Carbon credibility:
Transforming soil measurement

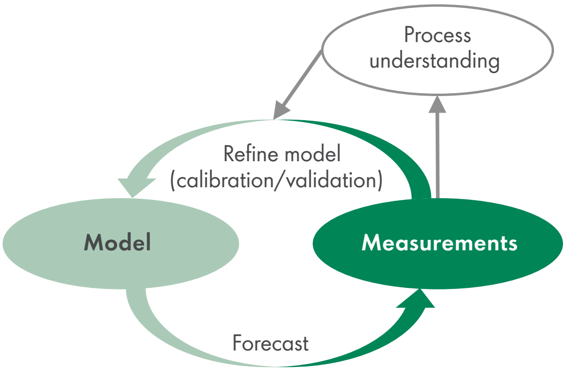
For Shell to generate high-integrity carbon credits and be a credible player in the voluntary carbon market, it must demonstrate measurable, science-based impact from its nature-based solutions (NBS) projects. In agricultural settings like grasslands and croplands, this means reliably quantifying increases in soil carbon (soil C) and reductions in greenhouse gas (GHG) emissions at scale. To this end, Shell's NBS team in its Projects & Technology organisation is developing the next generation of scale-up measurement and modelling technologies for the monitoring of soil C and associated indicators of soil health. This work is aimed at enhancing trust in NBS projects on the voluntary carbon market and supporting Shell's net zero ambitions.

Introduction

The reliable quantification of NBS project impact is essential for generating high-quality carbon credits and fostering public trust in the voluntary carbon market. In agricultural settings – such as grasslands (pasture and rangelands) and croplands – the primary goal is to increase the carbon content of soils while simultaneously reducing GHG emissions and improving biodiversity. However, accurately monitoring these parameters at the farm and project scale, which can span hundreds of farms (millions of hectares), presents significant challenges. Today's tools are limited in their ability to accurately measure small changes rapidly at low cost to meet the challenge. That is why Shell's NBS team is advancing the next generation of measurement and modelling technologies and their integration (Figure 1) to:

- enable project-scale soil C and land-management tracking;
- enhance local tools and data integration to improve accuracy and scalability; and
- expand impact monitoring to biodiversity and soil health to unlock premium credit value.

Figure 1 shows that process understanding, modelling and measurements must feed into each other for successful quantification of the carbon impact of NBS projects in agricultural settings, thus creating a positive feedback loop of measurement, reporting and verification (MRV). Although the NBS team is working on all of the elements depicted in Figure 1, this article focuses on measurements.



for (1) land-management optimisation and (2) carbon credits verification/issuance.

FIGURE 1
The MRV loop.

These fall into three strategic workstreams.

- **Developing new tools:** The objective is to measure project outputs (e.g. soil C) and model inputs (e.g. land-management practices) for the prediction of carbon and GHG changes at scale. This can sometimes leverage upstream approaches and technologies.
- **Improving existing tools:** The objective is to enhance tools for local-scale measurements (e.g. flux towers and soil sampling) and improve upscaling through model-guided methods.
- **Expanding current scope:** The objective is to monitor biodiversity and soil health to enable additional certification pathways, resulting in higher-value carbon credits.

