CHAPTER 4

Affordable and scalable techniques and tools for field monitoring of carbon and greenhouse gas data

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Introduction

Climate change intensified by greenhouse gas (GHG) emissions is one of the greatest challenges facing humanity this century, mainly due to its effects on food production and water availability. The social, environmental, and economic impacts are likely to become increasingly intense if no significant reduction in GHG emissions is attained. The United Nations Framework Convention on Climate Change (UNFCCC) established a universally agreed regulatory environment for countries to quantify their GHG emissions. Recently, the Paris Agreement made progress in establishing a periodic instrument to expand these ambitions internationally, in order to stabilize the increase in average global temperature at 1.5 ºC (preferably) or 2.0 ºC.

In this context, during the 26th Conference of the Parties (COP 26) to the UNFCCC in Glasgow, Brazil made a commitment to neutralize its emissions by 2050. This commitment is described in the Nationally Determined Contributions (NDC). Many organizations which are equally committed to this commitment (and possibly pressured by more demanding consumer markets) have also presented their ambitions to reduce GHG emissions over the next 30 or 40 years, in anticipation of the debates and regulatory policies that will need to be implemented to guarantee action from the economic agents responsible for emissions. At the same time, consumer markets will increasingly demand products and services that are less emissions-intensive (in terms of GHG emissions per unit of product) or more environmentally friendly. For this reason, there is a growing initiative among organizations to determine their contributions in terms of GHG emissions and removals in order to plan a transition towards neutrality or a significant reduction in these emissions.

As institutions search for ways to reduce and offset their GHG emissions with a target of "net zero" (in other words, to bring the impact of their emissions to zero), this has created an increasing demand for information on how to measure the carbon present in the environment, calculate the amount of polluting gases emitted, and set targets for reducing these emissions over time. Clearly defining strategies to monitor and control GHG emissions has become an important aspect in winning over markets, differentiating prices, and enhancing the value of brands and companies, and is now part of environmental and economic agendas at many organizations. The growing proliferation of corporate initiatives, coupled with the regulatory inducement established by the Paris Agreement, has driven the creation of instruments intended to improve climate performance and corporate environmental sustainability, such as voluntary markets, green and climate bonds, and the environmental, social, and governance (ESG) movement. This dynamic new panorama brings with it opportunities and challenges for managers, granting priority to climate management as a strategy for minimizing and offsetting emissions. The entire process, however, requires systematic monitoring, reporting, and verification practices (known by the acronym MRV).

In climate performance projects, the monitoring stage consists of generating information on emissions, removals, and other indicators related to climate change mitigation or adaptation criteria. Data collection for this monitoring can take place through inventories, estimates based on emission scenarios (using mathematical modeling), or direct measurement of climate-related targets and metrics, on a one-time or periodic basis. The reporting stage consists of transparent and accessible disclosure of this information to stakeholders. The verification stage corresponds to analysis of the disclosed information, ensuring its reliability through traceability audits and replication of the methodology in accordance with its purpose.

Like the other signatories to the Convention and the Paris Agreement, Brazil has committed to periodically inventory its emissions according to the methods and principles recognized for transparency, accuracy, consistency, compatibility, and completeness (TACCC) which have been established by the Intergovernmental Panel on Climate Change (IPCC). This activity must use the internationally agreed methodological framework recognized by the Convention of the Parties. It is up to Brazil, as a signatory to the Paris Agreement, to determine the set of nationally appropriate measures to foster an economic transition towards foundations which involve less intensive GHG emissions, as established in its NDC. The country has already carried out five national inventories (2004, 2010, 2016, 2020 as a National Communication, and 2024 as a Biannual Transparency Report), but still relies heavily on information based on technical coefficients and specific emission factors, since it does not yet have indicators measured on a national scale (Brasil, 2021, 2024a).

With the Paris Agreement in force, Brazil is entering a new phase where it will be required to draw up biannual GHG inventories, as well as demonstrate compliance with the emissions reduction targets determined in its NDC. Lack of information on the mitigation potential of agricultural systems and activities also affects the production sector, which needs to prove that its corporate climate performance targets have been met. Brazil's GHG emissions are mainly concentrated in the land use change sector (associated with deforestation and fires) and the agricultural sector (Brasil, 2024b). Both generate diffuse emissions which, considering the geographical expanse of the country, represent a major challenge for comprehensive and effective monitoring of emissions and removals.

Data collection is the backbone of any analysis, decision making, and direction-setting strategy. For a country like Brazil that spans a continent, accurately representing all environments and production models with viable costs and a satisfactory timeframe represents an additional challenge. This is why improving monitoring, reporting, and verification techniques has become a priority in Embrapa's work. The aim is to generate and adapt techniques and instruments that make collection and monitoring methods more accessible and scalable, permitting use on a large scale and with frequency appropriate for meeting national commitments as well as the needs of the productive sector. Many techniques and field evaluations can provide important inputs for analyzing GHG mitigation and adapting production systems to climate change.

This chapter highlights the collection and monitoring techniques adapted or developed by Embrapa to obtain technical coefficients for crops, estimate carbon stocks in different ecosystem compartments, measure GHG emissions released by soil and animals in production systems, as well as measure environmental and soil attributes that are essential for estimating emissions and removals, or even for understanding GHG emission and removal patterns. One of the premises adopted is that these techniques should be compared and validated with traditional field data collection methods, which are generally more expensive, require more manpower or specialized skills, and in many cases are too invasive, since they alter the collection site or destroy the sample. Alternative techniques must have the advantages of accessibility, agility, and lower cost, and also be easy to apply on a large scale.

