Assessment of Digital Measurement, Reporting and Verification

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

CLI White Paper

Zurich, 12 July 2022

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

Climate Ledger Initiative

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Editorial Information

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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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Executive Summary

Digitalization of Monitoring, Reporting and Verification (MRV) is lagging behind. MRV of climate change mitigation activities is an essential part of the project cycle in all relevant carbon standards and particularly important to assure the accuracy and credibility of carbon credits.

However, costs and complexity of conventional MRV constitute a significant barrier to scale up and accelerate climate action and access certified carbon markets. The lack of automation leads to inefficiencies and hampers a rapid upscaling of certified carbon markets and of climate action they potentially enable. 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 space 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 cook stoves), as well as
- carbon storage in forestry and agriculture.

The paper is primarily based on a series of interviews with commercial actors currently active in the field of digital monitoring for carbon credit generation in above mentioned project types. Additionally, it includes experience gained over four years with the Climate Ledger Initiative. The interviews were complemented by literature research to gain an understanding of current applications of and approaches to digital monitoring for various applications. 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 cook stoves, p.27) and section 3.3 (forestry and agriculture, p. 45).

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 implemented, requiring users to pay for energy before it's

use based on (digital) energy meters. Such systems have brought a general advancement of digital tools for measuring and billing energy services. Using these existing systems for MRV for carbon markets has many advantages: it is rather low-cost, reduces the need for site visits, increases credibility as unreliable manual transferring of meter readings is not necessary, has high acceptability with current methodologies and standards, and has generally high maturity and scalability. This is the easiest case for many actors to enter the field of digital MRV.

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

Concerning credibility, digital MRV for clean cook stoves 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, transparent availability of key performance data on a digital dashboard makes these cook stoves 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 to 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” for the determination of carbon stock changes due to project activities that may not be representative for the specific conditions in the activity. 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 interviewed actors commercializes recent research work on in-situ soil carbon measurement device using inelastic neutron scattering and gamma spectroscopy to measure total soil carbon levels.

Both digital approaches in forestry and agriculture potentially allow for cost savings through high volume sampling, 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 modelling, 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, monetization of carbon is seen more as a co-benefit than the key driver paying for the intervention (which 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 for the calculation of biomass volumes and emission reductions. However, in the case of soil organic carbon and woody biomass calculation, approaches are more indirect when compared to conventional approaches (typically laboratory testing and field measurements). Some actors claim accuracy and precision of their results to be 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 carbon estimation 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 when compared to 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 under a wide range of species and conditions seems lacking for many of the new approaches.

A similar picture is emerging for the 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

All discussed D-MRV approaches would allow for integrated digital systems encompassing monitoring, quantification, verification, and issuance processes, hence enabling continuous certification and issuance. This would make earlier and 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 essence. Continuous certification and issuance are also attractive for (retail) credit buyers who can monitor the performance of "their" projects on user-friendly dashboards.

Pervasive 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 accuracy and credibility of emission reduction/removal quantification and help optimizing 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 engage in a flurry of activities to enable D-MRV and concrete implementations. While "let a thousand flowers bloom" may be a very fruitful approach, it will be crucial going forward to increasingly link and coordinate the digital initiatives to enable "cheaper, better, 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

Digitalization of Monitoring, Reporting, and Verification (MRV) is lagging behind

Monitoring, Reporting and Verification (MRV) of impact of climate change mitigation activities is an essential part of the project cycle in all relevant carbon standards and particularly important to assure the accuracy and credibility of carbon credits. However, costs and complexity of conventional MRV constitute a significant barrier to scale-up and acceleration of climate action and access to certified carbon markets. While digitalization has transformed many areas of economy and society, such as social media, retail, finance, and manufacturing over the last decades, current MRV in carbon markets is often still based on reports, checklists, spreadsheets sent around by email. Further, it may require comprehensive on-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 became available. When using such platforms to streamline carbon market projects, it is critical that not only data capturing and processing, but also verification is 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.

The slow progress in digitalization of MRV and the carbon market project cycle over the last 15 years may be due to rather moderate levels of market activity since 2012 and the lack of adoption of digital approaches by program standards. This has been changing over the last few 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, internet of things, remote sensing, machine learning, advanced statistics on large datasets, blockchain, but also smart phone 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 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 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 and cook stoves), as well as
- carbon storage in **forestry and agriculture**.

The paper is primarily based on a series of interviews with commercial actors currently active in digital monitoring field carbon credit generation in 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 are not active as project developers but provide monitoring solutions (hardware, software, and data) to clients. Maturity ranges from early pilots to long-term established operations. The interviews were complemented with literature reviews to gain an understanding of current applications of and approaches to digital monitoring for various applications.

Based on the interviews, earlier work of the CLI and the use of the limited literature, 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 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 approaches for the determination of nature-based carbon stocks can be black boxes by design. Credibility therefore is 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.