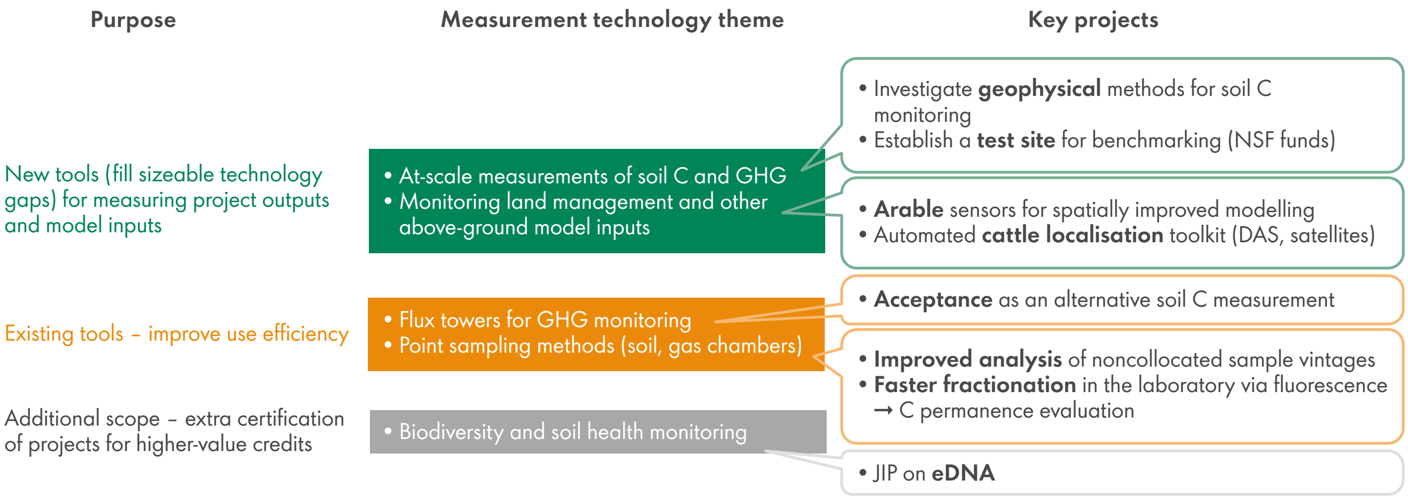
The themes and key ongoing projects in each of these workstreams are shown in Figure 2. Some of these projects, centred on soil C estimation, are discussed in the following sections.

Examples of ongoing work on measurements

The big picture: A toolkit for closing the loop

No single tool can act as a silver bullet, meeting the demand for information at all measurement scales (temporal and spatial) and budgets (cost is a major constraint under current voluntary carbon market conditions). Therefore, it is helpful to understand the role various tools can play in the MRV loop set out in Figure 1.

For this reason, the measurement–modelling loop for soil C is shown in more detail in Figure 3. Its realisation for NBS is still an aspiration, but a mature analogue exists in Upstream. The key tools needed for its realisation are shown in italic. Orange indicates the ongoing measurement pursuits of the NBS research and development (R&D) team. Note how they touch on practically every component of the loop shown in the figure.



Purpose	Measurement technology theme	Key projects
New tools (fill sizeable technology gaps) for measuring project outputs and model inputs	• At-scale measurements of soil C and GHG • Monitoring land management and other above-ground model inputs	• Investigate **geophysical** methods for soil C monitoring • Establish a **test site** for benchmarking (NSF funds) • **Arable** sensors for spatially improved modelling • Automated **cattle localisation** toolkit (DAS, satellites)
Existing tools – improve use efficiency	• Flux towers for GHG monitoring • Point sampling methods (soil, gas chambers)	• **Acceptance** as an alternative soil C measurement • **Improved analysis** of noncollocated sample vintages • **Faster fractionation** in the laboratory via fluorescence → C permanence evaluation
Additional scope – extra certification of projects for higher-value credits	• Biodiversity and soil health monitoring	• JIP on **eDNA**

NSF: National Science Foundation; DAS: distributed acoustic sensing; C permanence evaluation: to assess the longevity of carbon storage in soil; JIP: joint industry project; eDNA: environmental DNA, a method for detecting species present in a specific area.

FIGURE 2
Measurement themes and key ongoing projects.

The team is also working on improved modelling and tools for the integration of modelling and measurements, and leveraging advances in artificial intelligence.

