2.1. Technological approaches

Actors implementing D-MRV solutions for decentralized energy and clean cookstoves rely on new and more comprehensive project data sourcing and processing. Table 1 provides an overview of the two example technologies considered and the related digital approaches to MRV, followed by more details on their implementation.

Table 1: Differences between the conventional (non-digital) monitoring approach and D-MRV

	Conventional approach	Comparison with D-MRV
Decentralized energy	Continuous monitoring of energy generation with regular (e.g. monthly, annually) and often manual readings	Power generation data transmitted using a fully automated process and recorded on an advanced data platform
Clean cookstoves	Cookstove usage in baseline and project case typically determined from survey among sample of users; other parameters are determined based on physical tests (e.g. water boiling test)	Continuous and comprehensive remote recording of usage levels of project stoves through temperature sensors, LPG flow measurement, or electricity monitoring Household surveys are still necessary to determine e.g. baseline stove and fuel type

Table: INFRAS. Source: Own research and interviews with technology providers

In the considered technologies, aspects of D-MRV are implemented as follows:

- In **decentralized energy provision**, digital power meters capture generation activity continuously. These data are processed in a streamlined manner.
- **Clean cookstove monitoring**, which in the conventional case primarily relies on user surveys, is digitalized to enable more accurate activity tracking. In the cases presented in this paper, this is achieved using temperature sensors attached to the cookstoves. Sensor readings indicate cooking activity as soon as a threshold temperature is crossed. For other cookstove types, the automated measurement of electric cookstove activity with power meters is an established approach with great global potential (MECS, 2021), recently documented in the Gold Standard's "Methodology for metered and measured energy, cooking devices" (Gold Standard, 2021).

Figure 1: Improved cookstove equipped with a temperature sensor for remote monitoring.

Photo: Nexleaf Analytics

Figure 2: Biogas meter for remote monitoring.

Photo: Inclusive Energy Ltd

- **Digital monitoring data is stored with full time resolution**: Actors focus on continuous and automated activity data capture and management on dedicated data platforms. These platforms often also perform the complete emission reduction quantification calculations. Web-based dashboards provide data access to various stakeholders.
- **Actors place a strong emphasis on complete and well-managed data**: Basic data cleaning and plausibility checks are common features of the digital monitoring systems. This helps to improve the completeness, reliability, and accuracy of monitoring. For example, for decentralized energy production this may include comparisons of diurnal variation in production levels with similar plants and solar irradiation data from nearby weather stations, as well as comparisons with the maximum power that can be derived from installed capacity. With cookstove usage data, similar plausibility checks are made, including comparisons of the timing, length, and frequency of cooking activity, as well as temperatures reached.
- **More advanced data quality checks are being investigated**: In the case of decentralized renewable power, these could rely on additional meteorological data and possibly more sophisticated statistical approaches. However, actors have not reached a conclusion yet on whether the benefits of such approaches would be worth the cost.

2.2. Assessment of D-MRV for decentralized energy and cookstoves

In the following section the use cases in this paper (Box 2) are assessed according to the defined criteria (Box 1) to characterize the pros and cons of D-MRV for the considered technologies. The results of these assessments are presented in tables in Section 2.3.

2.2.1. Cost and cost savings of D-MRV

D-MRV entails additional (up-front) costs to establish the digital infrastructure for data capture with sensors and meters, data transfer, the platform, software, analytics, and potentially auxiliary data sources (e.g. solar irradiance). In operation, digital MRV leads to potential cost savings and other benefits over time, since the manual steps for data capture, transfer, and processing may be considerably reduced.

Cost and cost saving potentials are difficult to quantify and heavily technology dependent. However, some components are clearly dominant (see Table 2).

- **Decentralized energy – additional hardware costs may be low**, particularly for actors who already maintain a digital infrastructure for pay-as-you-go business models. This infrastructure largely consists of the same hardware (power meters) and—to a large extent—software necessary for the envisioned digital carbon monitoring. In this specific situation, the additional costs of adaptation are minimal.
- **Cookstoves – additional hardware costs can be high** for those actors whose D-MRV schemes require additional dedicated hardware (e.g. cookstove temperature sensors or LPG/biogas sensors) together with the appropriate processing software. Further, digital infrastructure in most cases only automates the monitoring at the project activity level, while surveys for baseline fuel and determining cooking activity remain necessary. However, major cost savings in increasing the scale of digital projects and in sensor procurement are expected once D-MRV efforts leave the pilot stage, and smart cookstoves with integrated sensors are mass-produced.
- **For all the technologies, software development and adaptation are required** because D MRV relies on advanced data platforms, pipelines, and dashboards. For one of the actors interviewed, these cost components turned out to be significant barriers, even though previous activities were already extensively digitalized. Efforts to implement the necessary degree of automation to participate in carbon markets turned out to be too expensive given the internal capacity and priorities at the time. This may also be due to the relatively small contribution of carbon market revenues to overall project cash flows. While this does not point to a fundamental barrier, it shows that even experienced actors with established monitoring systems require a certain degree of incentive to participate in carbon markets.
- **For all technologies, the need for site visits and manual data collection is generally reduced through sensor-based measurements**. Conventional monitoring methodologies rely heavily on manual interventions for data gathering. This includes surveys among clean cookstove users to determine usage rates for project stoves, or site visits to confirm the continuing operation of systems. These costs are exacerbated for distributed projects in remote rural areas with potentially great SDG benefits. They are alleviated through continuous sensor-based

monitoring. While these digital approaches significantly change current approaches, actors report good acceptance from standards in this regard (see e.g. Gold Standard methodology on electric cookstove monitoring (Gold Standard, 2021)). However, even with digital approaches a certain number of site visits are still necessary to collect data on households, stove numbers, usage practice, fuel types, etc., to determine baseline emissions. Further, remote areas can pose challenges for digital approaches, notably because of poor GSM coverage for data transfer.

- **For all the technologies, more accurate measurements using digital approaches can result in higher or lower revenues from carbon credits.** Since digital approaches differ significantly from conventional monitoring, the resulting number of carbon credits generated can vary. Depending on the project type, actors report either higher or lower emission reductions. Lower carbon credit revenues may nevertheless be justified by other benefits such as higher accuracy (see Section 2.2.2) or greater SDG impact.

Table 2 and Table 3 below provide cost indications. Costs and benefits of digitalization are not easily quantifiable, for example due to synergies, the fact that some project types are not viable in the absence of streamlined digital approaches, and the unpredictability of cost factors.

Where the costs entailed in D-MRV are higher, they may to a certain extent be justified by the resulting efficiency and transparency benefits (see Section 2.2.2).

For both technologies considered here, the increasingly widespread adoption of digital monitoring may lead to the development of specialized flexible software solutions with the ability to ingest a broad variety of data from various project types. Even today, certain actors offer solutions of this kind (see Section 4.2). A future push for digital MRV could diversify the landscape for digital monitoring software providers. The “software” cost component (see Table 2) could therefore be significantly lowered.

Table 2: Additional cost of D-MRV approaches compared to conventional MRV

		Hardware	Software	Capacity building	Costs of adaptation to standards' requirements
Clean cookstoves	Cost component description	- Significant additional cost component due to dedicated sensors and data processing and transmission systems. Details depend on the share of digitized cookstoves. Cost reductions are foreseeable according to project developers. - Total project costs will depend heavily on whether all stoves are equipped with sensors or whether sensors are limited to samples. While some project developers are aiming for comprehensive digital monitoring, the trend is not yet clear.	- Additional investments in data platform and data pipeline may be necessary (development or procurement for data management, analysis, aggregation and possibly verification). - Generally, no synergies with past activities are expected, as the reference case does not leverage digital data (except for electric or biogas cookstove pay-as-you-go schemes). - A digital system within the program enables economies of scale as the system is expanded.	- Local capacity is already established due to previous conventional MRV; if established programs are retrofitted with digital cookstoves, staff in the field may require additional training; in case of new cookstoves, training shifts to the management of data transmission and technical support	- Methodology adaptations require carbon project registration and negotiation e.g. for the use of remote digital monitoring.
Clean cookstoves	Illustrative costs	- Sensors and data transmission hardware in current pilot projects are estimated at USD 20-40 per stove, compared with typical improved cookstove costs of USD 10-30 per stove. - The switch to mass-production and the direct integration of sensors in the cookstoves reduce additional costs to USD 5-10.	- The cost for a very basic proof of concept has been estimated at USD 25k. - A robust, scalable system catering to a range of stoves in different contexts would come at a multiple of this cost and would include APIs, databases, a dashboard with user management system, data checks, carbon calculation, etc. may cost USD 100k-300k - Economies of scale are foreseeable.	- No extra cost expected compared with the reference case in an average project	Typical costs for adaptations of methodologies amount to USD 40k, including planning and Standards' fees. However, these costs are limited to the first project implementation of any kind.
Decentralized energy	Cost component description	- No additional cost if metering hardware already in place due to previously established pay-as-you-go energy sales with detailed consumption measurements - Incomplete hardware may require additional investments (e.g. irradiance sensor, GSM module).	- No fundamental differences with respect to clean cookstoves (see above). - However, in contrast to clean cookstoves, the existence of an established remote monitoring system (e.g. for pay-as-you-go electricity) is more likely.	Local capacity is already established due to previous pay-as-you-go schemes, in many cases. For entirely new projects, the same logic as for cookstoves holds.	See "clean cookstoves" above.
Decentralized energy	Illustrative	- Simple power meter: USD 200 - Basic data logger: USD 400 - Entry-level irradiance sensor: USD 400	- See "clean cookstoves" above.	See "clean cookstoves" above.	See "clean cookstoves" above.

Hardware	Software	Capacity building	Costs of adaptation to standards' requirements
- All these components are at a high level of maturity and mass-produced; no fundamental cost decreases beyond streamlining of hardware installation processes expected.			

Costs are based on experts' estimates, interview results, and figures given in the literature. They represent rough estimates for illustrative purposes.