The paper is structured as follows: First, an assessment of D-MRV examples is presented, related to off-grid energy technologies in photovoltaics 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 lies on decentralized provision of renewable power and clean cook stoves. These project types are considered representative to allow for assessment of issues typical for D-MRV in the decentralized energy sector (complemented by section 3 looking 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 MRV of projects based on small-scale systems*: According to interviewed actors, decentralized energy-based carbon projects are economically challenging, as the small scale of operated systems (e.g. single PV panels, single cookstoves) leads to considerable transaction costs. However, small-scale systems are desirable due to their higher positive SDGs impact for local communities. This contrasts with large systems such as hydropower dams or wind farms with fewer contact points and therefore lower positive social impact.
- *Accuracy of conventional monitoring approaches is often limited*: Clean cook stove 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 to 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: Analyzed use cases 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, emphasis is put 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 installation of solar home systems to software for payment management is covered. Establishment of projects for carbon markets is work in progress. https://www.bboxx.com/

Box 2: Analyzed use cases 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 Certificates (RECs)" that might be internationally recognized. In the wake of this approach, a pipeline for digital carbon credit generation programs is being implemented. For 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 systems and biogas digesters. Their measurement hardware is operated by project developers and feeds data into their Inclusive Energy's 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/

Development of digital ***clean cook stove*** monitoring has become an active area in recent years. However, corresponding projects are limited to relatively small scale so far. In the following, two examples from the portfolio of CLI supported use cases are presented:

- **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 distributed energy and clean cook stoves rely on new and more comprehensive project data sourcing and processing. Table 1 provides an overview on 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 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 advanced data platform
Clean cook stoves	Cook stove 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 level in project stoves through temperature sensors, LPG flow measurement, or electricity monitoring Household survey still necessary to determine e.g. baseline stove and fuel type

Table INFRAS. Source: Own research and interviewed 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 exploited in a streamlined manner.
- **Clean cook stove monitoring**, which in the conventional case primarily relies on user surveys, is digitalized to enable more accurate activity tracking. In the cases presented this paper, this is achieved using temperature sensors attached to the cook stoves. Sensor readings indicate cooking activity as soon as a threshold temperature is crossed. For other cook stove types, the automated measurement of electric cookstove activity with power meters is an established approach with large 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 capturing and management on dedicated data platform. These platforms often also perform the complete emission reduction quantification calculations. Web-based dashboards provide data access to various stakeholders.
- **Actors put a strong focus on complete and well-managed data**: Basic data cleaning and plausibility checks are common features of the digital monitoring systems. This helps to increase completeness, reliability, and accuracy of monitoring. For example, for decentralized energy production this may include the comparisons of diurnal variation in production levels with similar plants and solar irradiation data from nearby weather stations as well as the comparison with maximum producible power derived from installed capacity. With cook stoves usage data, similar plausibility checks are made, including the comparison of the timing, length and frequency of cooking activities, and 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 cook stoves

In the following, use cases of 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 the assessments are presented in section 2.3 in tabular form.

2.2.1. Cost and cost savings of D-MRV

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

Cost and cost saving potentials are difficult to quantify and strongly 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, 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. cook stove temperature sensors or LPG/biogas sensors) together with appropriate processing software. Further, digital infrastructure in most cases only automates the project activity level monitoring, while surveys for baseline fuel and cooking determination remain necessary. However, major cost savings for increasing scale of digital projects and 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 interviewed actors, these cost components turned out to be significant barriers even if previous activities were already extensively digitalized: Efforts to implement the necessary degree of automation to participate in carbon markets turned out as 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 also experienced actors with established monitoring systems require a certain level of incentives 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 cook stove users to determine usage rates for project stoves or site visits for the confirmation of 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 cook stove monitoring (Gold Standard, 2021)). However, also with digital approaches a certain amount of site visits to collect data on households, stove numbers, usage practice, fuel types etc. are still necessary, notably to determine baseline emissions. Further, remote areas can pose challenges also for digital approaches, e.g. because of a lack in GSM coverage for data transfer.
- **For all the technologies, more accurate measurements through digital approaches can result in higher or lower revenues from carbon credits:** Since digital approaches differ significantly from conventional monitoring, the resulting number of generated carbon credits can deviate. Depending on the project type, actors report either higher or lower emission reductions. In case carbon credit revenues are lower, this 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 indications on the costs. 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 unpredictability of cost factors.

In case of higher costs entailed by D-MRV, it may to a certain extend be justified by the resulting efficiency and transparency benefits (see section 2.2.2).