The state of the art

Throughout its history, Embrapa has effectively contributed to continuous growth in the country's agricultural production and productivity, boosting the competitiveness of Brazilian products in international markets, food security for Brazilian and global society, conservation of natural resources, environmental preservation, and finally to building and consolidating technical and scientific competence and leadership for conservationist tropical agriculture (Hungria; Vargas, 2000). One of the main challenges today (and also over the next 10 to 20 years) is to offer strategies for the ecological transformation of the economy, enabling innovative technologies that guarantee production of food, fiber, and energy within a global scenario of climate change that includes strong pressure on water, soil, biodiversity resources, and growing demands to reduce the environmental and social impacts of the production process.

Embrapa's role on the topic of climate change is very broad, supporting everything from the definition of climate mitigation and adaptation strategies to domestic estimates of GHG emissions and removals, since the first edition of the national inventory. Its work includes improving technical coefficients for crops, estimating sequestration rates and carbon stocks as a result of changes in land use and management practices, as well as defining emission factors adapted to national conditions (Brasil, 2020).

In recent years, Embrapa has increasingly been called upon by the private sector to help with emissions accounting, mainly in carbon balance and footprint calculations, estimates of GHG emissions, and characterization of environmental profiles for products. The carbon balance, like other related metrics, has become an important aspect in measuring the achievement of corporate targets to reduce GHG emissions. This measurement is essential for winning markets, differentiating prices, and adding value to brands, and is currently part of many organizations' environmental and economic agendas.

Given the growing number of corporate initiatives, associated with the regulatory inducement established by the Paris Agreement, there is also a growing need to improve techniques for collecting and monitoring GHG emissions in the agricultural and land use change sectors. The collection and monitoring of field data can be carried out using different technologies; the most suitable technique depends on the scale and the variable to be monitored. Within this context, Embrapa has been developing and adapting techniques and instrumentation to reduce costs, increase scalability, and speed up collection of data related to GHG flows, the carbon present in various compartments including the soil, and other equally important environmental aspects.

By increasing the efficiency and accuracy of the data generated, investments in expansion of collection infrastructure and methodological standardization of alternatives to traditional methods will have a strong impact on monitoring viability. These advances are relevant for the national GHG inventory, as well as for certifications, incentive programs, and commitments made by smaller-scale enterprises to achieve climate performance targets.

The agricultural sector is of great economic importance to Brazil, and occupies 32% of the country's territory. However, most of the country's area is covered by native forests, which account for 59% of the total and are in different states of preservation (Table 4.1). There are an additional 10 million hectares of planted forests, which correspond to 1% of the national territory. Brazil's native forests have high biodiversity and varied plant formations, which makes it difficult to measure carbon and GHG emissions in a representative manner. Despite these challenges, they are essential for meeting the targets set in the Paris Agreement, and in the national NDC they stand out as the most important sector for mitigating GHG emissions.

Table 4.1. Area allocated to individual land uses in Brazil, with agriculture broken down into the main sectors, based on MapBiomas data (2024).

Land use	Area (ha)	Area (%)
Forest	502,572,052	59.0
Shrubby and herbaceous vegetation	46,450,811	5.5
Area without vegetation	6,773,077	0.8
Bodies of water	18,298,211	2.2
Agriculture and livestock production	276,671,946	32.5
Pasture	164,574,066	59.5
Agriculture	60,992,647	22.1
Forestry	8,940,366	3.2
Other uses	42,164,867	15.2

The traditional method for estimating carbon stocks in forest biomass is based on field inventories. These surveys collect information such as tree diameter and height and identify species and botanical families. This data makes it possible to assess the quantity and quality of forest resources as well as to monitor tree mortality and growth over time, providing a more accurate view of the dynamics of the area studied. The stored carbon is estimated using allometric equations, which relate tree size to biomass. These equations can be specific to a plant species, or generic, applied to groups which do not have their own specific models.

The sampling method is most widely used, with part of the area assessed and considered representative of the whole. Field inventories are essential for estimating carbon stocks in plant biomass, but they present significant challenges: they require trained teams, take a long time, and are labor intensive. Moreover, subsequent processing of the data can be as time-consuming as the field collection itself, which may complicate revisions in the event of errors or questions. Due to their laborious nature, field inventories are of limited efficiency in generating data on a large scale, especially given the commitments made on a national scale.

Indirect methods based on non-destructive technologies have shown promise for expanding the capacity to generate information and supplement national inventories. New devices and methods are emerging every day with the evolution of geotechnologies, which has greatly benefited planning and execution of forest inventories and placed this activity in a new light. In this way, field inventories have gained new tools like remote sensing, through various techniques such as satellite images, unmanned aerial vehicles (UAVs or drones), and LiDAR scanning (Sousa et al., 2020; Santos et al., 2021; Ferreira et al., 2022; Costa et al., 2023). But like any new tool that arrives in the field, they need to be adjusted to the conditions and subjects where they will be applied, in turn requiring new models and response algorithms that are consistent with each forest situation (Souza et al., 2024).

In this context, Embrapa is developing techniques to identify forest species, quantify forest attributes, and estimate the carbon stocks present in plant biomass. These techniques vary widely in cost; services involving drones or UAV are most affordable, which makes it easier for the public to access these technologies. However, data processing still requires qualified human resources to ensure credible results.

The carbon present in the soil is just as important as that stored in vegetation. Agriculture and land use greatly influence the amount of carbon stored in the soil, which can be equal to or even greater than the quantity found in vegetation. In 2021, Embrapa released a map depicting soil carbon at 90 m spatial resolution (the equivalent of 1:250,000–1:100,000) in sub-layers up to 100 cm deep (Vasques et al., 2021). Although it represents a strategic advance, this database cannot yet be used as a reference for rural properties or to monitor changes in carbon stocks caused by good agricultural practices like no-till farming, integrated crop-livestock-forest systems, and the use of bioinputs.