Table: INFRAS. Source: (Bürgi, et al., 2019; World Health Organization, 2022; Verified Carbon Standard, 2020; UNFCCC CDM, 2021)

Table 3: Cost components and potential D-MRV savings (all project types)

	Estimated cost per project or program in the conventional reference case	Indicative savings from D-MRV approach as percentage of conventional costs
Planning and validation	**USD 10k – 90k** includes project planning, PDD writing, independent validation	**Saving of 0% – 20% of conventional costs** Savings are possible where existing digital systems are already well-adapted to the planned project type; in other cases, the development of digital systems may incur greater up-front costs, also covered in Table 2. However, potential savings are much lower than in other steps.
Monitoring and verification	**USD 5k – 65k per project per year** depending on project type and size	**Saving of 20% – 90% of conventional costs** Digital solutions are on a continuum with a broad range of potential savings. These are potentially substantial. A highly streamlined data pipeline in a vertically integrated project structure (e.g. project developer-operated established digital systems) could largely automate the system.
Issuance of certificates	**USD 0.025 – 0.3 per ton of CO_2** depending on project size, standard, certificate type, and year of issuance	**Saving of 30 – 90% of conventional costs 0.005 – 0.1 USD/t of CO_2** Significant cost reduction could be possible depending on how tightly digital platforms are integrated with the standards' systems. In the extreme case, carbon certificates could be issued in real time at virtually no variable cost.
Distribution of carbon revenues (e.g. to individual project owners, if applicable)	**USD 5k – 10k per year** Labor-intensive allocation of revenues among participants	**Saving of 20 – 80% of conventional costs** Potentially largely automated, e.g. through mobile phone-based pay-outs.

Costs are based on experts' estimates, interview results, and figures given in the literature. They represent rough estimates for illustrative purposes.

Table: INFRAS. Source: (Gold Standard, 2022; Verified Carbon Standard, 2020; GIZ HERA, 2021)

2.2.2. Credibility

In the context of decentralized energy provision, digital monitoring is deemed superior: When compared with the conventional approaches, digital online monitoring for decentralized energy provision adds greater detail and temporal resolution to the determination of emission reductions (e.g. measurements each (split) second or minute rather than daily or monthly averages). Also, automated data transfer rather than manual documentation in lists and spreadsheets reduces the risks for errors and increases the completeness of data. Overall, digital approaches yield more accurate, complete, and robust data. This improves the credibility of the resulting emission reduction calculations. For example, a study comparing survey-collected data with sensor data on cookstove usage showed that answers provided by households in surveys may considerably differ from actual usage patterns (Ramanathan, et al., 2017).

Table 4: Factors influencing D-MRV approaches' credibility

	Credibility strengths	Credibility weaknesses
Decentralized energy	Comprehensive high-frequency automated data collection and analysis replacing manual meter readings reduces risk of measurement inaccuracies and enables cross-checks (e.g. comparison with installed capacity).	None
Clean cookstoves	Direct activity measurement outperforms conventional survey-based usage assessments.	Additional surveys are required to determine baseline fuel type.

Table: INFRAS. Source: Interviews

Digital monitoring increases both the *quantity and quality of recorded data*, and ultimately also improves data handling processes, all of which leads to higher credibility for both considered technologies of decentralized energy provision and clean cookstoves:

- **Comprehensive data collection provides a full and accurate picture:** Some conventional monitoring methodologies require the direct measurement of power generation. However, the option of manual meter readings and the use of (often generous) default factors instead of monitoring[1] persists. Cookstove monitoring relies on sample-based surveys or measurement campaigns, which are limited in both scope and time. In contrast, digital monitoring approaches are designed to capture high temporal resolution activity data.

[1] For instance, VCM methodology VRM0006 for cookstoves allows a choice between (i) historical data, (ii) baseline survey, or (iii) a fixed default factor of 0.5t/capita/year when determining the amount of woody biomass used as the baseline. The saving in biomass may then be calculated simply by using the estimated efficiencies of old versus improved cookstoves (equation 3). Here, the use of surveys and sensors measuring the actual use of stoves may drastically improve the accuracy of emission reduction quantifications.

- **Data completeness increases quality and enables cross checks:** D-MRV approaches currently under development aim at continuous data capture with a high temporal resolution. This contrasts with e.g. monthly readings of renewable power production or the yearly survey-based determination of cookstove usage rates. Continuous data enables discrepancies to be detected and more systematic data quality control. Some actors are considering advanced cross checks, e.g. relying on irradiation data from independent weather stations to determine the credibility of PV generation data. However, the added value of such approaches remains to be proven.
- **Transparency and traceability increase credibility:** Dedicated digital solutions are often built with the intention of enhancing transparency to increase carbon credit value (cookstoves). In other cases (decentralized power) the transparency carries over from the legacy business case (pay-as-you-go electricity). All actors rely on dedicated data platforms and dashboards. They can be accessed by various stakeholders. Credit buyers obtain information on the projects, and thus on the origins of the carbon credits themselves. In some cases, clean cookstove users also have access to dashboards, which in turn is reported to increase usage.
- **Continuous automated monitoring enables the early detection of system faults and fading user engagement:** Interrupted or abnormal data streams point to problems in operation and enable timely targeted intervention. In addition to technical issues, automated monitoring also reveals reduced engagement in real time e.g. of clean cookstove users who may switch back to conventional wood stoves. Once detected, local project partners can intervene efficiently and communicate with members of the local communities to mitigate problems.
- **Data availability enables advanced downstream technologies:** Thanks to the completeness of the available data, D-MRV approaches enable advanced accounting approaches such as data storage supported by distributed ledgers. Some actors rely on such immutable approaches for unambiguous traceability.
- **Detailed measurements of activity enable determination of uncertainty:** Conventional methodologies often rely on rough point estimates for parameter values. Uncertainties are sometimes considered in the calculations, yet not systematically in all standards. In contrast, uncertainty quantification is possible for direct measurements using hardware with known properties. It can be communicated transparently for enhanced credibility.

2.2.3. Applicability with current standards

Digitalizing MRV is still in its early stages. An important question going forward is how well digitalized approaches to MRV will be accepted by program standards (with a focus on Gold Standard, Verra and future Article 6.4 mechanism based on the CDM). The interviews and analysis focus on the monitoring and reporting part of MRV, and only briefly touch on verification. A separate white paper is dedicated to verification using digital approaches (D-VER) (Climate Ledger Initiative, 2022).

Past assessments on this topic emphasized digital technologies' potential in terms of the reduced need for on-site inspections, as well as minimizing manual data checks for completeness, integrity, and accuracy (South Pole, 2020). Standards' digitalization efforts should therefore aim at enabling these goals by facilitating the corresponding changes to methodology. They should shift toward certifying monitoring systems rather than manually gathering results. To mitigate risks stemming from less frequent verifications, the introduction of a certificate "buffer" has been suggested, whereby a certain share of carbon credits is withheld until the subsequent in-depth verification has been completed (Bürgi, et al., 2019).

In addition to greater openness with respect to monitoring processes, standards need to establish a connection with automated data pipelines to work towards the fully automated issuance of carbon credits (South Pole, 2020; Bürgi, et al., 2019).

In these early days of D-MRV, the openness of standards toward digital approaches to monitoring is perceived as positive, but processes must be improved. Digital approaches to monitoring and data capture are the most advanced part of D-MRV. They are generally well accepted by standards and verifiers in energy projects that in general do not require any changes to existing methodologies and protocols. None of the interviewed actors report negative experiences with acceptance from the standards per se. However, the use of more integrated digital monitoring and quantification platforms is only emerging, and it appears that only very few standards have taken decisions on this. In many cases, the certification process for more integrated D-MRV approaches is a work in progress. On only few platforms is it well established. Early work under the CDM shows that novel D-MRV approaches are accepted even where they present significant departures from the status quo, e.g. substituting repeated site visits to biogas digesters with remote digital monitoring (UNFCCC CDM, 2021).

The main standards such as the Gold Standard and Verra are currently creating D-MRV working groups and expert networks that will support them on their way to digital approaches at all activity levels.

Interviewed actors report barriers to the implementation of D-MRV that are not directly connected to the digital nature of new approaches. Examples include lengthy and unpredictable feedback processes to methodology changes. This is further summarized in Table 5. Consequently, it would be beneficial for standards to streamline their review and feedback processes to reduce the time needed to get changes approved and mitigate the risk of delays and additional costs.

Table 5: Action areas to improve standards' acceptance and readiness

	Current state	Action areas mentioned by interviewed actors
Decentral-ized energy	In some cases, new approaches have been successfully implemented (UNFCCC CDM, 2021). In others, the conversation with standards is a work in progress.	Standards need to embrace digital approaches and take appropriate measures to facilitate and encourage introduction by other actors: ▪ **Guiding principles** need to be defined to communicate a general willingness to accept digitalization. Digital approaches' acceptance by standards is still not clear in many cases. These principles should also include basic technical requirements for new digital methodologies, such as minimum quality for hardware and data, as well as new rules on field visit frequency. ▪ **Handling of suggested methodology changes** needs to be streamlined. D-MRV systematically requires significant adaptations to methodologies. Development is therefore associated with additional risk due to unpredictable turnaround times. ▪ **Harmonization between standards is desirable:** Standards should reach a common understanding concerning the acceptability of digital approaches and should define common rules to guide actors' activities. This would contribute to streamlining the implementation and adaptation of methodologies, support D-MRV platforms' ability to flexibly generate different credit types, and future-proof the operations of the standards themselves. ▪ **Exploit synergies** in the digitalization of methodologies: The comprehensive adaptation of all methodologies is an urgent yet challenging task, not least due to its sheer volume. It may be facilitated through the streamlined consideration of multiple methodologies/technologies at once. Inefficiencies arising from the individual discussion of project types could be avoided.
Clean cookstoves	Projects are at an early pilot phase with initial engagement but limited feedback from standards. The Gold Standard methodology for electric cookstoves was established recently (Gold Standard, 2021).	

Table: INFRAS. Source: Interviews and own analysis

2.2.4. Maturity and scalability

A key characteristic of D-MRV approaches is their level of maturity as a technology and practice, as well as their scalability to much larger numbers of projects and activities.

The D-MRV solutions considered in this paper are technologically mature and at an early-to-advanced demonstration stage in their applications in the carbon context. Currently, most of them mainly have pilot projects which have been successfully implemented. However, actors have a strong track record with other relevant activities. These include either non-carbon business models (e.g. pay-as-you energy services) or conventional carbon credit projects (large-scale deployment of clean cookstoves).