For both technologies considered here, increasingly widespread adoption of digital monitoring may lead to the development of specialized flexible software solutions with the ability to ingest broad variety of data from various project types. Already today, certain actors offer solutions of this kind (see section 4.2). A future push for digital MRV could diversify the landscape of 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 cook stoves	Cost component description	Significant additional cost component due to dedicated sensors and data processing and transmission systems. Details depend on share of digitized cookstoves. Cost decreases are foreseeable according to project developers. Total project costs will strongly depend on whether all stoves will be equipped with sensors or whether sensors are limited to samples. While some project developers aim for comprehensive digital monitoring, the trend is not yet clear.	- Additional investments into 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). - The establishment of a digital system on 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 management of data transmission and technical support	Methodology adaptations require carbon project registration and negotiation e.g. for the use of remote digital monitoring.
	Illustrative costs	- Sensors and data transmission hardware in current pilot projects are estimated at USD 20-40 per stove, compared to typical improved cook stove costs of USD 10-30 per stove. - The switch to mass-production and integration of sensors into the cook stoves reduce additional cost due to sensors 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 to 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. irradiation sensor, GSM module).	- No fundamental differences with respect to clean cook stoves (see above). - However, in contrast to clean cook qstoves, the existence of an already 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 cook stoves holds.	See "clean cook stoves" above.
	Illustrative	- simple power meter: USD 200 - basic data logger: USD 400 - entry-level irradiation sensor: USD 400	See "clean cook stoves" above.	See "clean cook stoves" above.	See "clean cook stoves" 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 experts' estimates, interview results, and literature values. They represent rough estimates for illustrative purpo ses.

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 programme 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 0-20% of conventional costs** Savings are possible in case existing digital systems are already well-adapted to the planned project type; in other cases, development of digital systems may incur greater upfront costs, also covered in Table 2. However, the potential saving is much lower than in other steps.
Monitoring and verification	**USD 5k-65k per project per year** depending on project type and size	**Saving 20%-90% of conventional costs** Digital solutions are a continuum with a broad range of potential savings. However, savings 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 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 20-80% of conventional costs** Potentially largely automated, e.g. through mobile phone-based pay-outs.

Costs are experts' estimates, interview results, and literature values. They represent rough estimates for illustrative purposes.

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

2.2.2. Credibility

Digital monitoring in the context of decentralized energy provision is deemed superior: When compared to 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, the automated data transfer rather than manual documentation in lists and spreadsheets reduces the risks for errors and increases completeness of data. Overall, digital approaches yield more accurate, complete, and robust data. This improves credibility of resulting emission reduction calculations. For example, a study comparing survey-collected data with sensor data on cook stove 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 to installed capacity).	none
Clean cook stoves	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 the data handling processes, all of which leads to higher credibility for both the considered technologies of decentralized energy provision and clean cook stoves:

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

[1] For instance, VCM methodology VRM0006 for cook stoves allows to choose 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 in the baseline. The saving in biomass may then be simply calculated by using estimated efficiencies of old versus improved cook stoves (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 capturing with high temporal resolution. This contrasts with e.g. monthly reading of renewable power production or yearly survey-based determination of cookstove usage rates. Continuous data enables detection of discrepancies 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 for carbon (e.g. the case of cookstoves) are often built with the intention of enhancing transparency to increase carbon credit value. 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 stakeholder: Credit buyers obtain information on the projects, hence obtaining information on carbon credit origins. In some cases, also clean cook stove users have access to dashboards, which in turn is reported to increase usage.
- **Continuous automated monitoring enables early detection of system faults and fading user engagement:** Interrupted or abnormal data streams point to problems in the operation and enable timely targeted intervention. In addition to technical issues, automated monitoring also reveals reduced engagement in real-time e.g. of clean cook stove users that 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 precision**: Conventional methodologies often rely on rough point estimates for parameter values. Uncertainties are sometimes considered in the calculations, yet not in all Standards in a systematic manner. 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

It is still early in digitalizing MRV. 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 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 corresponding methodology changes. Efforts should shift toward certification of monitoring systems rather than manually gathered 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 (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 toward fully automated issuance of carbon credits (South Pole, 2020; Bürgi, et al., 2019).

In these early days of D-MRV, openness of Standards toward digital approaches for monitoring is perceived as positive, but processes must be improved. Digital approaches to monitoring and data capturing are the most advanced part of D-MRV and 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 the 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 work-in progress, in few platforms it is well-established. Early work under the CDM shows that novel D-MRV approaches are accepted even in case they present significant departures from the status quo, e.g. substituting repeated site visits to biogas digesters by remote digital monitoring (UNFCCC CDM, 2021).

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 on 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, such as 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 work in progress.	Standards need to embrace digital approaches and take appropriate measures to facilitate and encourage the introduction by other actors: ▪ **Guiding principles** need to be defined to communicate a general willingness for acceptance of digitalization. The digital approaches' acceptance from 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 the 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 implementation and adaptation of methodologies, support D-MRV platforms' ability to flexibly generate different credit types, and future-proof 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 streamlined consideration of multiple methodologies/technologies at once. Inefficiencies arising from the individual discussion of project types could be avoided.
Clean cook stoves	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 the scalability to much larger numbers of projects and activities.