Two main measurements are required to monitor soil carbon stocks: carbon concentration and soil density. Both are costly assessments, in terms of both physical effort and financial cost. On the other hand, soil carbon monitoring is gaining importance, and the search is intensifying for faster and more accessible methods for collecting and analyzing soil samples. These methods must be efficient, affordable, and generate as little laboratory waste as possible.

Accurately quantifying the temporal variation in carbon concentration is a challenge, given its slow evolution over time and high variability in space (Haynes, 2005). In order to monitor and analyze soil carbon variation, it is essential to define reliable quantification methods. Carbon can be measured using dry combustion methods (ISO 10694:1995) as well as wet processes, such as the Walkley-Black method (FAO, 2020), which oxidizes the carbon present in the sample with a potassium dichromate solution and is also known as wet combustion. While this method has the disadvantage of generating a large amount of chemical waste, it is the most common process used in soil analysis laboratories that serve rural properties in Brazil, since it is relatively inexpensive and does not require the use of specialized equipment.

Although the data obtained with this method are widely used to calibrate nitrogen fertilization recommendations for many crops, their application in monitoring changes in soil carbon stocks has been questioned. This is due to the inherent inaccuracy of the results, since oxidation of the carbon in the most transformed fractions is not complete and depends on the recalcitrance (physical-chemical stability) of the carbon present in the sample (Fontana; Campos, 2017).

The dry combustion method is considered the international standard, and is widely accepted and recognized due to the high precision and accuracy of results (Nelson; Sommers, 1996; Fontana; Bianchi, 2017). In this method, the soil sample is incinerated at a temperature of at least 925 °C, which results in complete oxidation of all forms of carbon present, transforming them into CO_2. The C-CO_2 is then detected using an infrared sensor. The main disadvantage of this method is the high cost of analysis, which exceeds that of the wet method. This cost stems from the need for specialized equipment, consumption of specific materials, and high maintenance costs, making it accessible only to a few commercial laboratories with high demand for analysis and limiting its application on a large scale.

In response, Embrapa and its partners have sought to develop technical methods that are robust, accessible, and capable of meeting national demands on an adequate scale. Two technologies derived from these initiatives that are currently available in the private sector are AgLIBS (Babos et al., 2024a) and the use of Vis-NIRS (Coelho et al., 2018). Both stand out for their low cost and agility of analysis, as well as the fact that they are already accepted in voluntary market certification programs. The use of technologies such as radio detection and ranging (RADAR)/synthetic aperture radar (SAR) also shows promise for monitoring and assessing carbon in soil and roots (Machado et al., 2025), and is already being investigated in research projects.

Soil density (Ds, also known as bulk density) is a fundamental factor in calculating carbon stocks, and represents the greatest source of uncertainty in this process. As interest grows in determining changes in soil carbon stocks because of their role in reducing GHG emissions, assessment of Ds has become indispensable and is now required on a broader scale. The methods available for determining Ds are laborious and require specific caution as well as the use of appropriate tools, which limits their application in large areas or studies with many repetitions because of the meticulous work and the high operational costs involved.

Ds can be determined directly, by taking undeformed samples of a known volume of soil in the field, or indirectly by estimating it via mathematical equations. Standard methods include the volumetric ring and excavation, both of which are recognized by national (Oliveira, 2014; Zanatta et al., 2015; Fontana et al., 2024) and international (FAO, 2020) protocols. These methods require a trench to be dug either manually or mechanically, usually 50 to 100 cm deep, to access the layers of interest.

In the volumetric ring method, a cylinder of known volume (ring) is carefully inserted into the soil in order to preserve its structure. The soil contained in the ring is then removed, dried and weighed. Soil density is calculated as the ratio between the dry mass of the soil and the volume of the ring. The excavation method is suitable for loose soils or soils with a high gravel content, when more than 15% of the volume is made up of coarse materials. In this case, a "hole" is made in each layer of soil, which is filled with fine sand of known density (density of sand = mass of sand / volume of sand). The Ds of the soil is calculated based on the ratio between the mass of dry soil extracted and the volume occupied by the sand used.

The trenches opened to apply these methods must be properly closed after collection, which takes time and a great deal of effort, whether manual or mechanical. To avoid this step, automated methods have been proposed that use probes to obtain undeformed samples. However, these techniques still need to be validated against reference methods such as the volumetric ring. Collection via automated probe obtains a soil monolith (or core) that can be subdivided into layers of interest, after which Ds can be determined according to traditional procedures.

The most modern methods for determining Ds are based on nuclear techniques, such as computerized tomography (Timm et al., 2005; Pires et al., 2010) and the use of neutron-gamma surface probes (Cássaro et al., 2000a, 2020b, 2020e). Both techniques use very expensive equipment and require highly skilled labor, which means they are very costly to implement.

Alternatively, technical teams have developed Ds prediction models that use some attributes obtained from disturbed samples after routine soil analysis, such as particle-size fractions (sand, silt, and clay), C, pH, and sum of bases, which are correlated with soil aggregation and structure. The models known as pedotransfer equations are well accepted, and may offer alternatives with interesting cost-benefit ratios. Some models that are already available are described under innovative solutions for soil density, along with technical adaptations for the use of automated mechanical probes. These solutions serve the productive sector, since they are inexpensive techniques that can be applied on a large scale and with adequate operational performance. This approach will be detailed in the technological solutions section, since teams are developing prediction models with very satisfactory results (Reis et al., 2024; Santos et al., 2025).

Monitoring GHG flows is also a very laborious activity. Methodologies for assessing GHG flows *in situ* in the soil-atmosphere system generally require the use of chambers to collect samples and then analyze them in the laboratory. Manual static chambers are most commonly used to measure soil gas flows, because they are portable, simple to operate and can be inexpensive, depending on the method used (Dalal et al., 2003; Parkin; Venterea, 2010). When used according to recommended criteria, these chambers are very valuable and cost-effective (Hutchinson; Rochette, 2003; Parkin; Venterea,2010).