Existing tools for soil C measurements work on a small spatial scale and require intelligent interpolation to make them usable at the project scale. They reside in the inner loop of Figure 3, which is analogous to what is called assisted history matching in oil and gas field development. Since some of those localised tools provide a continuous stream of data, this loop can be run relatively frequently (e.g. yearly) to monitor whether field performance meets expectations from models and, if it does not, take corrective actions by either updating the forecasting or adjusting field operations. However, the reliability of the spatial data away from the measurement points from localised tools is low, as they rely heavily on assumptions and indirect information. Therefore, and as is known from extensive Upstream experience, it is important to have an occasional actual measurement over the entire area of the project, for the purposes of a reality check and to make better-informed model updates. In Upstream, that is known as "4D close-the-loop", as it typically uses four-dimensional (time-lapse 3D) seismic as an areal measurement. In NBS, there is not yet a functionally equivalent tool for sensing soil properties over a large area. Developing one is an important aspiration, so the overview will start with that.

In-situ soil C monitoring at scale

To enable reliable in-situ soil C monitoring at the project scale, the team is exploring geophysical methods because, if successful, they would enable a step-change in speed and efficiency. This approach contrasts with the industry norm of incremental improvements of point

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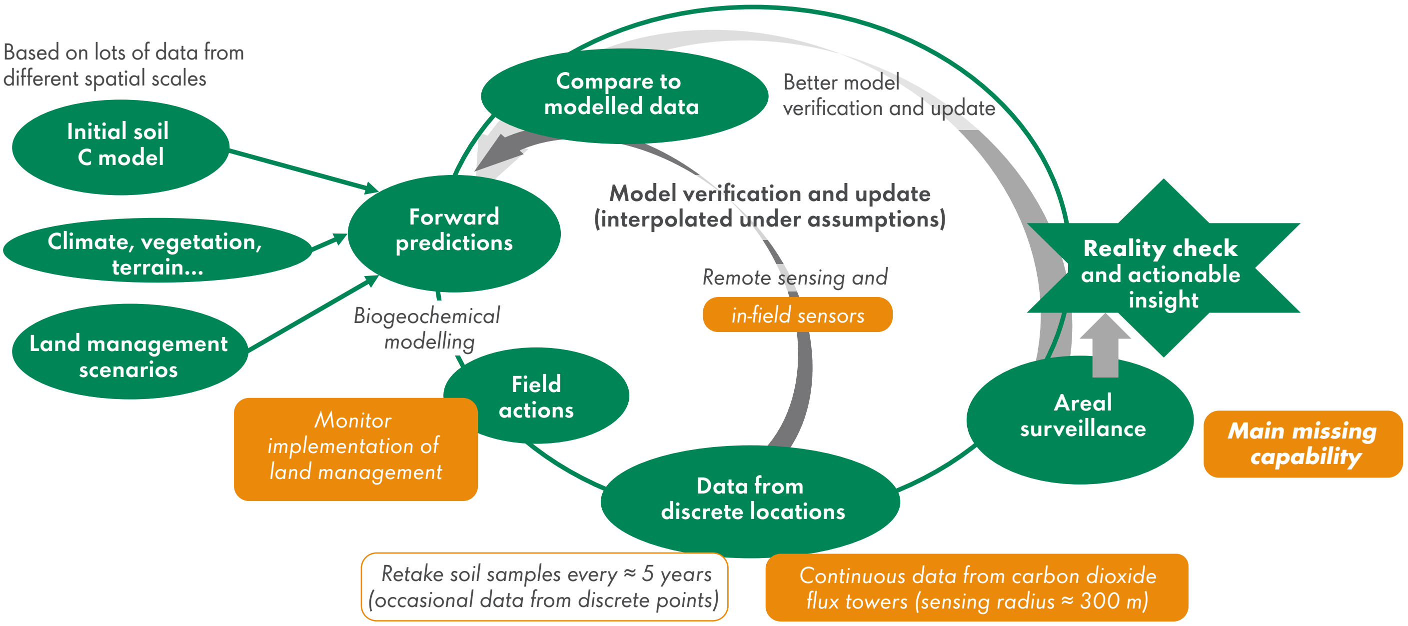
FIGURE 3
Closing the loop between measurements and modelling for soil C characterisation.