Prospects for scalability are positive, yet the lack of experience, in particular the transfer of data from remote areas, adds uncertainty. Ample experience with large-scale projects of international scope likely provides a good basis for the expansion of digitalized MRV. Still, all considered cases are at an early development stage in terms of MRV digitalization for carbon credits. Barriers to scalability specific to D-MRV still need to be explored.

Table 6: Current D-MRV maturity and scaling opportunities

	Maturity	Opportunities	Risk and barriers to scaling
Decentralized energy	Digital approaches are well established for other applications (power plant control systems, pay-as-you-go energy, renewable energy certificates).	The necessary hardware and software are in place, technical challenges are largely solved.	Existing carbon project methodologies are found to be a poor fit for the development of decentralized power projects under some circumstances.
Clean cookstoves	Digital approaches for temperature measurement-based cookstove monitoring are a recent development, being developed at a pilot-project level for the past decade. However, some actors have a strong background in conventional clean cookstove programs.	Ample experience and existing local capacities. Partnerships are being established for hardware and software implementation.	Sensor and data transmission costs still need to fall significantly. The approach's acceptance from standards is still not clear, except for electric cookstoves under the CDM. The conversation is a work in progress.

Table: INFRAS. Source: Interviews

Scaling strategies are diverse, yet generally guided by the actor's previous activities:

- **Geographic scaling of D-MRV follows conventional carbon projects**: With the first successful small-scale implementations of digitally monitored projects in India, one actor envisages the use of sensors for cookstoves to be expanded to African countries, where ample experience with conventional carbon projects already exists.

Expected economies of scale are heavily technology-dependent and focus either on hardware or processes, depending on legacy operations.

- **With cookstoves, the cost of dedicated measuring hardware is expected to decrease considerably over time**: The use of dedicated sensors for cookstove activity monitoring is a new development, limited to small-scale projects until now. Hardware is therefore expensive and

has not been cost-optimized yet. However, economies of scale in sensor procurement are expected. Anticipated cost reductions may be up to 80%. The switch to cheaper hardware will in turn expedite upscaling.
Measurement hardware for decentralized power is mature due to its established use for non-carbon applications. Smaller future cost decreases are nevertheless expected as part of the normal development cycle.

- **Pooling of project registrations reduces overheads**: Registering smaller programs causes financial overheads and in some reported cases prevents them from reaching breakeven. Shifting registration responsibility from small project developers to operators of large-scale aggregating data platforms allows much larger programs to be implemented, generating associated cost savings in the registration process. While this strategy is also applicable to non-digital projects, automated monitoring necessarily facilitates the approach.
- **Automated data platforms and pooling enable small stakeholder participation**: Small-scale projects have closer community ties and higher SDG impacts. Streamlining the monitoring process reduces overheads and enables sufficient cost savings to make these projects viable, hence increasing the pool of potential projects benefitting local communities.

Barriers to upscaling are also being discussed:

- **Future demand for carbon credits is uncertain:** Strongly rising demand on voluntary carbon markets is currently being observed. However, the market is flooded by (very low cost) nature-based carbon credits. This keeps current carbon prices at (excessively) low levels (of 2-4 USD/t) that are not enough to provide meaningful additional revenues rendering energy and cookstove projects viable. In this context, digital approaches with higher up-front costs are at an even greater risk of sunk costs if prices remain low or decline further.
- **Challenges in scaling existing software packages in energy projects:** The growing scope of pay-as-you-go business models for decentralized electricity required major updates to data platforms. While this is not directly related to D-MRV, similar requirements can be expected for an established D-MRV system. However, software scaling is a standard problem with established solutions across all industries.
- **Data transfer for remote rural monitoring:** The considered technologies all rely on the availability of a mobile network for data transfer. This represents a major barrier to scalability, as the solution cannot be expanded into more remote areas without GSM connectivity. Although some actors are content to be restricted to areas with mobile network connections, it is a fact that in many more remote areas, mobile connectivity is very limited in terms of reliability and bandwidth, or non-existent. This includes remote rural areas in developing countries.

2.3. Assessment results

Table 7 shows an overview of the discussion in Sections 2.2.1-2.2.4. It contains a summary for each technology and criterion. The stars (★) provide a visual representation of the authors' overall expert estimates. They are relative ratings and serve to compare the technologies by highlighting differences rather than referring to an absolute scale.

In all cases, descriptions and stars refer to differences relative to conventional monitoring. For example, if one technology is triple star rated, digitalization in this case provides especially large benefits when compared with peer technologies and the conventional case.

The corresponding table for part 3 of this report (D-MRV in forestry and agriculture) is presented in Section 3.3.

Table 7: Summary: Assessment of D-MRV for distributed energy systems and cookstoves

	Decentralized energy	Clean cookstoves
Description of digital monitoring technologies		
	Power (or biogas) consumption is measured with high temporal resolution. Data is transferred (generally via GSM, in batches or in real time) to a centralized database. A strong emphasis is put on efficient data management on a dedicated data platform.	Cookstoves are equipped with digital sensors which enable the automatic detection of cooking events. Traceable and transparent data management on a dedicated platform is central.
Comparison with the reference case of conventional (non-digital) monitoring approaches		
	Streamlined digital monitoring acts primarily as an enabling technology, as projects are often too small to be viable for conventional carbon projects. The aggregation of many small projects using an efficient data platform facilitates scaling and enables data checks.	The digital approach automates monitoring of the critical usage parameters. In contrast, conventional cookstove monitoring generally relies on surveys to determine to what extent the cookstoves are being used.
Cost savings potential		
	★★☆	★☆☆
	▪ High potential for cost saving through digitalization if power meters are already in place (from pay-as-you-go energy services). ▪ Challenge: Cost of data transmission in remote areas.	▪ Reduced cost due to avoidance of survey-based monitoring of project activity. However, the cost of digital devices is considerable at this stage. Next steps in scaling are expected to allow for significant cost improvements e.g. if sensors are mass produced. ▪ Challenge: Cost of sensor and data transmission
Increase in credibility		
	★★☆	★★★
	▪ The online measurement of renewable energy generation allows for higher levels of accuracy and gives less scope for tampering with data. Further, transparency is increased as carbon credits can be traced back to their physical origins.	▪ The sensor-based determination of use times for cookstoves may be considerably more accurate than survey-based approaches. The data tampering risk may be mitigated through direct data transmission without manual intervention.

	Decentralized energy	Clean cookstoves
Applicability with current standards		
	★★★	★★☆
	▪ Digital approaches are already integrated into existing standards, or positive preliminary feedback (e.g. from the Gold Standard) indicates that this will be straightforward. The digital monitoring of biogas digestors using flow meters has recently been accepted as part of the CDM methodology (UNFCCC CDM, 2021).	▪ The feedback process from standards concerning sensor technologies is still a work in progress. ▪ Challenge: Need for optimum combination of survey (e.g. for baseline fuel) and usage time (sensor). ▪ Challenge: Combine sensors with sampling approach
Maturity and scalability		
	★★★	★★☆
	▪ Power meter technology is mature. Low-cost metering devices, software and transmission are works in progress. ▪ Scalability depends on the ability to lower costs for power meters and data transmission. Pooling of projects and working with communities is key to scaling.	▪ D-MRV systems are still at a demonstration stage in an increasing number of use cases. ▪ Cost of sensors and data transmission are still too high at this stage. ▪ Scalability depends on the ability to drastically lower the costs of dedicated sensors (e.g. for cookstove temperature measurement) and data transmission. ▪ Data transmission is a limiting factor for scalability into more remote areas.

Table: INFRAS. Source: Interviews and own analysis

3. D-MRV in forestry and agriculture

Alongside energy-related project types, projects for carbon removal in forestry and agriculture represent another important contribution to carbon markets. Compared with technical energy systems, MRV in natural systems tends to be more complex and challenging. For the sake of simplicity, we limit the discussion to projects encompassing carbon sinks in soil or above-ground biomass, and not related to e.g. nitrogen fluxes.

Conventional monitoring approaches in these areas are primarily based on extensive field data collection and approximate assumptions, e.g. “land use factors” and “tillage factors” to determine carbon stock changes due to project activities. More advanced models are increasingly relevant for monitoring: The use of remote sensing (VCS, 2017) or more sophisticated process-based modeling approaches (VCS, 2020) is an (optional) part of the methodology in some cases.

Novel digital approaches address various shortcomings of conventional approaches in relation to cost and scalability. Claimed superior accuracy is often an additional key selling point. Inter- views were conducted with a sample of actors in the D-MRV space to gain insights into current business models and challenges.

Box 3: Use cases analyzed in Section 3

Afforestation and reforestation monitoring—much like decentralized energy—sees a strong push toward broad data utilization and sophisticated modeling. However, the following section also presents an example that uses high-detail bottom-up tree tracking.

- **FlintPro**: Originally starting from national CO2 monitoring, the company is centered on the commercialization of the Flint open-source application. Large numbers of spatial and temporal data layers are combined to provide as accurate a carbon assessment as possible, including above and below ground carbon stock.
  flintpro.com
- **Space Intelligence**: As a university spin-off, the company is specialized in modeling land cover as well as forest carbon. Combining satellite data with a variety of other information and machine learning approaches, the focus lies on the provision of carbon estimates. In addition, support along the carbon credit MRV chain is provided.
  www.space-intelligence.com
- **WithOneSeed**: This carbon forestry program in Timor-Leste focuses on the community-based tracking of single-tree biomass. Through carbon credit payments, smallholder farmers are given an incentive to care for planted trees in the long term. Data on tree biomass

Box 3: Use cases analyzed in Section 3

is regularly acquired using a dedicated mobile phone app. Monitoring is streamlined and data is automatically uploaded to a dedicated digital platform.
withoneseed.org.au

For ***soil organic carbon in agriculture*** actors are employing new data sources and models to determine carbon stocks with greater purported accuracy and scalability. In addition, new approaches to direct carbon measurement are being brought to market.