Despite being widely used around the world, chambers present significant operational challenges. The method requires a great deal of work, and has limitations related to sensitivity, frequency of evaluations, and the need for specialized labor to interact with the system and collect the air samples. Furthermore, efficient collection depends on both the capacity of the collector and the distance between the chambers, restricting application on a large scale. One person can normally collect samples from up to 10 chambers, distributed over a radius of up to 30 m. This capacity limits the number of repetitions and replicates to be monitored, making comparative analyses difficult due to the low number of field repetitions. It is important to note that soil GHG flows are influenced by several factors (La Scala et al., 2000; Jantalia et al., 2008; Veloso et al., 2019), resulting in high spatial and temporal variability (Deng et al., 2020). It is consequently necessary to increase the number of repetitions in the collection to obtain more accurate and representative results.

Another limiting condition is that in systems with manual collection, it is practically impossible to carry out daily monitoring of GHG emissions over consecutive days. These difficulties severely limit studies that are more comprehensive in terms of time and space. Flow towers provide indirect measurements of GHG flows on a highly detailed and representative time scale for a larger area, typically between 2 ha and 10 km^2; this size depends on the characteristics of the monitored area as well as installation of the towers, making them valuable tools for large-scale studies. However, the results obtained by this method are not directly comparable with those obtained from chambers installed in the ground, because while flow towers describe the GHG balance in the soil-plant-atmosphere system, the chambers represent the net flow in the soil-atmosphere system. Because of the inherent characteristics of the tower method, installation requires large areas of relatively flat terrain, as well as qualified professionals for operation and maintenance.

One way to expand collection capacity when using chambers is through automatic systems for collecting air and analyzing the flow of GHGs. These systems are connected to a gas analyzer, which may be a gas chromatograph or laser spectrometer. In this case, the chambers are programmed in advance and air samples can be taken and analyzed several times a day. Despite the excellent quality of the information generated, use of these systems is restricted to experimental fields with adequate security and depends on the presence of analysis equipment in the field, which for chromatographic systems implies limitations in terms of equipment sensitivity, since it operates under controlled temperature conditions. This technique yields very large amounts of data, and can lead to much more accurate conclusions about daily emissions cycles and also identify the direct response of the GHG flow to changes in soil conditions, especially temperature and humidity. All of the automatic chambers currently available on the market are imported and still relatively expensive, and must be adapted for use in Brazilian conditions.

Considering this challenge, Embrapa and its partners developed a semi-automatic sample collection system that the operator can bring into the field, turn on, and return at the end of the campaign (usually 2 hours) to collect the air samples and the device. This new system boosts collection capacity in the field involving one operator at least three-fold compared to the traditional collection system (involving a manually operated static chamber).

Many of the difficulties mentioned for monitoring soil GHG fluxes are also true for monitoring enteric methane from ruminant animals. Monitoring enteric methane requires non-invasive methods that are sufficiently accurate, which represents an additional difficulty. Rumen fermentation is a complex process influenced by various factors such as type of diet, forage quality, animal genetics, and environmental conditions. Generalizing the results to different production systems requires studies with large numbers of animals and multiple conditions. Methods for measuring enteric methane include containment chambers, tracer techniques, sniffing techniques, and portable laser methane detectors. While methods like breathing chambers are accurate, they are invasive and limited to a small number of animals. The search for portable and less intrusive methods, such as laser methane detectors, is underway. More recently, an automated head chamber system known as GreenFeed (GF) has been developed for spot sampling of exhaled and eructated gases (Zimmerman; Zimmerman, 2012). Comparisons with respiration chambers or the SF6 method have established that, when used correctly, GF is a reliable technique for measuring enteric methane emissions from ruminant animals (Dorich et al., 2015; Hammond et al., 2015).

Many techniques and tools have been developed to facilitate monitoring and increase access to field data. The evolution of these techniques is also driven by growing demand from organizations to generate more detailed information on emissions and removals, both to improve climate management and with a view to investing in mitigation mechanisms. Indeed, given Brazil's expansive size, large-scale techniques are essential to provide the country with information that meets the demands of the Paris Agreement rules, as well as to promote efficient planning and control of emissions at the rural property level.

Innovative solutions for monitoring soil carbon

Obtaining accurate, large-scale data on soil organic carbon (SOC) is fundamental for understanding soil health, the global carbon cycle, and the potential for carbon sequestration in agricultural systems (Minhoni et al., 2021; Lima et al., 2025; Petropoulos et al., 2025). The importance of this data lies in the ability to map the distribution of soil carbon over large areas, identify areas with the greatest potential for carbon sequestration or risk of carbon loss, and monitor changes over time in response to management practices or extreme weather events (Minhoni et al., 2021). This information is crucial for implementation of low-carbon agricultural practices and development of climate change adaptation and mitigation policies in the agricultural sector (Petropoulos et al., 2025).

The innovative soil analysis techniques developed by Embrapa, such as AgLIBS and SpecSolo, can make a decisive contribution to strengthening Brazil's role in leading actions aimed at agricultural sustainability and tackling climate change, in direct alignment with the Sustainable Development Goals (SDGs) of the UN's 2030 Agenda, especially SDG 2 (Zero hunger and sustainable agriculture), SDG 12 (Responsible consumption and production), SDG 13 (Action against global climate change) and SDG 15 (Life on land). These connections reinforce the strategic role of spectroscopic techniques as technologies that enable public policies aimed at the ecological transformation of agriculture and effective monitoring of the environmental commitments made by Brazil at national and international level.