Soil C sequestration

Relevance to Shell

Soil C sequestration is emerging as a new business opportunity, by increasing carbon stored in soil and simultaneously reducing emissions of other GHGs, thereby unlocking options to generate carbon credits. The regulations and protocols around carbon-removal credit generation are constantly evolving, but they are tending towards increasing strictness in measurement protocols. The combination of these technologies, though they are not yet required, is more stringent than current protocols and could influence future methodologies, reducing the need for frequent physical soil sampling. Shell aims to become a net zero emissions energy business by 2050. To reach this goal, Shell is investing in and developing a diverse portfolio of innovative energy decarbonisation pathways, including the use of carbon credits, such as those from NBS projects, to support customers in their decarbonisation efforts. NBS activities include the protection, restoration and management of terrestrial and marine ecosystems to generate emissions reductions and carbon sequestration.

Technology is critical to ensuring high-quality, low-cost carbon credits.

measurements, which are slow and not sufficiently scalable. To understand this choice, consider the categories of soil measurement tools depicted in Figure 4 – "touch", "visit", "remote" and "permanently in situ". These categories differ greatly in speed and maturity. "Touch" methods, such as sampling and probing, are the norm, but they are very slow – classical sampling takes a couple of days per point, while in-ground probes take a couple of minutes per point (after the probe has been calibrated by soil samples). That is a great improvement in speed, but it is still too slow when studying large areas.

"Visit" methods, such as mobile inelastic neutron scattering (MINS), electromagnetic induction (EMI) and ground-penetrating radar (GPR) are in their infancy when it comes to soil C measurements (although EMI and GPR are mature for other purposes), but some vendor offerings are already available. These methods are faster, as they can use a vehicle-mounted instrument to hover above a spot for some tens of seconds to take a measurement over a square metre or so and then drive on to the next spot. To speed up acquisition, geostatistical methods are sometimes used to minimise the number of points to acquire. But even so, these methods are not fast enough: it would still take months to acquire enough points in large projects. In that time, seasons will change, plants will grow and many things will change in the soil. To speed up the process further, one could use several machines at once, if available, but that would increase cost.

A fundamentally faster approach would be to send some waves to sample an area – here, called "remote" methods. For example, in 10 s, a seismic wave would have travelled several kilometres. Such geophysical probing is very appealing, but it has not been investigated for soil C yet. The team considers it the largest untapped potential to deliver a much-needed step-change in soil data acquisition.

The term "remote sensing" has been traditionally associated with satellite data, but the team uses it in a broader sense, to include ground-based and airborne geophysical measurements. Satellites are already in use in NBS for monitoring above-ground targets, such as vegetation, but below ground, they do not penetrate deep enough (typically, a penetration of up to 5 cm while we seek soil measurements down to 1 m). Airborne geophysics may be more helpful than satellites for deep-soil sensing but it is more tool-limited than ground-based geophysics.

A final category of tool to mention is the permanently in-situ sensor, such as a distributed chemical- (DCS), temperature- (DTS) or acoustic sensor (DAS), which uses fibre-optic cables. These sensors are an interesting option but the question is where to put them, especially DCS and DTS, so that they measure relevant soil changes without being in the way of farming activities.

The team's pursuit of geophysical methods for a step change in acquisition speed can leverage the background knowledge of several specialised communities.

Soils are an object of study in agro-geophysics. Historically, agro-geophysics has focused on electrical and electromagnetic methods, mainly to map moisture and sometimes study root development for the purposes of irrigation and crop management [Ref 1]. But for soil C characterisation, a more attractive – and currently underutilised – method might be seismic because, in principle, it is sensitive to a greater number of soil properties that are known to influence carbon sequestration, including not only moisture but also porosity, permeability, density, clay content and matrix stiffness.