- **Regrow:** At the interface between agriculture and climate tech, the company relies on a data platform with a broad variety of inputs, including data from farm management systems, satellite imagery, etc. Based on these inputs, the platform provides insights on soils and crops for farming decisions and carbon tracking.
www.regrow.ag
- **Perennial**: Soil carbon is measured using remote sensing combined with below-ground modeling and above-ground validation. In addition to data services, clients are supported at all steps along the MRV chain.
www.perennial.earth
- **Carbon Asset Solutions**: Built around a novel in-situ measurement technique for soil carbon, the company is in the demonstration and early commercialization phase. The approach promises to yield fast and accurate measurements of below-ground carbon concentrations. The company aims to cover the complete pipeline from field measurement to carbon credit generation.
www.carbonassetsolutions.com

3.1. Technological approaches

Accessing novel types of data and/or sophisticated modeling efforts enable greater detail, accuracy, and scale. Interviewed actors in this space rely on a broad variety of input data, ranging from conventional (also improved) field measurements to satellite imagery, weather data and comprehensive tracking at the single-tree level.

Three different key approaches to digital MRV are considered:

- **Ecosystem modeling for forestry biomass and soil organic carbon**: Many actors supporting or implementing nature-based carbon projects rely on comprehensive process-based and/or empirical modeling and machine learning approaches to obtain estimates of above and/or below-ground carbon stocks. Models are supported by empirical data for calibration, validation, and as an input. Both open/peer-reviewed and proprietary models are employed, depending on actor and application. Comprehensive data platforms aggregate a broad range of data from various sources, including field measurements, satellite imagery, LiDAR, and weather data. One area of focus is on high levels of data coverage and consistency (notably time series). Some actors incorporate and scale client-provided process-based models on their data processing platforms. Existing data streams from other actors are integrated (for example from farm management systems in the case of soil organic carbon). Models rely on large numbers of variables. According to the interviewed actors, in some cases this inhibits their application without dedicated support from domain experts. Products are therefore often offered as software as a service (SAAS).

Figure 3: Artist's illustration of one of the two Sentinel-2 satellites whose imagery is used to estimate forest biomass.

Illustration: ESA/ATG medialab

- **Contactless in-situ measurement of soil carbon:** One of the interviewed actors commercializes recent research work on in-situ soil carbon measurement devices using inelastic neutron scattering and gamma spectroscopy. A comparatively large soil volume of 0.75 m^3 within the

30 cm topsoil layer is measured at once. Built as a compact integrated and mobile device, the measurement apparatus is promised to be flexibly deployable in the field and moved easily, thus enabling high coverage while being pulled across a field. The device measures total soil carbon levels. Inorganic carbon is assumed to represent a constant background in the context of carbon accumulation. Concerning measurement accuracy, the solution is advertised as a viable alternative to laboratory-based analyses. Commercial rollout is scheduled for the near future. The resulting data is stored on a distributed ledger database.

Figure 4: Device for in-situ measurement of soil carbon based on inelastic neutron scattering.

Source: Carbon Asset Solutions

- **Single-tree tracking of biomass:** In one of the use cases considered in this paper, smallholder farmers in developing countries engage in community reforestation projects and benefit from resulting carbon revenues. For this purpose, biomass of all trees is regularly measured using RFID tag identification and efficient data entry using a dedicated app. Due to continuous monitoring, local communities have an incentive to care for "their" trees. The focus on detailed tracking is thus a tool to increase local community benefits and engagement.

General approach to remote sensing for forest biomass estimation

Most interviewed actors rely on proprietary methods. While they provided some insights into the current state of digital monitoring for forest biomass estimation, details of their approaches are confidential. However, remote sensing for carbon and biomass assessments is a very active area of research, with a wealth of recent academic and other publicly funded projects and publications.

Generally, biomass (and therefore carbon) estimation from remote sensing follows a multi-step process: Structural variables (e.g. canopy height or stem diameter) are derived from remotely acquired data. For this purpose, data such as the spectral components of satellite imagery are fed into suitable algorithms including machine learning. This results in estimates of the geometric properties of trees in monitored forest patches, notably canopy height (Csillik, et al., 2019) and stem dimensions (Miettinen, et al., 2021). The accuracy and precision of estimates can be improved by including additional data (such as LiDAR airborne laser scanning data) or higher-resolution imagery (Miettinen, et al., 2021). Further, it is found that larger trees correlate with smaller errors, thus making results for areas with high biomass density more robust (Csillik, et al., 2019).

Once the basic geometric properties of the area of interest are known, allometric models are used to determine biomass volume from this geometric information. These models exhibit strong dependencies on tree types and external factors such as climatic conditions. Excellent availability of ground-truthing data and parameters for allometric equations is thus paramount. However, this availability is often limited, particularly in some developing countries with large natural forests—such as the Congo basin—, which makes remote sensing applications challenging (Rodríguez-Veiga, et al., 2017).

Different remote sensing options are available, with specific strengths and weaknesses. **Passive optical measurements** can rely on openly accessible satellite image data. Vegetation types and geometric plant properties can be identified by analyzing the selective absorption of light in certain spectral bands. Data is available at a broad variety of spatial resolutions, up to 50 cm. Higher-resolution imagery has drawbacks in terms of cost and lower acquisition frequency (which in turn reduces the probability of cloud-free observations) (Rodríguez-Veiga, et al., 2017). While higher-resolution imagery can improve biomass estimate accuracy (Miettinen, et al., 2021), some actors argue that lower spatial resolution is beneficial for their specific approach, as a certain degree of spatial averaging is desirable (Space Intelligence, 2021). The general drawbacks of passive optical sensing include its limitation to daylight signal acquisition, the possibility of cloud obstruction, and signal saturation due to dense canopies (Rodríguez-Veiga, et al., 2017).

Some of these issues are mitigated by the combination of passive remote sensing data and **Light Detection and Ranging (LiDAR)**, which uses the reflected signal from actively emitting lasers to measure distances to points within the field of view. This results in a 3-D-point cloud representing objects within the scanned area (see Figure 5). This notably reduces the saturation issue: Signals from the forest ground and information on vertical biomass distribution are captured even in case of very dense canopies (Rodríguez-Veiga, et al., 2017; Dubayah, et al., 2020). Since LiDAR scans are generally carried out using dedicated aircraft, their acquisition is costly, especially if large forest areas are to be monitored. They are therefore often used to calibrate passive optical methods or as secondary data source (Csillik, et al., 2019). Satellite-borne LiDAR could mitigate this cost issue, yet is a relatively recent development with limited availability to date (Rodríguez-Veiga, et al., 2017). A notable example is NASA's GEDI mission, currently deployed aboard the International Space Station (GEDI, 2022; Dubayah, et al., 2020).

The problem of cloud obstruction faced by all (passive or active) optical systems is in principle solved by **microwave earth observation sensors** using synthetic apertures. Both aircraft-borne and satellite-borne approaches exist. In these cases, the ability to image biomass underneath a dense canopy crucially depends on the wavelength of the generated radiation, whereby longer wavelengths are better suited to penetrate to lower forest levels. While no space-borne solution with an appropriate wavelength exists at present (Rodríguez-Veiga, et al., 2017), the ESA's upcoming "biomass" mission is intended to fill this gap and enable a global microwave-based assessment of above-ground biomass (European Space Agency, 2022).

Figure 5: Example of LiDAR point cloud data for a forest. Individual trees and their geometric properties can be identified.

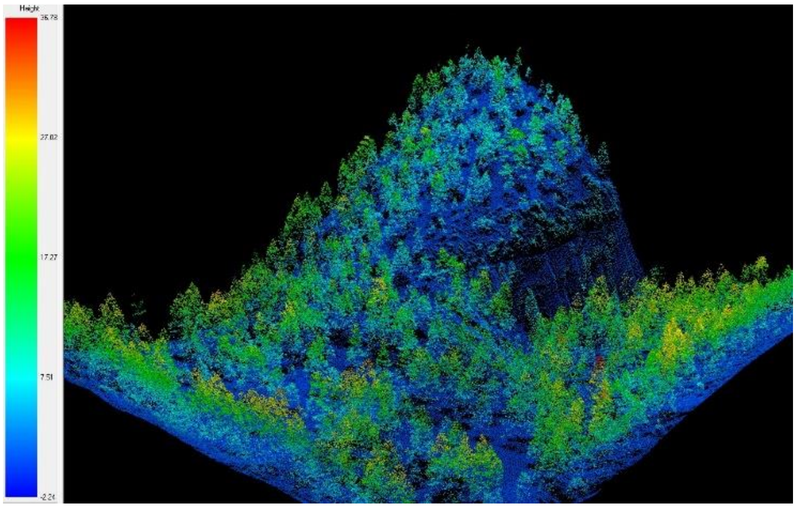

Image: Southwestern Region, USDA Forest Service/CC-BY-2.0

Given the challenge of uncertainty in remote sensing for biomass stock estimates, small growth increments in trees in afforestation projects over time are even harder to detect as they represent the difference between rather ambiguous biomass stock values.

Table 8: Differences between the conventional (non-digital) monitoring approach and D-MRV

	Conventional approach	Comparison with D-MRV
Ecosystem modeling for forestry biomass and soil organic carbon	▪ Field measurements ▪ Rough assumptions on carbon stock development given certain tillage practices, forest types, etc.	▪ More sophisticated process-based modeling and machine learning approaches using a broad variety of input data ▪ Field measurements as ground-truthing data for calibration and validation
Contactless in-situ measurement of soil carbon	▪ Some standards' methodologies include the use of process-based models in agriculture (VCS, 2020) or remote sensing for forest biomass monitoring (VCS, 2017)	▪ Geographically denser field measurements are possible due to low-cost technology (compared with laboratory sampling)
Single tree tracking of biomass		▪ More detailed (single-tree level) assessment of biomass volume using bottom-up project structure with strong ties to local communities

Table: INFRAS. Source: Own research and interviewed technology providers

3.2. Assessment of D-MRV for activities in in forestry and agriculture

Below, the use cases selected for this paper (Box 3) are assessed according to the defined criteria (Box 1) to characterize the pros and cons of different D-MRV solutions. The results of the assessment are provided in a table in Section 3.3.