Furthermore, potential techniques are being improved in scientific circles, especially those involving high performance capacity and remote application. From this perspective, data from satellites equipped with SAR sensors like Sentinel-1 and ALOS PALSAR is used through two main techniques: 1) dual polarization, which can be used to estimate SOC (El-Jamaoui et al., 2025) by means of the SAR Vegetation Index (SARVI); 2) ground penetrating radar (GPR), which complements the information obtained by orbital RADAR/SAR, although it operates on a smaller spatial scale, offering details on the structure of the subsoil including root distribution and soil stratification which can influence carbon storage (Jol, 2009). Both technologies will be discussed in the section that addresses future prospects.

The AgLIBS AI platform

AgLIBS AI is a digital platform for quantifying carbon, nutrients, and other physical and chemical parameters in soils. The physical foundation of this platform is laser-induced breakdown spectroscopy (LIBS), a technique which is widely applied in the analysis of materials as well as rocks and soils by various research institutions (Bublitz et al., 2001; Cremers; Radziemski, 2013) that include the US National Aeronautics and Space Administration (NASA) in its last two expeditions to Mars. This is a multi-elemental analysis method, based on atomic and ionic emissions of chemical elements from plasma created by a high-power laser. Figure 4.1 illustrates this technique, showing a typical emission spectrum indicating one of the emission lines of the carbon atom at 193 nm and a diagram of a typical LIBS measurement system.

The technique has been studied at Embrapa since 2006 as an alternative to traditional methods of analyzing carbon concentration. This technology makes it possible to quantify carbon, soil nutrients, texture, pH, and cation exchange capacity (CEC) more quickly and affordably than conventional methods, and also provides digitized data for analysis and decision making.

As part of a public-private partnership, this technique has evolved into a platform, AgLIBS AI, which generates agronomic recommendations for producers, optimizing soil management. It also makes it possible to create detailed maps of carbon stocks more quickly and at a lower cost than the dry combustion method, helping to make carbon credit projects viable for rural producers and agribusinesses. Additionally, it permits analysis and mapping of plant macro- and micronutrients present in soils, as demanded by precision agriculture for more efficient and sustainable soil management, resulting in increased agricultural productivity and/or reduced production costs. Importantly, the AgLIBS AI platform is a product with a patent shared between Embrapa Instrumentation and the Agrorobótica company.

In 2023, the LIBS technique was approved by the US-based Verra international certification

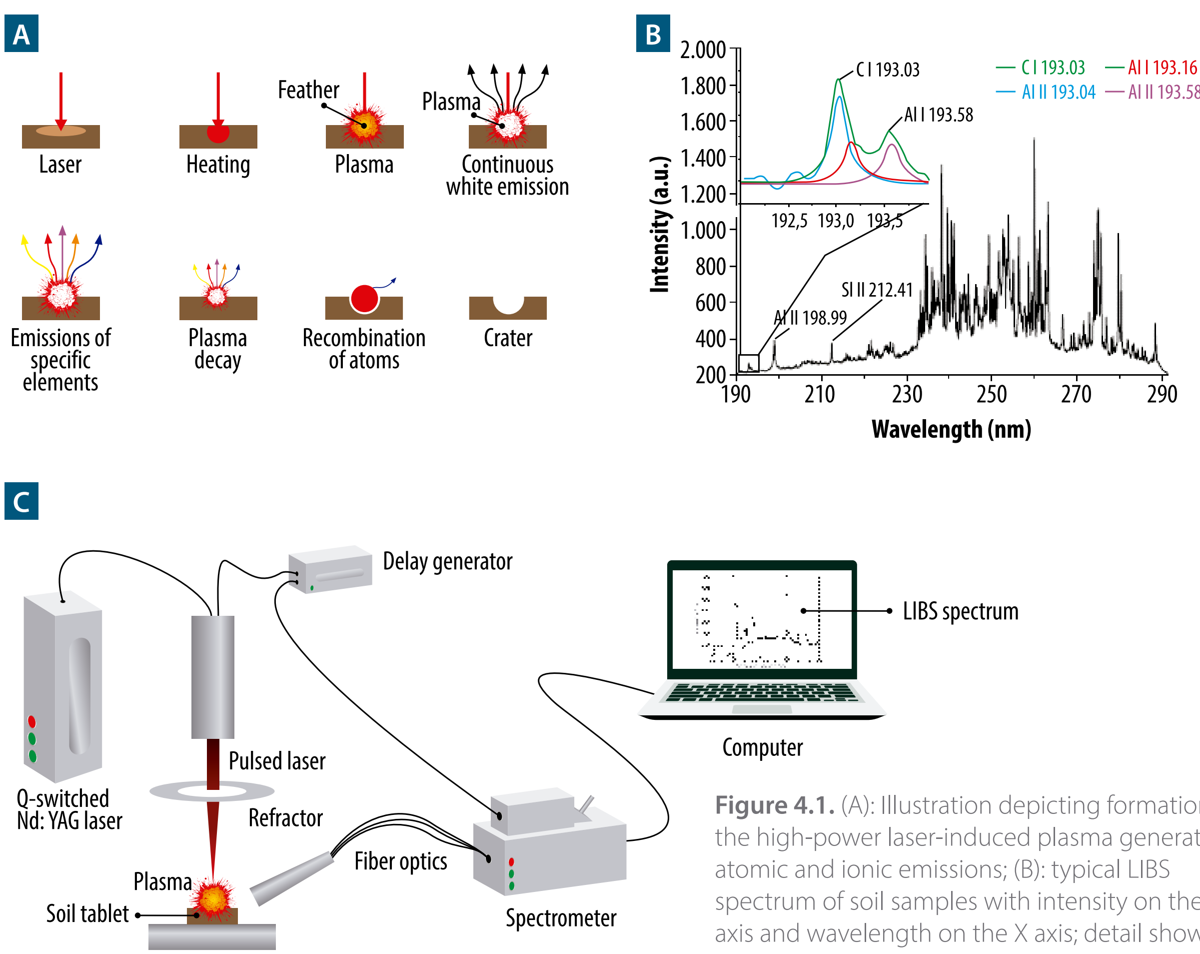


Figure 4.1. (A): Illustration depicting formation of the high-power laser-induced plasma generating atomic and ionic emissions; (B): typical LIBS spectrum of soil samples with intensity on the Y axis and wavelength on the X axis; detail shows detection of the C atom emission line at 193.03 nm; (C): diagram illustrating a typical LIBS system.