Moreover, in the field of bio-geophysics for environmental and geotechnical applications [Ref 2], seismic has been shown to be sensitive to hydrogels and carbonates. In other words, seismic can function as a multitool – acquiring one type of data that can be analysed in various ways to get different soil properties or their combinations. That is very attractive from a cost and acquisition point of view, and so merits further investigation. While there are many technical challenges to overcome in the development of seismic (specifically surface waves and near-surface refractions) into a tool for soil C characterisation, the very first challenge is raising awareness of soil C as an object of interest (as it is a new one), and breaking down the barriers between silos of specialised communities with relevant skills, such as agro-geophysics, critical-zone geophysics, bio-geophysics and time-lapse geophysics.

The team is pursuing that through an assortment of external engagements, as well as active participation in cross-disciplinary research grants like the NSF-funded Colorado and Wyoming Advanced Sensing and Computation for Environmental Decision-making (ASCEND) Engine, which offers up to $160 million in funding over 10 years.

Land-management monitoring

Modelling requires land-management inputs, and the outcome of projects is directly related to the implementation of that management. The efficient and independent monitoring of land management is needed for verification. For example, in optimised grazing projects, cattle locations still need to be tracked, but it remains cumbersome and is often performed manually. Assorted approaches to automation have been attempted in industry but are not yet mature. Those include satellite- and video-tracking and animal-based sensors (e.g. Vence collars – tested in collaboration with Kateri, a company in the Shell Ventures portfolio). The team is selectively pursuing opportunities to improve upon these industry approaches, as well as testing fundamentally new ones that arise from Shell's unique set of expertise in diverse technical fields.

An example of an improvement project is leveraging the team's digitalisation capabilities to make better use of satellite data for cattle tracking, in collaboration with the University of Exeter in the UK (an internship project is ongoing). An example of an innovation project would be the use of optical fibres and the DAS technology to monitor herds by listening to cow footsteps. That borrows heavily from microseismic localisation techniques from Upstream, as well as from industry experience with other DAS applications, such as perimeter and infrastructure monitoring. A proof-of-concept (PoC) trial is in preparation at Prairie View A&M University (PVAMU) near Houston, USA, where Shell is supporting the creation of a centre of excellence for NBS, including an instrumented farm test site. If the PoC test is successful, maturation will be sought through external collaborations, with multiple synergies in mind, including with rural telecommunications initiatives (an opportunity to piggy-back on existing fibre) and additional NBS purposes. For example, the same optical cables used for cattle localisation can serve as an array of seismic receivers for soil characterisation, and potentially (depending on the mode of cable deployment) as bioacoustics sensors to aid biodiversity characterisation and as spatially extensive temperature sensors to aid carbon modelling. Regardless of the outcome from the PVAMU PoC, the generated data set can aid engagement with universities with relevant geophysical skills (see previous section on raising awareness and bridging silos).

Improved use of existing tools

Flux towers and soil samples

Eddy covariance towers (flux towers) are the most advanced type of localised, yet areal, measurement in use for NBS. Flux towers use circular air currents, known as eddies, found centimetres to metres and even kilometres above vegetation. They measure carbon dioxide (CO_2) concentrations at the top and bottom of these eddies to determine vertical CO_2 exchange between the land and the atmosphere. These measurements are taken many times per second, covering a wide area (5–10 ha, or a radius of 100–300 m). By accumulating data over time, researchers can track CO_2 absorption or release to quantify the net carbon exchange between the ecosystem and the atmosphere. The towers also measure other atmospheric data, such as precipitation, pressure and evapotranspiration, in support of improving system modelling and carbon forecasting.