Most proposed digital approaches to nature-based projects focus strongly on the efficiency and scalability of carbon assessments and measurements, as well as data integrity and consistency. In other cases, an emphasis on transparency and inclusion prevails, yet this also drives innovation in terms of process streamlining.

Compared to the standards' existing methodologies for calculating emission reductions, major disruptions are being pushed forward by some actors: For example, the heavy reliance on sophisticated ecosystem models and a broad range of input data promises the more accurate determination of carbon stocks. The accuracy and precision claims of interviewed actors could not be verified as part of this study, however. The corresponding approaches are sometimes treated as black boxes due to their reliance on machine learning and/or intellectual property. Reportedly this does not pose a fundamental barrier to certification, as demonstrated model performance in relation to ground truth is accepted by standards. However, actors lament the continued need for extensive field sampling as an unnecessary cost factor. The right balance between modeling and measurement of carbon stocks is yet to be found.

The results of the assessments are provided in a table in Section 3.3.

3.2.1. Costs and cost savings

Cost savings and higher throughput are the primary motivations for the establishment of digital MRV approaches in forestry and agriculture. Proposed solutions aim to streamline processes or render the main cost factors of conventional approaches (like field sampling) partly obsolete. Many are more recent developments, building on significant amounts of R&D. Assuming that their credibility is equal or superior to conventional approaches, major cost reductions can be expected to manifest.

Table 9: Additional cost of D-MRV approaches compared with conventional MRV

	Investments	Running costs	Costs of adaption to Standards	Cost benefits compared with conventional approach
Ecosystem modeling for forestry biomass and soil organic carbon	Actors are at different stages of development, yet systems are operational. Potentially considerable development cost for models, platforms, and data pipelines as well as data acquisition for calibration in the pilot phase.	Automated approach enables cost reductions despite data procurement and model setup. Field measurement requirements are potentially relaxed. Interviewed actors often rely on relatively low-resolution satellite imagery at low cost.	The certification burden is often shifted to client and the focus put on data generation. Actors still provide support along the MRV chain.	Potential for reducing field measurements; costs of digital monitoring decrease as scope of activities increases and available data becomes more comprehensive.
Contactless in-situ measurement of soil carbon	Development of measurement technology incl. R&D, calibration, and commercialization, setup of MRV pipeline.	Actors expect low maintenance costs, once technology is mature, notably in units per measurement due to high data acquisition rate.	Conventional carbon standards are found to be unsuitable for this specific approach at this stage. Development of dedicated ISO certified product is planned.	Alternative low-cost soil carbon measurement method with high throughput is claimed to be more cost effective than conventional laboratory analyses. SOC data is also beneficial to optimize agricultural practice and yield.
Single-tree tracking	Established approach, incremental development of data pipeline.	Added cost of comprehensive tree measurements compared with sampling yet found to be worthwhile in terms of transparency for small projects.	The approach is well-accepted. Changing requirements especially on the SDG side require costly adaptations.	High cost due to comprehensive measurements, according to interview, yet benefits prevail.

Table: INFRAS. Source: Interviews

Additional costs compared with conventional MRV arise mainly due to the development of models, software, and novel hardware for data capture, transmission, and processing. The reliance on a broad set of additional data sources may be an additional potential cost factor.

- **Software and model development necessarily a cost factor, yet actors build on previous activities**: This includes academic research, existing open source data aggregation platforms, and smart farming products.
- **More comprehensive data acquisition is worthwhile due to higher impact of carbon projects**: Tracking of single trees necessarily entails cost premiums when compared with sampled field data campaigns, yet the increase in transparency is considered by technology providers to make this approach worthwhile.

Cost reductions are made possible through efficiency gains (e.g. for gathering data on monitoring parameters) and the (partial) avoidance or streamlining of field data acquisition (soil carbon measurements, systematic tree measurements).

- **Detailed data-heavy modeling may reduce the need for costly field data:** Soil sampling is described as a major component of total project cost. The same holds for field data campaigns in forestry. According to actors, sophisticated models and the comprehensive use of available data sources provide carbon estimates at equal or higher accuracy and precision. However, claims are not verified within the context of this report. Standards' methodologies nonetheless still require field data to a larger extent than interviewed actors would consider necessary for calibration. According to some actors, the new technology allows for higher levels of accuracy with fewer field measurements.
- **Novel measurement technology enables high-volume sampling at low cost:** Business models are being built on top of low-cost soil carbon measurement methods. High-frequency in-situ sampling of soil carbon is claimed to constitute an equivalent or superior alternative to time-consuming and expensive laboratory analyses, hence ultimately promising lower costs.
- **The project economics of model-based approaches improve over time:** Carbon assessments using data-centered modeling approaches mainly require an investment in their initial setup. Once data and methods are established and calibrated for a given project, the costs of assessments decline over subsequent years.
- **Data acquisition is made more efficient using digital approaches:** Actors innovate digital systems to make parameter and specifically field data collection more efficient. For example, dedicated data management systems streamline MRV processes along the whole chain, from data entry to verification. RFID tree tagging combined with a dedicated mobile app allows biomass volumes to be determined comprehensively.

3.2.2. Credibility

Thanks to greater accuracy and/or transparency, all considered approaches potentially constitute significant improvements in credibility when compared with conventional carbon projects. This is enabled through higher degrees of sophistication, the streamlining of data acquisition and presentation, as well as more comprehensive data gathering. At the same time, field sampling continues for calibration purposes and to meet standards' requirements:

- Reliance on proprietary approaches and machine learning reduces transparency compared with conventional methodologies. However, more sophisticated approaches are claimed to yield superior accuracy and precision when compared with conventional methodologies. Claims could not be verified in the context of this study.
- Novel soil carbon measurement technology claims similar accuracy and precision to the conventional soil sampling approach, backed by peer-reviewed publications on the approach for specific environments (Yakubova, et al., 2015). ISO 14064-2 2019 and ISO 14064-3 2019 certification is under development.
- Comprehensive single-tree monitoring increases detail level beyond any conventional monitoring method.

Table 10: Factors influencing the credibility of D-MRV approaches

	Credibility strengths	Credibility weaknesses
Ecosystem modeling for forestry biomass and soil organic carbon	Higher data quality: Sophisticated ecosystem models with broad range of input data promise to deliver higher accuracy.	Transparency: Proprietary models are intransparent to some degree, yet standards are reported to accept comparison with ground truth as evidence of validity.
Contactless in-situ measurement of soil carbon	Accuracy: Fast in-situ measurement is claimed to offer accuracy on a par with conventional soil sampling and laboratory analyses. This would boost credibility if realized in production.	Novelty: Technology not yet commercialized; the development of certification pipeline is a work in progress. Lacking validation: No comprehensive independent third-party validation of the measurement and modeling approach seems to have been published to date.
Single-tree tracking of biomass	Data quality: Detail level beyond conventional methodologies' requirements	None

Table INFRAS. Source: Interviews

Data quality: Suggested approaches rely on broader data sources for the calculation of biomass volumes and emission reductions. However, in the case of both soil organic carbon and woody biomass calculation, approaches are more indirect when compared with conventional approaches (typically laboratory testing and field measurements). Some actors claim the accuracy and precision of their results are superior to conventional approaches. It appears that these claims have not been independently validated at this stage. In other cases, the limited accuracy of remote sensing for carbon estimation is reported to be a barrier to the adoption of the approach by certain potential customer groups. Instead, the potential benefit lies in significant cost reductions (Forest Flux, 2022).

- **Large data collections ensure consistency in time and across variables:** Actors maintain large datasets which are applied across projects. This use of continuous, consistent time series is especially crucial when determining changes in carbon stocks.
- **Data management system removes points of failure in the data pipeline** by facilitating data gathering and traceability during the verification process.
- **Comprehensive data collection and analysis enable uncertainty to be determined:** Clients can be provided with information on the uncertainty of determined emission reductions. This information can then be used flexibly for various applications (e.g. more, less conservative carbon credits for corporate goals or more conservative for fewer certified credits). For other actors, uncertainty analysis is in active development.
- **Time series availability enables assessment of situation prior to project planning:** Historic satellite images allow an analysis of forests' or fields' states for time periods long before the start of the carbon project. According to actors, past tillage practices claimed by farmers can be independently verified.
- **Internal data are complemented with project-specific data depending on client needs:** Out-of-the-box models for above and below-ground biomass facilitate timely carbon estimates. Internal data are complemented with more targeted data (e.g. client-provided) for better adaptation to the project in question.
- **Possibility of flexibly increasing accuracy:** The digital methods for forest biomass calculation that have been developed to date can be boosted in accuracy at a cost premium through additional data sources (e.g. LiDAR) or higher-resolution satellite data (e.g. very-high-resolution commercial imagery rather than open Sentinel-2 data (Forest Flux, 2022).

Transparency: In addition to superior data quality and completeness, digitalization boosts transparency and traceability:

- **Full traceability of input:** Actors employ data platforms (around models and for data aggregation) with an emphasis on the full traceability of results. Input data generating certain output values can be efficiently identified, even if the intermediate steps rely on proprietary solutions.
- **Single-tree tracking demonstrates the long-term effectiveness of climate action:** Continuously tracking single trees in reforestation projects shifts the approach from planting trees to

growing trees. Payments based on effectively determined carbon stock provide local communities with incentives to take care of trees.

- **Proprietary data and models are not made public for verification:** Some actors operate proprietary models which are kept confidential or rely on machine learning approaches which possibly operate as black boxes by design. Also, client-provided input data and models can impose considerable IP-related constraints.
- **Lack of data openness**: One of the issues blocking innovation is that data is commonly considered the property of the party gathering it. This prevents the establishment of large datasets in the public domain, which would boost model development.

3.2.3. Applicability with current standards

Acceptance from standards is described as good or a work in progress, yet the requirements of legacy methodologies may pose barriers. According to interviewed actors, standards accept digital approaches combined with field sampling, as the need to scale carbon markets efficiently has been recognized.