program for use in quantifying carbon in the soil, within the Verified Carbon Standard (VCS) program (Methodology VM 0042, Version 2, from May 30, 2023). Among the mostly international publications used by Verra to accept the LIBS technique for quantifying soil carbon in its VM 0042 Methodology, five were published by researchers from Embrapa Instrumentation associated with the Brazilian National Laboratory of Agri-Photonics (Milori et al., 2011; Nicolodelli et al., 2014; Segnini et al., 2014; Villas-Boas et al., 2020a, 2020b).

The AgLIBS AI platform has been used in projects throughout Brazil (Figure 4.2). In some recent results, Babos et al. (2024a) found an average root mean square error of prediction (RMSEP) of 0.47% for LIBS measurements of C; this result was obtained by comparing measurements from over 1,000 soil samples on 11 rural properties. These properties were distributed in the Cerrado, Atlantic Forest and Pampa biomes, with soil

Figure 4.2. Soil carbon measurement sites using the LIBS technique by Embrapa Instrumentation, from long-term field experiments at public institutions and mainly private rural properties ("on-farm research"), in different production centers and Brazilian biomes. Legend shows Brazilian biomes, while carbon measurements are depicted as green circles.

carbon content varying from 0.23% to 8.78%, as determined by the CHN Elemental Analyzer. The coefficients of determination (R^2) between the measurements obtained by LIBS and the CHN Elemental Analyzer were 0.94 and 0.75 for calibration and validation, respectively.

The implementation of advanced technologies like the AgLIBS AI platform has contributed significantly to national competitiveness in the agricultural sector. Adopting technologies like AgLIBS AI not only improves the efficiency and sustainability of agricultural operations, but also strengthens Brazil's position in the global market, meeting demands for more sustainable products and contributing to climate change mitigation. Access to advanced digital tools also allows for more efficient management of rural properties, particularly the ability to monitor and quantify increases in soil organic matter (SOM) and, in turn, soil carbon, with a significant impact on improving soil structure and actions related to adapting to the impacts of climate change.

Although the benefits of proper soil management are widely recognized, resilient and adaptive agriculture will require efficient monitoring of the soil-plant-atmosphere system, linking management practices to changes in SOM. LIBS can also be an important ally in consolidating and benefiting from the adoption of precision agriculture, since it reduces the costs of soil and plant analysis and simplifies application techniques to expand the use of variable-rate management of inputs and pesticides in soils and crops on a large scale.

In addition, the ability to quantify and monitor soil carbon on a large scale creates opportunities for producers to participate in carbon credit projects, generating additional income and granting them access to new international markets that value sustainable agricultural practices. These initiatives are aligned with government programs such as the Sectoral Plan for Adaptation to Climate Change and Low

Carbon Emissions in Agriculture and Livestock, with a view to Sustainable Development 2020-2030 (the ABC+ Plan). Furthermore, the AgLIBS AI platform plays a strategic role in reducing risks and boosting the adaptive capacity of Brazilian agriculture, making farms more resilient and sustainable. By leading investments in sustainability, Brazil not only improves its domestic agricultural practices, but also offers solutions that can be adapted globally, contributing to the sustainability of food production on a global scale.

The SpecSolo platform

The SpecSolo digital platform represents one of the most significant innovations in soil analysis over the past five decades in Brazil, based on the use of infrared spectroscopy. This approach makes it possible to quickly, accurately, and reliably replace traditional methods of analysis, many of which are costly and potentially polluting to the environment.

By eliminating the need for chemical reagents and drastically reducing waste, SpecSolo helps mitigate environmental impacts and reduce laboratory operating costs related to the treatment and proper disposal of this waste. Moreover, the platform has enormous potential for large-scale soil carbon analysis, making it a strategic tool for advancing low-carbon agriculture and the carbon trading mechanism that is currently gaining strength in Brazil.

The SpecSolo platform is based on infrared spectroscopy techniques, which involve the relationship between electromagnetic radiation and matter and are widely used in the physical and chemical characterization of soils. It is essentially based on the selective absorption of energy by specific chemical bonds, promoting vibrational transitions which reflect the molecular composition of the material being analyzed. This capability makes infrared spectroscopy a strategic tool for quantifying soil organic carbon, permitting identification and estimation of compounds related to organic matter while also providing important information for understanding carbon dynamics and assessing soil quality and fertility.

The spectral regions of greatest agronomic interest include the mid-infrared (MIR, 4,000–400 cm^{-1}), near-infrared (NIR, 1,500–4,000 cm^{-1}), and combined visible-near-infrared spectrum (Vis-NIR, 25,000–4,000 cm^{-1}). Each of these ranges offers specific advantages and can be used in a complementary way, depending on the purpose of the analysis, laboratory logistics, and degree of robustness required for the predictive models.

NIR has established itself as an important alternative for application in large-scale soil analysis due to its speed, non-destructiveness, low cost per analysis, absence of chemical reagents, and possibility of automation. The spectral bands in this region are the result of overtones and ranges that combine fundamental vibrations and result in broad, overlapping bands. For this reason, chemometrics and machine learning techniques are essential to properly interpret these spectra, and include partial least squares (PLS) regression, support vector machines (SVM), random forests (RF), and neural networks (NN), methods which extract information from spectral data and permit simultaneous quantification of multiple soil attributes from a single spectral reading. Figure 4.3 illustrates a typical NIR spectroscopy system, consisting of a monochromator and an integrating sphere, used to collect diffuse reflectance spectra from soil samples prepared as fine air-dried soil.