The considered D-MRV solutions 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 relevant other 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 cook stoves).

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 with 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 and 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).	Necessary hardware and software are in place, technical challenges are largely solved.	- Existing carbon project methodologies are found not to be a good fit for the development of decentralized power projects under some circumstances.
Clean cook stoves	Digital approaches for temperature measurement-based cookstove monitoring are a recent development, being developed on a pilot-project level for the last decade. However, some actors have a strong background in the development of conventional clean cook stove programs.	Ample experience and existing local capacities. Partnerships are being established for hard- and software implementation.	- Sensor and data transmission cost still needs to decrease significantly. - The approach's acceptance from Standards is still not clear, except for electric cook stoves under the CDM. The conversation is 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 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 strongly technology-dependent and focus either on hardware or processes, depending on legacy operations.

- **With cook stoves, the cost for 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 scales 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 registration reduces overhead costs**: Registration of smaller programs causes financial overhead and in some reported cases prevents them from reaching break-even. Shifting registration responsibility from small project developers to operators of large-scale aggregating data platforms allows for implementation of much larger programs and associated cost savings in the registration process. While this strategy is applicable also to non-digital projects, automation in 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 overhead cost and enables sufficient cost savings to make these projects viable, hence increasing the pool of potential projects benefitting local communities.

Barriers to upscaling are being discussed:

- **Future demand for carbon credits is uncertain:** Strongly rising demand on voluntary carbon markets is currently be observed. However, the market is flooded by (very low cost) nature-based carbon credits. This keeps current carbon prices on (too) low levels (of 2-4 USD/t) to provide meaningful additional revenues rendering energy and cook stove projects viable. In this context, digital approaches with higher upfront cost are even at a greater risk of sunk costs in case prices decline further or remain low.
- **Challenges in scaling existing software packages in energy projects:** Growing scope of pay-as-you-go business model for decentralized electricity required major updates to data platforms. While not directly related to D-MRV, analogous 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 fine 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 criterium. 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, the digitalization in this case provides especially large benefits when compared to peer technologies and the conventional case.

The analogous 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 cook stoves

	Decentralized energy	Clean cook stoves
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. Also here, traceable and transparent data management on a dedicated platform is central.
Comparison to 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 cook stove monitoring generally relies on surveys to determine, to what extent the cookstoves are being used.
Cost and cost savings		
	★★☆	★☆☆
	▪ High potential for cost saving trough 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, 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		
	★★☆	★★★
	Online measurement of renewable energy generation allows for higher levels of accuracy and less room for tampering with data. Further, transparency is increased as carbon credits can be traced back to their physical origins.	Sensor based determination of use times for cook stoves may be considerably more adequate than survey-based approaches. Data tampering risk may be mitigated through direct data transmission without manual intervention.

	Decentralized energy	Clean cook stoves
		▪ Challenge: monitoring of fuel type and usage practice
Applicability with current standards		
	★★★	★★☆
	Integration of digital approaches in existing standards is already made or appears rather straight forward due to positive preliminary feedback, e.g. from the Gold Standard. Digital monitoring of biogas digestors using flow-meters has recently been accepted as part of the CDM methodology (UNFCCC CDM, 2021).	Feedback process from Standards concerning sensor technologies is still 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 is work in progress. ▪ Scalability depends on 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 (far) too high this stage. ▪ Scalability depends on ability to drastically lower costs for dedicated sensors (e.g. for cook stove temperature measurement) and data transmission. ▪ Data transmission is limiting factor for scalability into more remote areas.

Table INFRAS. Source: Interviews and own analysis

3. D-MRV in forestry and agriculture

Besides energy related project types, projects for carbon removal in forestry and agriculture represent another important contribution to carbon markets. Compared to 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” for the determination of 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) are an (optional) part of the methodology in some cases.

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

Box 3: Analyzed use cases in section 3

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

- **FlintPro**: Originally starting from national CO_2 monitoring, the company is centered on the commercialization of the open-source application Flint. Large amounts of data layers in space and time are combined to provide as accurate carbon assessments 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 community-based tracking of single tree biomass. Through carbon credit payments, smallholder farmers are provided an incentive to care for planted trees long-term. Data on tree biomass is regularly

Box 3: Analyzed use cases in section 3

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 employ new data sources and models to determine carbon stocks with greater claimed accuracy and scalability. In addition, new approaches for direct carbon measurement are being brought to the 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 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 is promised to yield fast and accurate measurements of below-ground carbon concentrations. The company aims at covering 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 higher 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 on 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 input. Both open/peer-reviewed and proprietary model 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. A focus lies on high levels of data coverage and consistency (e.g. time series). Some actors incorporate and scale client-provided process-based models in 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 number of variables, which in some cases—according to interviewed actors—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 has been used for forest biomass estimation.