Table 11: Actors' current experience with standards' acceptance and areas of concern

	Current state	Areas of concern
Model-based estimates	▪ Certification is possible in all reported cases. ▪ Even if models are proprietary, standards accept a demonstration of model accuracy in relation to ground truth. ▪ Actors focus on best-in-class carbon assessment while remaining neutral with respect to carbon credit generation.	▪ According to actors, remaining sampling requirements inhibit full cost-saving realization. ▪ Interaction with standards is described as tedious. ▪ Information on model uncertainty is often not provided at present, leading to the approaches' ineligibility for project certification under certain standards.
In-situ soil carbon measurement	▪ Actor considers independent ISO certification as an opportunity for standard-independent application and possible route to future acceptance by standards.	▪ Acceptance by standards remains uncertain given early stage of development.
Single-tree tracking	▪ Performance in standards' audits is high. ▪ Program is fully self-sustaining based on carbon credit revenue.	▪ Actors describe tedious communication with standards as general problem.

Table: INFRAS. Source: Interviews

Not directly affected by leading standards' rules: Some interviewed companies are not directly impacted by standards' requirements since they either focus on data services or seek alternative routes to monetize carbon outside of established carbon standards:

- **A focus on data service provision (as accurate as possible carbon assessments)** enables actors to shift certification burden to clients. Openness with respect to target standards increases the client base and certification options.
- **Setting up alternative certification to most common standards** by defining an ISO-compliant approach (ISO 14064) for voluntary markets. Based on feedback from leading standards, actors found the current approaches too constraining given the potential of their novel measurement technology. Therefore, an alternative route to carbon monetization was sought. Discussions with standards are still ongoing, however.

Standards' requirements add significant cost, yet proprietary data and models do not stand in the way of certification:

- **Laboratory sampling requirements are described as a major concern for project economics**: Methodologies for soil organic carbon in agriculture call for sampling and laboratory tests to some extent. According to actors, this presents a deal-breaker in terms of cost. Further, the accuracy and precision of calibrated and established models is claimed to be comparable to soil sample analysis. In addition to the high sampling requirements, actors describe the lack of harmonization between standards as barrier.
- **Standards are found to be sufficiently flexible in approving methods**, even if models are proprietary, interviewed actors claim. However, new approaches have the potential to reduce the number of ground measurements required, the cost of which is described as a major barrier. Nevertheless, actors report difficulties in communicating with standards to implement novel approaches (see also Section 2).

3.2.4. Maturity and scalability

Both the maturity and (anticipated) scalability of systems are promising, yet depend heavily on the technology type. Maturity ranges from very established single-tree tracking practices to rather novel in-situ measurement and remote-sensing platforms. A broad range of experience and prior history (e.g. academic research) also exists in the latter case.

Scalability is theoretically high for data-centric approaches. Cost savings, efficiency improvements and broad applicability have enabled or are likely to enable further growth. The shift from physical (e.g. measurements) to digital processes further benefits this. However, the persistent need for field data for calibration and verification acts as a natural barrier to scaling in the current environment. This could be alleviated through the broader availability of calibration and verification datasets, for example from carbon programs and standards. Another factor hindering scalability is the need for the costly development of data platforms allowing for efficient project setup and high throughput.

Table 12: Current maturity and scaling opportunities

	Maturity	Opportunities	Risk and barriers to scaling
Ecosystem modelling for soil organic carbon and forestry biomass	▪ Established models and data platforms. ▪ Partial track record in national GHG assessments or smart farming. ▪ Improvement of accuracy in novel remote sensor-based approaches still needed and work in progress.	▪ Current level of automation promises high scalability. ▪ Automation is being improved to enable efficient realization of small-scale projects. ▪ To some extent: Role as data provider reduces scalability constraints and shifts related challenges to project developers.	▪ Sampling requirements under new digital paradigm are not yet determined. ▪ Costly adaptation to other geographical areas. ▪ Small projects require labor-intensive setup. ▪ Land ownership and rightful beneficiaries of carbon credits difficult to determine in some countries (registries missing). ▪ Software development for high scalability is a work in progress.
Contactless in-situ measurement of soil carbon	▪ Current system at demonstration stage. ▪ Commercialization is in development.	▪ Technology is designed for fast throughput and potentially allows for rapid coverage of large areas. ▪ Direct measurement is claimed by actors to be applicable to ▪ many geographies/soil types.	▪ Commercialization is only at an early stage.
Single-tree tracking of biomass	▪ Established project with strong community ties. ▪ Ongoing expansion to other ap- plications	▪ Expansion to new environments and applications is being actively pursued. ▪ Due to bottom-up approach, local community scales along with project size. ▪ Flexibility of approach enables scaling beyond originators' activity sphere.	▪ Scaling is naturally limited by the need for manual data gathering. The approach is therefore only applicable to forests with nearby communities engaging in MRV.

Table: INFRAS. Source: Interviews

- **Remote sensing boosts scalability**: Apart from persisting sampling requirements, sufficiently sophisticated model-based approaches have virtually no scale limits, within the limits imposed by the need of data procurement and model adaptation to new geographies or environments. Further, interviewed actors claim that model performance is sufficiently high to render field sampling at least partially obsolete. This would be an additional contribution to the scalability of carbon credit generation. However, significant limitations are imposed by the need for field data gathering and calibrating models for adaptation to new geographies, species, practices, and other influencing factors in both forestry and agriculture).
- **Technological innovation increases throughput of carbon credit generation:** In-situ soil carbon measurement technology is promised to deliver very high measurement rates and instantaneous results compared with laboratory analysis. Current developments in the technology in the commercialization phase are claimed to outperform measurement rates reported in peer-reviewed literature (Yakubova, et al., 2015).
- **Purely measurement-based method is transferrable to other markets:** Due to the lack of geography-specific parameter assumptions, the solution's claimed applicability to other geographies is a core component of the actor's business case. However, the broad applicability of the described approach can not be independently verified in the context of this study.
- **Actors are finding new applications for existing D-MRV approaches:** As an example, an efficient single-tree tracking method originally developed for developing countries is being applied to farms in Australia. Opening up these new markets enables farmers enabled to generate income from above-ground biomass on their land.
- **Openness of software potentially contributes to scaling of approach:** By licensing a platform for single tree tracking to other actors, or offering it for free to small project developers, approaches can be scaled beyond the originator's activity sphere.

Some issues could have negative impact on scalability, however:

- **Model applicability limited to certain geographies, species, soils, etc.:** Forest ecosystem models are typically designed for a specific environment and require major adaptations if they are to be applied to e.g. boreal forests instead of the tropics. This need for targeted adaptation is even more pronounced for soil organic carbon models in agriculture, due to higher model complexity.
- **Remote sensing reduces connection with local actors:** Data and modeling-based approaches operate in a streamlined manner, yet potentially lack the connection with local communities. This may exacerbate problems such as the determination of rightful land ownership. The rapid scaling of operations in countries with a lack of registries can mean that carbon credits do not benefit rightful landowners, including local indigenous communities.

- **Only partial automation inhibits small-scale project implementation:** The degree to which model-based approaches are automated is a continuum between actors. In some cases, the need for manual intervention persists, often due to the comparatively recent establishment of commercial operations and the lack of up-front investment in a digital infrastructure covering all aspects of the project cycle. The actors concerned are actively working on streamlining and automating model deployment.

3.3. Assessment results

Table 13 shows an overview of the discussion in Sections 3.2.1-3.2.4. The rationales behind the relative star ratings are described in section 2.3.

Table 13: Summary table: Assessment of D-MRV for nature-based solutions

Criteria	Ecosystem modeling for forestry biomass and soil organic carbon	Contactless in-situ measurement of soil carbon	Single-tree tracking of biomass
Description of digital monitoring technologies			
	Ecosystem modeling approaches using large data sets (e.g. global satellite imagery) from remote sensing and field measurements. Data pipelines are streamlined. Applicability of a given model is generally limited to specific forest types/geographies.	A novel measurement approach based on inelastic neutron scattering is in the demonstration/early commercialization phase. Installed on a small trailer, the device promises rapid scanning of large areas of agricultural land.	Detailed tracking of each individual tree within the project using RFID tags and streamlined data entry.
Comparison with the reference case of conventional (non-digital) monitoring approaches			
	Models are claimed to be much more sophisticated. According to actors, accuracies are sufficiently high to render field data acquisition for monitoring partly obsolete, thus enabling cost savings. Claims could not be verified as part of the analysis.	The approach is advertised as a more cost-effective and faster alternative to conventional spot soil carbon measurements. Further, it allows for more rapid screening of large areas, as all analysis is performed on the spot.	Comprehensive biomass estimation (rather than sampling) and more sophisticated data management for highly transparent and accurate carbon quantification. Continuous tracking by the community fosters maintenance of trees.
Cost savings potential			
	★★☆	★★☆	★☆☆
	Model-based approaches have cost-saving potentials if the purported accuracy and precision are indeed sufficient to avoid soil sampling laboratory analyses. However, uncertainty remains concerning standards' requirements for expensive field data acquisition.	Announced cost efficiency is partly overshadowed by R&D costs in the demonstration and early commercialization phase.	Detailed bottom-up biomass tracking entails higher cost, which is however balanced out by community and transparency benefits. Further, higher costs are mitigated by efficient digital approaches.

Criteria	Ecosystem modeling for forestry biomass and soil organic carbon	Contactless in-situ measurement of soil carbon	Single-tree tracking of biomass
Credibility			
	★★☆	n.a.	★★★
	Sophisticated calibrated models considering broad ranges of input data. Actors promise to deliver higher accuracy and precision compared with the reference case based on simpler models and limited field data. These claims are not verified in the context of this study. The primary challenge is the lack of transparency for proprietary and partly opaque approaches.	The performance of the technology has been studied in peer-reviewed academic research. However, due to the novelty of the approach, no statement on credibility in the context of carbon credit generation can be made.	High detail and transparency push credibility ahead of any conventional approach.
Applicability with current standards			
	★★☆	n.a.	★★★
	According to the interviewed actors, their approaches are generally well received by leading standards, if calibration and validation are appropriately demonstrated. However, questions remain concerning the optimum extent of field sampling given the higher sophistication of modeling approaches.	The actor is aiming for a custom solution along the whole credit generation chain from measurement to issuance. For this purpose, ISO-based certification is being developed as a first step.	Fully accepted by Gold Standard performance audits, according to interviewed actors. Barriers are reportedly tedious communication with carbon standards concerning feedback on methodologies.
Maturity and scalability			
	★★☆	Maturity: ★☆☆/Scalability: ★★☆	Maturity: ★★★/Scalability: ★☆☆
	Systems are established with different levels of maturity. The accuracy of some approaches needs further development to reduce uncertainties. Scalability issues in some cases (e.g. high cost to set up small projects) are not fundamental constraints and subject to active development.	The approach is in the demonstration phase. Provided that technology develops as planned and demand for soil organic carbon credits reaches anticipated levels, scalability claims appear reasonable.	Processes are established, scalability is given by bottom-up structure with strong community involvement as well as the ongoing expansion of the methodology to other geographies/project types. However, by design, the approach neither targets nor is suited to the large-scale monitoring of forests without nearby communities.