The Vis-NIR technique further expands this potential by integrating the visible spectrum (400–700 nm), associated with soil coloration and indicative of the presence of organic matter, iron oxides, and mineralogical characteristics. This approach has demonstrated strong performance in predicting physical and chemical properties in tropical soils, such as those found in Brazil.

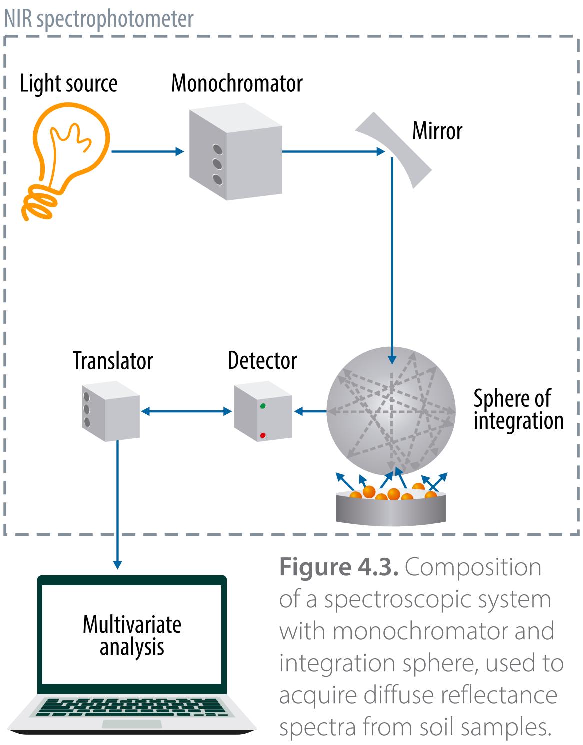


Figure 4.3. Composition of a spectroscopic system with monochromator and integration sphere, used to acquire diffuse reflectance spectra from soil samples.

This is the basis of technologies such as SpecSolo,[1] which uses Vis-NIR spectroscopy integrated with a system of hardware, software, and algorithms hosted in the cloud to offer fast and reliable results for large-scale soil fertility analysis.

This technology is helping to improve Brazil's competitiveness in the face of the challenges posed by climate change. The combination of NIR spectroscopy with artificial intelligence algorithms, along with the consolidation of robust spectral databases and advancement of miniaturized devices, has significantly expanded the potential use of this technique in large-scale routine analysis. Applications of infrared spectroscopy have also been catalyzed by national structuring projects such as those involving soil mapping and monitoring (like PronaSolos) and proficiency testing such as the Programa de Análise de Qualidade de Laboratórios de Fertilidade (Quality Analysis Program for Fertility Laboratories),[2] which since 2024 has included carbon measurement using NIR in its proficiency tests. This movement coordinated by Embrapa is intended to ensure methodological standardization, quality control, and inter-laboratory validation of the use of this technique in routine analyses.

By permitting rapid and non-destructive soil analysis, NIR spectroscopy could be integrated into public policy tools (such as Agricultural Climate Risk Zoning, or ZARC) to provide more accurate data on soil carbon content and encourage safer and more sustainable decisions regarding the use and management of agricultural land. Its application is also highly strategic for monitoring and verifying the sustainable practices envisaged in the ABC+ Plan, making it possible to monitor the potential for CO_2 mitigation through soil organic matter (SOM) content and carbon stocks, key indicators for low-carbon agriculture. In short, technology facilitates knowledge of carbon stocks in the soil and can therefore serve as a tool to help reduce the risk exposure of agricultural crops, boosting the adaptive capacity and competitiveness of production systems in an increasingly dynamic environment.

In summary, infrared spectroscopy through the SpecSolo platform represents a revolution in the way soil analysis is carried out, promoting a transition towards sustainability, digitalization and valorization of carbon in the soil. Its integration with modern methodologies and national public policies helps position Brazil as an important player in the use of clean and intelligent technologies for environmental monitoring and the strengthening of carbon markets to benefit Brazilian society.

[1] Available at: www.specsolo.com.br/antiga_pg_specsolo_scan.

[2] Available at: www.embrapa.br/solos/paqlf.

Innovative solutions for monitoring soil density

Soil density (Ds) varies due to a number of factors that include soil mineralogy, particle distribution and shape (the packing effect), as well as land use and management, topography, drainage and climatic conditions, which influence the accumulation of organic matter, pore size distribution, aggregation, and soil structure. For this reason, Ds exhibits high spatial and temporal variability across the landscape and at different soil depths.

Over the past two decades there has been growing interest in predicting Ds, an essential parameter for quantifying carbon and nutrient stocks in the soil which is also fundamental for modeling various soil processes. One alternative approach that costs significantly less than the conventional procedure for determining Ds is the use of mathematical prediction models. This prediction has been based on more readily available soil attributes; some models are already available and have been calibrated through tests carried out by Embrapa and its partners.

Another potential approach to circumvent the difficulties involved in collecting soil samples to obtain Ds is the use of automatic probes (whether operated by machines or manually). This technique is being tested at various Embrapa research units, with promising results. The potential of this technique will be discussed below in the future prospects section.

Development of pedotransfer equations

The concept of pedotransfer function (PTF) refers to methods that "transfer" available data to estimate soil properties or other variables that are difficult to measure but are necessary for modeling or evaluating soils. These PTFs make it possible to estimate Ds based on other soil attributes, such as granulometry (sand, silt, and clay fractions), pH, sum of bases, cation exchange capacity (CEC), and organic carbon content. The values of these attributes can be obtained from soil samples collected via coring, without the need to dig trenches.