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 device 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 can be flexibly deployed on 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 viable alternative to laboratory-based analyses. Commercial rollout is scheduled for the near future. 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, but details on 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 spectral components of satellite imagery are fed into suitable algorithms including machine learning. This results in estimates on geometric properties of trees in monitored forest patches, notably canopy height (Csillik, et al. 2019) and stem dimensions (Miettinen, et al. 2021). Accuracy and precision of estimates can be improved by including additional data (such as airborne laser scanning LiDAR 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 basic geometric properties of the area of interest are known, so-called 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. Identification of vegetation types and geometric plant properties is enabled by analysis of 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 lower spatial resolution to be beneficial for their specific approach, as a certain degree of spatial averaging is desirable (Space Intelligence, 2021). General drawbacks of passive optical sensing include its limitation to daylight signal acquisition, 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 with **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 aircrafts, their acquisition is costly, especially if large forest areas are to be monitored. They are therefore often used for calibration of 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 the 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 optical (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 generated radiation, whereby longer wavelengths are better suited to penetrate to lower forest levels. While no space-borne solution with adequate wavelength exists to date (Rodríguez-Veiga, et al., 2017), the upcoming ESA "biomass" mission is envisioned to fill this gap and enable a global microwave-based assessment of above-ground biomass (European Space Agency, 2022).

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

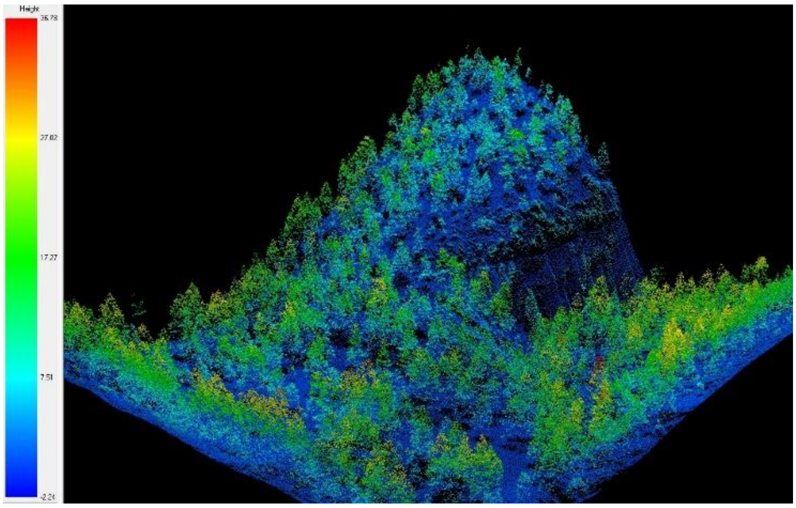

Image: Southwestern Region, USDA Forest Service/CC-BY-2.0

Given the challenge of uncertainty in remote sensing biomass stock estimates, the uncertainty of small growth increments of trees in afforestation projects over time are even harder to detect (being the difference between rather uncertain biomass stock values developing in time).

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

	Conventional approach	Comparison D-MRV
Ecosystem modeling for forestry biomass and soil organic carbon	▪ field measurements ▪ coarse 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 for 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 possible due to low cost technology (compared to 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

In the following, use cases of 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 section 3.3 in tabular form.

Most proposed digital approaches to nature-based projects put a strong focus on 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 also this drives innovation in terms of process streamlining.

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

The results of the assessments are provided in section 3.3 in tabular form.

3.2.1. Costs and cost savings

Cost savings and higher throughput are primary motivations for the establishment of digital MRV approaches in forestry and agriculture. Proposed solutions aim at streamlining processes or rendering main cost factors (like field sampling) of conventional approaches partly obsolete. Many are more recent developments, building on significant amounts of R&D. Under the condition that 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 to conventional MRV

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	Investments	Running costs	Costs of adaption to Standards	Cost benefits compared to conventional approach
Ecosystem modeling for forestry biomass and soil organic carbon	Actors are at different stages of development, yet systems are operational. Potentially considerable cost for development of models, platforms, and data pipelines as well as data acquisition for calibration in pilot phase.	Automated approach enables cost reductions despite data procurement and model setup. Field measurement requirements are potentially relaxed. Interviewed actors often generally 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 reduction of field measurements. Costs for 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, set-up 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 of biomass	Established approach, incremental development of data pipeline.	Added cost of comprehensive tree measurements compared to 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 comprehensive measurements, according to interview, yet benefits prevail.

Table INFRAS. Source: Interviews

Additional costs compared to conventional MRV arise mainly due to 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 to 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 data gathering of monitoring parameters) and the (partial) avoidance or streamlining of field data acquisition (soil carbon measurements, systematic tree measurements).