Under certain conditions, data from flux towers can be used to estimate soil C changes, although this method is not yet accepted by regulators as a

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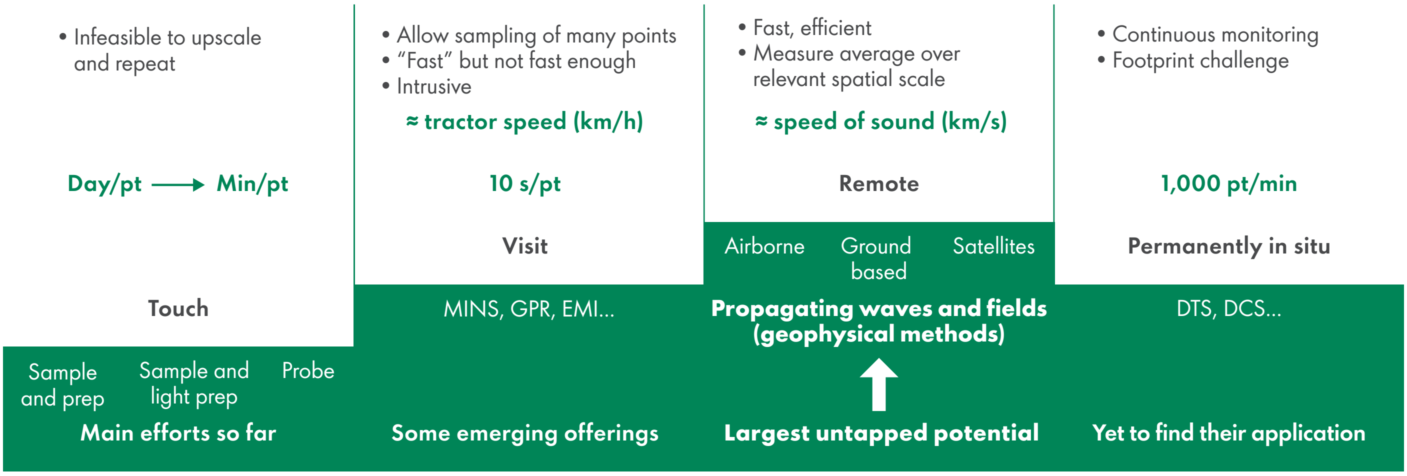
FIGURE 4

Categories of tools for soil monitoring based on acquisition approach.



soil C measurement. To address this, the team analysed historically collocated flux tower and soil sample data through Quanterra, a company previously in the Shell Ventures portfolio, in collaboration with the University of Exeter. The findings will be published in peer-reviewed journals to support broader acceptance.

In parallel, the team is improving the analysis of noncollocated soil samples over time to better manage heterogeneous project conditions and facilitate the comparison of soil C change estimates from flux towers, soil samples and models.

Intelligent interpolation of localised monitoring

Upscaling localised data from flux towers to farm-level decision-making is a known challenge. In cropland settings, the team is exploring the possibility of integrating crop-monitoring data from sensors used by farmers to get ecosystem and weather information between flux towers, to aid carbon estimate upscaling. For that purpose, the team is testing the latest Mark 3 farming sensors from Arable at 14 crop sites in Brazil and combining the data from those sensors with remote-sensing data to feed into a modelling framework developed by HabiTerre. If successful, the deployment of this upscaling approach would be facilitated by the ongoing proliferation of sensors for precision agriculture.

Beyond soil C: Biodiversity and soil health

NBS projects can generate higher-value credits if proven to have a net-positive impact on biodiversity and soil health. In support of biodiversity monitoring, the team is leveraging novel tools, such as environmental DNA (eDNA). Maturation is underway through multiple NBS business pilots and via participation in the International Association of Oil and Gas Producers' Environmental Genomics Joint Industry Programme (JIP34). Its benefits can extend beyond the context of NBS to other Shell projects where ecological impacts and biodiversity assessments are of relevance.

Conclusion

The NBS team is advancing the science and technology of soil C monitoring to generate credible, high-quality carbon credits and strengthen trust in the voluntary carbon market. By developing scalable tools, improving integration of models and field data, and expanding into biodiversity and soil health, the team aims to deliver reliable and valuable project outcomes.

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This content follows Shell's net carbon footprint and net-zero emissions target principles as documented here: www.shell.com/investors/disclaimer-and-cautionary-note.html.

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