Table: INFRAS. Source: Interviews and own analysis

4. Overarching characteristics of D-MRV approaches

4.1. Potential for continuous D-MRV, continuous issuance, and earlier cash flow

In a conventional project cycle, the verification and issuance of credits takes place every monitoring period, typically on an annual basis. This means that after implementation, project participants must wait for the monitoring period to start, plus an additional two months approximately for manual verification before issuance and transfer are possible. This results in delays of up to 13-15 months from the start of implementation to selling the credits. This time lag is significant in projects with typically higher discount rates, as it reduces investment attractiveness.

D-MRV solutions allow for an integrated system of digital monitoring, quantification, verification, and issuance processes that enable continuous certification and issuance. This makes earlier and continuous payments possible, pulling positive cash flows forward in time. This increases attractiveness, particularly for projects with high up-front costs, where quick repayment is of the essence.

Continuous D-MRV and issuance is also attractive for (retail) buyers. For instance, in the FairClimate "cooking as a business" use case funded by CLI, potential buyers can see on a dashboard which cookstoves are generating their credits over time.

4.2. Digital MRV as a service

Various types of actors operate in the D-MRV space and cover different ranges along the MRV chain. Some limit their activities to the operation of digital platforms and the provision of data, in other cases the whole chain from monitoring to credit issuance is envisioned or already implemented. To close the link between project implementation and carbon credit issuance, actors usually establish partnerships. For example, an operator of distributed energy hardware partners with another actor to establish the digital link to certification.

Some actors develop dedicated data platforms to support a broad variety of project types. The main service provided is digital project management. This demonstrates that even if project structure and data content stay close to or are equal to conventional methodologies, there is added value because of increasing efficiency in data management.

In the dedicated MRV platform use cases presented in Box 4 below, a data system for carbon projects in the agricultural sector was subsequently expanded to other industries and project types, from clean cookstoves to abatement measures in the gas industry. Built with the goal of facilitating parameter collection to the greatest possible extent, the system handles the gathered data in an integrated, centralized, and traceable manner, thereby lowering verification costs significantly. The verification focus can shift to the digital MRV platform system, including the underlying data processing, equations etc., rather than the data itself. The system's flexibility allows for broad applicability, beyond conventional projects.

Compared with conventional approaches with a focus on manual, often spreadsheet-based data handling, such systems enable:

- Streamlined collection of and quality checks on relevant parameters in line with standards' requirements.
- Aggregation on a centralized platform for easy access, traceability, and transparency.
- Harmonized treatment of different project types to maximize synergies in the software's application.
- Removal of failure points in the monitoring process (e.g. due to manual data transfer and the reliance on spreadsheets).

These advantages hold especially where the data platform is highly mature.

Box 4: Analyzed use case with dedicated MRV platform
▪ **Radicle:** A flexible and very mature data management system for carbon projects, streamlining the MRV process from the efficient monitoring of data acquisition to verification. While originating from carbon projects in the agriculture sector, the platform is largely neutral with respect to project types. This enables its application in a broad variety of other projects. radiclebalance.com

4.3. Approaches to developing D-MRV

4.3.1. Development pathways for D-MRV

D-MRV solutions are sometimes built as a dedicated approach. However, in many cases they were more gradually developed from previous operations and products. Thanks to synergies, established capacities, and relevant experience, these previous activities enable or facilitate the establishment of D-MRV. Three possible approaches leading to the implementation of D-MRV solutions can be summarized:

First, D-MRV built as part of a dedicated business model: These solutions aim to streamline carbon credit generation from the start. In the examples considered, this is given by the employment of a novel in-situ carbon measurement method with a dedicated D-MRV pipeline.

Second, some of the solutions were designed with the explicit goal of making existing MRV processes more efficient: For example, the digitalization of clean cookstove monitoring builds on previously established MRV workflows.

Third, in many other cases, D-MRV activities were built on top of existing digital and/or modeling-based activities. This notably enables synergies concerning software, data pipelines, and in some cases also measurement hardware:

- **Commercialization of an open-source data integration system**: The actor found the usability of complex modeling frameworks for nature-based credits to be a greater barrier than the availability of data or software. Therefore, a commercial company was built around the provision of software as a service, with an open source framework at its core.
- **Commercialization of available data sources**: The Forest Flux project's explicit purpose was the development of commercial products exploiting Copernicus Earth Observation data (Forest Flux, 2022). Starting as an EU-financed project, the assessment of demand for the provided biomass and carbon inventories went hand in hand with their development.
- **Data platform for decision support in agriculture**: Comprehensive data collection and soil/ecosystem modeling was already established before carbon credit activities began. Legacy products inform farm owners about issues related to water, nutrients, and crop stress. The available data presented a good starting point for carbon estimates.
- **Academic remote sensing research** led to requests from public and private actors. A spin-off company was established to provide the corresponding services. There, the focus shifted to scalability and robustness.
- **National CO2 monitoring**: Multiple actors used models primarily for contributions to national emissions assessments for the GHG inventory. Subsequently, services were expanded to carbon monitoring for monetization purposes.
- **Pay-as-you-go energy services**: With the goal of improving energy access in the Global South, actors implemented solutions enabling pay-as-you-go energy services. Approaches range from fully vertically integrated solutions (all hardware including e.g. PV and fridges) to approaches providing data acquisition hardware to be integrated into existing systems. In all cases, detailed measurement and sophisticated data management systems are part of the solution. This paved the way for D-MRV independent of whether carbon credits were part of the business plan from the beginning.
- **Non-carbon certificates**: A dedicated digitalized system was implemented with the overarching goal of streamlining processes around the issuance of Renewable Energy Certificates (RECs). D-MRV for carbon credits followed in its wake. This approach benefits from the fact that REC issuance is structurally simpler than for carbon credits.

4.3.2. Rationales for adopting D-MRV by actors

Building on the foundations described in Section 4.3, actors proceeded to establish D-MRV for a broad variety of reasons. These include efficiency of operations, cost savings, and specific market needs. While there is a large overlap with D-MRV benefits (see Sections 2.2 and 3.2), rationales for adoption may be summarized as follows:

Cost and revenue improvements are naturally a strong driver to adopt digital systems. These target different cost factors and revenue streams:

- **Cost reductions by substituting the expensive practices of conventional approaches:** The expensive field measurement requirements of conventional methodologies incentivize actors to develop more efficient approaches, e.g. sophisticated models relying on a broad range of input data.
- **Cost reductions by streamlining conventional methodologies' monitoring approaches:** Even without disruptive changes to the underlying methodologies, large savings can be gained by providing project developers with the option of efficient data gathering, followed by partly automated verification using sophisticated data management systems (e.g. single-tree tracking of biomass in Section 3.2.1, dedicated D-MRV platform in section 4.2).
- **Revenue increase through diversified operations:** Comprehensive data pipelines that were put in place for other activities (e.g. digitalized pay-as-you-go energy sales, renewable energy credits, farm management systems, and national GHG assessments) mean low entrance barriers to carbon markets. The established systems mean that the D-MRV requires fewer software adaptations and less negotiation with standards.
- **Upscaling through inclusion of small-scale projects:** Small-scale projects (e.g. small decentralized power or local reforestation projects) are closer to communities yet suffer from accessibility issues, as market participation in a strongly segmented environment has high overhead costs. Facilitating market access for these projects typically enables considerable SDG impact.

Operations can be streamlined thanks to the comprehensive availability of monitoring data. Naturally, this reason for adopting D-MRV also ultimately reduces costs and increases revenues:

- **Smoother operations:** Direct activity monitoring allows issues in project operations to be identified, e.g. related to technical problems or the underutilization of cookstoves. Issues can then be mitigated through targeted intervention by local partners.
- **Providing information to local community members improves efficiency:** Giving cookstove users access to information on their own behavior fosters their understanding of benefits and

incentivizes greater utilization rates. In addition, information on funding origins is also appreciated and helps to improve acceptance.

Markets for carbon credits are expected to scale up significantly, which translates to a call for higher liquidity. Further, some particular markets needs were identified, which are best met using digital pipelines:

- **Throughput for market liquidity**: Actors expect demand on voluntary carbon markets soon to far outstrip supply. Improvements in efficiency and the rate of carbon credit generation are aimed at providing the necessary liquidity.
- **De-risking small-scale decentralized projects**: Through automated monitoring and aggregation, small projects become accessible to the market, therefore also providing greater liquidity.
- **Flexibility to generate various types of certificates**: A digitalized platform incorporating a wide range of data sources while maintaining maximum detail allows for the flexible generation of multiple certificate types (e.g. depending on the client's needs) while simultaneously excluding the risk of double-counting.
- **Flexible aggregation according to market needs**: A digital platform with full data resolution enables flexible aggregation in line with clients' needs, while avoiding information loss. For example, relevant energy volumes from decentralized projects are in the order of Wh, yet the downstream market requires MWh.
- **Low prices for carbon credits**: With much of private emission commitments still voluntary, carbon credit buyers are highly price sensitive. This drives the adoption of streamlined schemes for cost reduction.
- **Transparency and traceability**: Digitalizing monitoring enables the establishment of fully transparent data pipelines, whereby the buyer of carbon credits obtains detailed information on how the corresponding emissions reductions were achieved. According to some actors, this level of transparency meets a concrete market demand.

4.4. Connectiveness and openness

Current dynamics in the D-MRV space favor cooperation in a multitude of ways. However, the dynamics may also lead to redundancies because the scopes of activities are not fully defined yet. Partnerships between actors are primarily built on the mutually beneficial use of data. However, participation to shape the industry according to actors´ needs has also been reported as an overarching goal.