- **Detailed data-heavy modeling may reduce 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 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. However, Standards' methodologies still require field data to a larger extent than what interviewed actors would consider necessary for calibration. According to some actors, new technology allows for higher levels of accuracy at lower numbers of 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 alternatives to time consuming and expensive laboratory analyses, hence ultimately promising lower cost.
- **Project economics of model-based approaches improves over time:** Carbon assessments using data-centered modeling approaches mainly require initial setup. Once data and methods are established and calibrated for a given project, costs of assessments decrease over for subsequent years.
- **Data acquisition is made more efficient using digital approaches:** Actors innovate digital systems to render 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 tagging of trees combined with dedicated mobile app allows for comprehensive determination of biomass volumes.

3.2.2. Credibility

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

- Reliance on proprietary approaches and machine learning reduces transparency when compared to conventional methodologies. However, more sophisticated approaches are claimed to yield superior accuracy and precision when compared to conventional methodologies. Claims could not be verified in the context of this study.
- Novel soil carbon measurement technology claims similar accuracy and precision as 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 D-MRV approaches' credibility

	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 are promised to deliver higher accuracy.	Transparency: Proprietary models are partly untransparent, yet Standards are reported to accept comparison to ground truth as evidence for 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; development of certification pipeline is work in progress. Lacking validation: Comprehensive independent third-party validation of the measurement and modelling approach seems not to have been published until now.
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, both in the case of soil organic carbon and woody biomass calculation, approaches are more indirect when compared to conventional approaches (typically laboratory testing and field measurements). Some actors claim accuracy and precision of their results to be 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 carbon estimation is reported to be a barrier to 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 stock.
- **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 determination**: Clients can be provided with uncertainty information on the determined emission reductions. This enables flexible use of the provided information for various application (e.g. more carbon credits with low conservativeness for corporate goals or higher conservativeness for fewer certified credits). For other actors these are active development efforts.
- **Time series availability enables assessment of situation prior to project planning**: Historic satellite images allow 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 enable timely carbon estimates; internal data are complemented with (e.g. client-provided) more targeted data for better adaptation to the project under consideration.
- **Possibility to flexibly increase accuracy:** Developed digital methods for forest biomass calculation 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 the 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 full traceability of results. Input data generating certain output values can be efficiently identified, even if intermediate steps are proprietary.
- **Single tree tracking demonstrates long-term effectiveness of climate action:** Continuous tracking of single trees in reforestation projects shifts the approach from planting trees to growing trees. Payments based on effectively determined carbon stock provides 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 or models can impose strong IP-related constraints.

- **Lack of data openness**: One of the issues blocking innovation is that data is commonly considered property of the collecting party. 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 work in progress, yet requirements of legacy methodologies may provide barriers. According to interviewed actors, Standards accept digital approaches combined with field sampling as the need for efficient scaling of carbon markets 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 demonstration of model accuracy when compared to ground truth. ▪ Actors focus on best-in-class carbon assessment while remaining agnostic with respect to carbon credit generation.	▪ According to actors, remaining sampling requirements inhibit full cost saving realization. ▪ Interaction with Standards is described as tedious. ▪ Model uncertainty is currently often not provided, leading to non-applicability for project certification under certain Standards.
In-situ soil carbon measurement	▪ Actor considers independent ISO certification as opportunity for Standard-independent application and possible route for future acceptance by Standards.	▪ Acceptance by Standards remains uncertain given early stage of development.
Single tree tracking	▪ Performance in Standards' audits is high. ▪ Programme 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 carbon monetization outside of established carbon standards:

- **A focus on data service prevision (as accurate as possible carbon assessments)** enables actors to shift certification burden to clients. The 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 to constraining given the potential of their novel measurement technology. Therefore, an alternative route to carbon monetization was sought. Still, discussion with Standards remains alive.

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

- **Laboratory sampling requirements are described as 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, 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 missing harmonization between standards as barrier.
- **Standards are found to be sufficiently flexible to approve methods**, even if models are proprietary, interviewed actors claim. However, new approaches have the potential to reduce the number of ground measurements required, whose cost is described as major barrier. Nevertheless, much like in section 2, actors report difficulties in communicating with Standards in order to implement novel approaches.

3.2.4. Maturity and scalability

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

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 necessity for costly development of data platforms allowing for efficient project set-up and high through-put.

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 ▪ partly 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 ▪ partly: The 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 geographic areas. ▪ Small projects require labor-intensive setup. ▪ Land ownership and rightful beneficiaries of carbon credits difficult to determine in some countries (missing registries). ▪ Software development for high scalability is work in progress.
Contactless in-situ measurement of soil carbon	▪ current system at demonstration stage ▪ commercialization is work-in-progress	▪ 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 applications	▪ expansion to new environments and applications is being actively pursued ▪ due to bottom-up approach, local community scales together 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 close-by 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 scalability of carbon credit generation. However, significant limitations are given by the need for field data gathering and model calibration 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 when compared to laboratory analysis. Current development of the technology in the commercialization phase is 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 claimed solution's applicability to other geographies is a core component of the actor's business case. The broad applicability of the described approach can not be independently verified in the context of this study.
- **Actors find new applications of existing D-MRV approaches:** As an example, efficient grassroots single tree tracking method in developing countries is applied to farms in Australia. By opening these new markets, farmers are enabled to generate income from above-ground biomass on their land.
- **Openness of software potentially contributes to scaling of approach:** By licensing platform for single tree tracking to other actors or offering it for free to small project developers, approaches are scaled beyond the originator's activity sphere.

Some issues could have negative impact on scalability:

- **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 link with local actors:** Data and modeling-based approaches operate in a streamlined manner, yet potentially lack the connection with local communities. This potentially exacerbates problems such as the determination of rightful land ownership: Fast scaling of operations in countries with a lack of registries potentially causes carbon credits not to benefit rightful landowners, including local indigenous communities.
- **Not fully implemented automation inhibits small-scale project implementation:** The degree of automation of model-based approaches among actors is a continuum. 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 investments for a digital infrastructure covering all aspects of the project cycle. Corresponding actors actively work 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 to the reference case of conventional (non-digital) monitoring approaches			
	Models 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 high transparency and accuracy of carbon quantification. Continuous tracking by the community fosters maintenance of trees.
Cost and cost savings			
	★★☆	★★☆	★☆☆
	Model-based approaches have cost saving potentials if claimed 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 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 when compared to 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 given by the lack of transparency for proprietary or not fully transparent approaches.	The performance of the technology was studied in peer-reviewed academic research. However, due to the novelty of the approach, no statement on the credibility in the context of carbon credit generation can be made.	High detail and transparency push credibility beyond 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 optimal volumes of field sampling given the higher sophistication of modeling approaches.	Actor aims for a custom solution along the whole credit generation chain from measurement to issuance. For this purpose, an ISO-based certification is developed as a first step.	Fully accepted by Gold Standard performance audits according to interviewed actors. Barriers are reportedly given by tedious communication with carbon Standards concerning feedback on methodologies.
Maturity and scalability			
	★★☆	Maturity: ★☆☆/Scalability: ★★☆	Maturity: ★★★/Scalability: ★☆☆
	Systems are established with different levels of maturity. 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 at a 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 ongoing expansion of method to other geographies/project types. However, by design, the approach is neither targeting nor suited for large-scale monitoring of forests without close-by communities.

Table INFRAS. Source: Interviews and own analysis

4. Overarching characteristics of D-MRV approaches

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

In a conventional project cycle, 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 approximately 2 months for manual verification before issuance and transfer is possible. This results in delays from implementation start to selling the credits of up to 13-15 months. Such time lag is significant in projects with typically higher discount rates because it reduces the attractiveness of investments.

D-MRV solutions allow for integrated system of digital monitoring, quantification, verification, and issuance processes that enable continuous certification and issuance. This makes earlier and continuous payment possible, pulling positive cash flows forward in time. This increases attractiveness, particularly for projects with high up-front costs, where quick repayment is of 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 cook stoves are generating their credits over time.

4.2. Digital MRV as a service

Various types of actors are active in the D-MRV space and cover different ranges along the MRV chain. Some actors 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 use cases "dedicated MRV platform" 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 cook stoves to abatement measures in the gas industry. Built with the goal to facilitate parameter collection to the greatest possible extent, the system handles gathered data in an integrated, centralized, and traceable manner, thereby lowering verification costs significantly. The verification focus can shift to verifying 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 to conventional approaches with a focus on manual, often spreadsheet-based data handling, such systems enable:

- Streamlined collection and quality checks of relevant parameters in line with Standards' requirements.
- Aggregation in 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 in case of high technical maturity of the data platform.

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 efficient monitoring data acquisition to verification. While originating from carbon projects in the agriculture sector, the platform is largely agnostic with respect to project types. This enables its application to 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 at streamlining carbon credit generation from the start. In the considered examples, 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 rendering 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**: Actor found usability of complex modeling frameworks for nature-based credits to be a greater barrier than 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 prior to the onset of carbon credit activities. Legacy products inform farm owners on issues related to water, nutrients, and crop stress. 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 of approaches.
- **National CO_2-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.
- **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 in 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**: With the overarching goal of streamlining processes around the issuance of Renewable Energy Certificates (RECs), a dedicated digitalized system was implemented. D-MRV for carbon credits followed in its wake. This approach benefits from the fact that REC issuance is structurally simpler when compared to 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 the D-MRV for a broad variety of reasons. These reasons are given by 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 naturally are a strong driver for the adoption of digital systems. These target different cost factors and revenue streams:

- **Cost reductions by substituting expensive practices of conventional approaches:** Expensive field measurement requirements of conventional methodologies incentivize actors to develop more efficient approaches, e.g. the development of sophisticated models relying on a broad range of input data.
- **Cost reductions by streamlining conventional methodologies' monitoring:** Even without disruptive changes to the underlying methodologies, large savings can be gained by providing project developers with the possibility of efficient data gathering, followed by partly automated verification on sophisticated data management systems (example: single tree tracking of biomass in section 3.2.1, dedicated D-MRV platform in section 4.2).
- **Revenue increase through diversified operations:** Existing comprehensive data pipelines put in place for other activities (e.g. digitalized pay-as-you-go energy sales; renewable energy credits; farm management systems; national GHG assessments) allow for low entrance barriers to carbon markets. The established systems reduce the efforts of the D-MRV uptake to software adaptations and negotiation with the Standards ().
- **Scale increase 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 cost. Enabling market access to these projects typically enables large SDG impact.

Operations can be streamlined thanks to the comprehensive availability of monitoring data. Naturally, also these reasons for D-MRV adoption ultimately result in cost reductions and revenue increases:

- **Smoother operations:** Direct activity monitoring allows for identification of issues in the project operation, e.g. related to technical problems or underutilization of cookstoves. Issues can then be mitigated through targeted intervention by local partners.
- **Providing information to local community members enables greater 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 equally appreciated and beneficial for acceptance.

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

- **Throughput for market liquidity:** Actors expect demand on voluntary carbon markets soon to far outstrip supply. Improvements in efficiency and rate of carbon credit generation aims at providing 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:** Digital platform with full data resolution enables flexible aggregation in line with clients' needs, while avoiding information loss. For example, relevant energy quantities of decentralized projects are on 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**: Digitalization of 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 scopes of activities are not fully defined yet. Partnerships between actors are primarily built around mutually beneficial use of data. However, also participation to shape the industry according to actors´ needs has been reported as an overarching goal.

Up- 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 for example farm management systems. In the case of forest monitoring the data from actors generating ground measurements are 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 the business model, which leads to the 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 in 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 digitalized MRV space sees novel methods of data generation as well as actors with sophisticated models using those data as inputs. Previously unavailable detailed field data (e.g. comprehensive biomass tracking on the single tree level) is thus as input to these models, which in turn provide growth predictions to the upstream partners.
- **Actors restrain 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. of dairy) 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 are repeated data checks in consecutive D-MRV systems. It is unclear, to what extent such redundancies create inefficiencies. At the current stage, they are being considered acceptable, since at each stage certain quality requirements must potentially 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 being pointed out primarily concerning processes related to 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 other cases, 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 open source.
- **Actors share their D-MRV frameworks for greater impact:** Actors, whose D-MRV solutions consist in efficient data management tools, enable their use to other parties, either through licensing or free distribution. In this way, the 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 cook stoves) and section 3.3 (forestry and agriculture). in the following we provide preliminary findings from the assessment:

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 implemented, requiring users to pay for energy before it's use based on (digital) energy meters. Such systems have brought a general advancement of digital tools for measuring and billing energy services. Using these existing systems for MRV for carbon markets has many advantages: it is rather low-cost, reduces the need for site visits, increases credibility as unreliable manual transferring of meter readings is not necessary, has high acceptability with current methodologies and standards, and has generally high maturity and scalability. This is the easiest case for many actors to enter the field of digital MRV.

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

Concerning credibility, digital MRV for clean cook stoves 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, transparent availability of key performance data on a digital dashboard makes these cook stoves 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 to 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" for the determination of carbon stock changes due to project activities that may not be representative for the specific conditions in the activity. 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 interviewed actors commercializes recent research work on in-situ soil carbon measurement device using inelastic neutron scattering and gamma spectroscopy to measure total soil carbon levels.

Both digital approaches in forestry and agriculture potentially allow for cost savings through high volume sampling, 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 modelling, 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, monetization of carbon is seen more as a co-benefit than the key driver paying for the intervention (which 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 for the calculation of biomass volumes and emission reductions. However, in the case of soil organic carbon and woody biomass calculation, approaches are more indirect when compared to conventional approaches (typically laboratory testing and field measurements). Some actors claim accuracy and precision of their results to be 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 carbon estimation 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 when compared to 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 under a wide range of species and conditions seems lacking for many of the new approaches.

A similar picture is emerging for the 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

All discussed D-MRV approaches would allow for integrated digital systems encompassing monitoring, quantification, verification, and issuance processes, hence enabling continuous certification and issuance. This would make earlier and 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 essence. Continuous certification and issuance are also attractive for (retail) credit buyers who can monitor the performance of “their” projects on user-friendly dashboards.

Pervasive 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 accuracy and credibility of emission reduction/removal quantification and help optimizing 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 engage in a flurry of activities to enable D-MRV and concrete implementations. While “let a thousand flowers bloom” may be a very fruitful approach, it will be crucial going forward to increasingly link and coordinate the digital initiatives to enable “cheaper, better, 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 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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