Upstream and downstream connections are established for various reasons, for both partnerships and product delivery:

- **Operators of data integration systems rely on a broad variety of input variables**: Partnerships with upstream data providers are established for this purpose. In the case of soil organic carbon these are farm management systems, for example. In the case of forest monitoring the data from actors generating ground measurements is used for model calibration.
- **Upstream data requirements as part of the business model**: Some actors assume an enabling role, establishing a link between project developers and carbon markets. Monitoring and raw data generation is not part of this business model, which leads to a reliance on partners for upstream data sources.
- **Strong focus on corporate clients puts emphasis on downstream API**: Some operators of modeling and data aggregation platforms see their primary role as the provision of data rather than the generation of carbon credits. Consequently, the service puts an emphasis on downstream API for clients.
- **Mutually beneficial partnerships are established within the D-MRV space**: The digital MRV space provides for novel methods of data generation as well as actors with sophisticated models using that data as inputs. Previously unavailable detailed field data (e.g. comprehensive biomass tracking at the single tree level) is thus an input to these models, which in turn provide growth predictions to upstream partners.
- **Actors restrict their role and rely on partners for added features**: For example, actors modelling soil organic carbon in agriculture may include life cycle emission results (e.g. from dairy farming) in a comprehensive carbon assessment, yet rely on external LCA companies to perform the underlying calculations.

Redundancies due to actors' partnerships: Despite the general focus on complementarity in actor interactions, the parallel development of D-MRV systems occasionally results in redundancies. The most prevalent example is the repeated data checks conducted in consecutive D-MRV systems. It is unclear to what extent such redundancies create inefficiencies. At the current stage, they are considered acceptable, since at each stage certain quality requirements must be met. This is especially relevant if each of the chained systems provides data for multiple downstream applications.

Gaps in the D-MRV space are pointed out primarily in relation to processes for carbon credit verification: Also at this far end of the MRV chain, data flows should be streamlined and automated. Redundancies with respect to upstream D-MRV actors' activities should be avoided. Monitoring parameters, which are constant, should be treated accordingly.

Barriers to partnerships have reportedly arisen due to proprietary models resulting in restrictive non-disclosure agreements. Early plans for partnerships were therefore abandoned in some cases. In others, no connections were established yet due to the early stage of D MRV operations, even though future partnerships are considered desirable.

While much of the software used by D-MRV actors is proprietary, some notable exceptions exist, where management tools are either built for wider use, or existing open-source tools are commercialized.

- **Existing open-source MRV frameworks such as FLINT are used for commercial operations** to lower the barrier to their application.
- **Actors build dedicated solutions to satisfy their needs, yet do not see themselves as long-term maintainers.** Software is therefore published as open source.
- **Actors share their D-MRV frameworks for greater impact:** Actors whose D-MRV solutions consist of efficient data management tools permit their use by other parties, through either licensing or free distribution. In this way, project types are more easily replicated, thereby increasing impact.

5. Preliminary findings

The present paper provides a snapshot of the state of activities, actors, opportunities, and barriers in the digital MRV space. It analyses and assesses D-MRV in the context of two project areas that are particularly important to current voluntary carbon markets: technologies for decentralized energy provision, and carbon removal in forestry and agriculture. An overview of the detailed assessment results of the considered technologies is provided in Section 2.3 (decentralized renewable energy and clean cookstoves) and Section 3.3 (forestry and agriculture). Preliminary findings from the assessment are presented below:

In **decentralized renewable energy** such as photovoltaics (PV), some companies are already well advanced in the use of digital tools for MRV. For decentralized PV, for example, pay-as-you-go systems are increasingly being implemented, requiring users to pay for energy before its use based on (digital) energy meters. Such systems have brought about the general advancement of digital tools for measuring and billing energy services. Using these existing systems for MRV for carbon markets has many advantages. They are rather low-cost, reduce the need for site visits, increase credibility as the unreliable manual transfer of meter readings is not necessary, are well accepted among current methodologies and standards, and have generally high level of maturity and scalability. This is the easiest way for many actors to enter the field of digital MRV.

With **clean cookstoves**, where e.g. digital temperature sensors or power meters are used to track stove usage time, cost benefits may be less obvious. We conclude that only the mass production of clean cookstoves with integrated sensors, and the related economies of scale, could bring down costs sufficiently for large-scale sensor application. Cost reductions may also be achieved by equipping only a (random) sub-sample of stoves with sensors. Still, cost reductions may be limited, as determining the baseline (fuel type and quantity, efficiency, usage time) still requires costly household surveys in most cases.

Concerning credibility, digital MRV for clean cookstoves may bring considerable benefits, because preliminary data indicate that the sensor-based measurement of usage times and frequency is more reliable than conventional surveys. In addition, the transparent availability of key performance data on a digital dashboard makes these cookstoves attractive for (retail) consumers of carbon credits, as they can transparently track the performance of “their” projects over time. Also, the approach allows for direct payments to households (and particularly to women) and therefore strengthens SDG benefits.

Projects for carbon removal in forestry and agriculture represent another important contribution to carbon markets. Compared with technical energy systems, MRV in natural systems tends to be more complex and challenging. Conventional monitoring approaches in these areas are primarily based on extensive field data collection and approximate assumptions. Such simplifications include the use of rather generic “land use factors” and “tillage factors” to determine changes in the carbon stock as a result of project activities. These may not be representative of the specific conditions of the activity in question. More advanced models are increasingly relevant for monitoring carbon removals. The field is developing rapidly. The following key approaches to digital MRV in forestry and agriculture are considered:

- **Ecosystem modeling for forestry biomass and soil organic carbon**: Many actors supporting or implementing nature-based carbon projects rely on comprehensive process-based and/or empirical modeling and machine learning approaches to obtain estimates of above and/or below-ground carbon stocks and their changes. Comprehensive data platforms aggregate a broad range of model input data from various sources, including field measurements, satellite imagery, LiDAR, and weather data.
- **In-situ measurement of soil carbon:** One of the interviewed actors commercializes recent research work on in-situ soil carbon measurement devices using inelastic neutron scattering and gamma spectroscopy to measure total soil carbon levels.

Digital approaches in forestry and agriculture potentially allow for cost savings through high-volume sampling, and the extensive use of model-based and data processing approaches, including machine learning and artificial intelligence, to reduce the need for (expensive, manual) in-situ field measurements for biomass or soil organic carbon content. However, up-front investments in modeling, technology, software, equipment, and skilled labor are usually considerable. In agriculture, data generation on soil organic carbon is often driven by purposes independent of carbon projects, notably to optimize farm management. With this, monetizing carbon is seen more as a co-benefit than the key driver paying for the intervention. This may weaken the additionality of the activity.

In general, the use of digital tools in forestry may provide for higher levels of accuracy e.g. in the calculated amount of carbon removed. Digital approaches rely on broader data sources to calculate biomass volumes and emission reductions. However, in the case of soil organic carbon and woody biomass calculations, approaches are more indirect than in the conventional case (typically laboratory testing and field measurements). Some actors claim the accuracy and precision of their results is superior to conventional approaches. It appears that these claims have not been independently validated at this stage. In other cases, limited accuracy of remote sensing for estimating carbon is reported to be a barrier to adoption of the approach by certain potential customer groups. Further, reliance on proprietary approaches and machine learning reduces transparency compared with conventional methodologies.

In effect, the emerging field of digital approaches to MRV in forestry and agriculture presents itself somewhat opaque and inconsistent. Many credibility claims from tech developers and innovative start-ups are difficult to assess today, as broad independent validation for a wide range of species and conditions seems lacking for many of the new approaches.

A similar picture is emerging for acceptability by standards. Major standards are planning to provide guidelines as well as digital tools fostering D-MRV in all sectors. However, it remains to be seen how fast they can develop the related technical and human capacity to fulfil their rule-setting role in these novel technological areas.

General findings

D-MRV approaches would allow for integrated digital systems encompassing monitoring, quantification, verification, and issuance processes, hence enabling continuous certification and issuance. This would enable earlier and more continuous payments, shifting positive cash flows forward in time. This may increase attractiveness, particularly for projects with high up-front costs, where quick repayment is of the essence. Continuous certification and issuance are also attractive for (retail) credit buyers who can monitor the performance of "their" projects on user-friendly dashboards.

The consistent use of digital technologies in MRV on all levels of the project cycle would provide verifiers, standards, and researchers with a wealth of data. Access to such open data in a common repository could be used to improve methodologies, verification, and certification, increase the accuracy and credibility of emission reduction/removal quantification, and help to optimize crediting activities. It is only with maximum connectiveness and openness that the emerging D-MRV ecosystem will provide its full benefits and accessibility, notably including smaller market participants.

The present study provides a snapshot of the current developments in D-MRV with a focus on specific example technologies in energy, forestry, and agriculture. Further research is needed to gain a more comprehensive picture, including other project types and digital technologies in the voluntary carbon markets. Also, the validity of some of the more complex applications (notably forestry and agriculture) will need comprehensive testing and validation to become viable tools.

Major standards have established working groups on digital approaches. In addition, standards and certification bodies, project developers, industry associations, multilateral institutions, and tech entrepreneurs are involved in a flurry of activity to enable D-MRV and its concrete implementation. Although this proliferation of different projects may be a very fruitful approach, it will be crucial going forward to increasingly link and coordinate the digital initiatives to enable cheaper, better, and faster D-MRV.

For more CLI platform activities involving partners and stakeholders, and for more knowledge products on D-MRV – including a parallel CLI White Paper specifically on Principles for Digital Verification for SustainCERT (Climate Ledger Initiative, 2022)*, visit the Climate Ledger Initiative website:* https://climateledger.org/

Glossary of acronyms and abbreviations

CDM: Clean Development Mechanism

CLI: Climate Ledger Initiative

D-MRV: Digital Monitoring, Reporting, and Verification

LPG: Liquified Petroleum Gas

MRV: Monitoring, Reporting, and Verification

PV: Photovoltaics

(D-)REC: (Distributed) Renewable Energy Certificates

UNFCCC: United Nations Framework Convention on Climate Change

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