Various studies have been conducted to develop PTFs, commonly using sand, silt, clay, and C content as predictor variables with different linear and non-linear regression methods and, more recently, machine learning techniques. Accurate estimates of Ds are fundamental for reliable application in different contexts, such as quantifying soil carbon stocks, assessing soil compaction, and hydrological modeling. When using Ds estimates obtained by PTFs to replace data obtained by direct methods, it is essential to assess the accuracy of the predictive model used. Table 4.2 presents a summary of the literature on PTFs developed to estimate Ds, highlighting their scope (local or national), associated accuracy expressed by root mean square error (RMSE), as well as the type of model and predictor variables used.

Models with a local scope have been developed for micro-basins (Souza et al., 2016; Sevastas et al., 2018), soil classes (Beutler et al., 2017; Cunha et al., 2017), regions with specific climatic characteristics (Al-Quinna; Jaber, 2013), biomes (Bernoux et al., 1998; Tomasella; Hodnet, 1998), and land uses and covers (Barros; Fearnside, 2015; Choudhury et al., 2023), among others. In general, the models developed on a national scale involve more complex relationships between soil properties and Ds on broader scales that incorporate multiple land uses, different geomorphological domains, and biomes. Another relevant point is that methods based on machine learning performed better than conventional regression methods, such as multiple linear regression (MLR), multiple non-linear regression (MNLR) and non-linear least squares (NLLS).

Table 4.2. Summary of work to develop pedotransfer functions for soil density in Brazil and other countries.

Work	Country	Scope	Method[1]	RMSE[2]	Predictor variable[3]
Schillaci et al. (2021)	Italy	Local	ANN	0.07	Clay, sand, SOC, pH, clim, rel
Obidike-Ugwu et al. (2023)	Nigeria	Local	MLR	0.075	Sand, SOC, q
Zheng et al. (2023)	China	Local	SVMR	0.08	Clay, silt, sand, SOC
Botula et al. (2015)	Congo	Local	k-NN	0.09	Sand, silt, clay, SOC, Fe, Al
Choudhury et al. (2023)	India	Local	ANN	0.09	Sand, silt, SOC
Gomes et al. (2017)	Brazil	Local	MLR	0.11	Clay, SOC, pH, SB, Al
Sevastas et al. (2018)	Greece	Local	MNLR	0.11	Clay, silt, sand, SOC
Al-Qinna and Jaber (2013)	Jordan	Local	MLR	0.13	Sand, SOC
Botula et al. (2015)	Congo	Local	MLR	0.13	SOC, Fe, Al
Souza et al. (2016)	Brazil	Local	RF	0.15	Clay, SOC, pH, SB, env
Palladino et al. (2022)	Italy	Local	RF	0.16	Clay, silt, sand, SOC, pH, $CaCO_3$, rel
Santos et al. (2025)	Brazil	National	RF	0.12	Clay, sand, SOC, clim, rel, others
Han et al. (2012)	China	National	MLR	0.13	Clay, SOC, N
Ramcharan et al. (2017)	USA	National	RF	0.13	Clay, sand, SOC, pH, env, others
Reis et al. (2024)	Brazil	National	MLR	0.14	Clay, fine sand, SOC
Nanko et al. (2014)	Japan	National	NLLS	0.14	SOC
Boschi et al. (2015)	Brazil	National	MLR	0.18	Clay, sand, SOC, Ph
Abdelbaki (2018)	USA	National	MLR	0.18	SOC
Benites et al. (2007)	Brazil	National	MLR	0.19	Clay, SOC, SB
Chen et al. (2024)	Europe	National	RF	0.19	Clay, sand, SOC, pH, N, clim, rel
Heuscher et al. (2014)	USA	National	MLR	0.19	Clay, silt, SOC, q
Beutler et al. (2017)	Brazil	National	MLR	0.22	Clay, SOC

[1] ANN: artificial neural networks; MLR: multiple linear regression; SVMR: support vector machine regression; k-NN: k nearest neighbors algorithm; MNLR: multiple non-linear regression; RF: random forest; NLSS: non-linear least squares.

[2] RMSE: root mean square error.

[3] SOC: organic carbon; q: soil moisture; Fe: iron; Al: aluminum; SB: sum of bases; clim: variables related to climate; rel: variables related to relief; env: environmental variables; others: additional numerical and categorical variables; N: nitrogen.

In general terms, it has been observed that in soils from temperate regions, carbon is the main variable explaining Ds, and is often the only variable selected in the PTFs of these regions (Nanko et al., 2014; Abdelbaki, 2018). On the other hand, in tropical regions characterized by highly weathered soils, soil texture is more relevant in Ds prediction models, with carbon as the second most important variable, as demonstrated in the studies by Benites et al. (2007), Reis et al. (2024), and Santos et al. (2025). The main limitation of the PTFs that use granulometric variables, SOC, and other soil physicochemical variables is that these variables are expressed on a gravimetric basis, and capture only part of the effects on Ds.

One promising approach to overcome this limitation consists of incorporating other variables (both numerical and categorical) that add knowledge to the predictive model through information related to soil structure. These variables include the silt/clay ratio, which tends to increase with the soil's aggregation capacity; the clay/sand ratio, associated with greater cohesion and lower porosity; and water-dispersed clay content and the flocculation index, where high values indicate low structural stability. Furthermore, topographic and relief-related variables such as slope, altitude, topographic moisture index, curvature of the terrain, and slope orientation (aspect) also influence the structural quality of the soil by affecting processes such as erosion, redistribution of particles, accumulation of organic matter, and variations in the water regime across the landscape.

The approach of using numerical and categorical variables together has gained prominence in recent years, as shown in studies such as Santos et al. (2025). However, for effective application it is essential to have the geographical coordinates of the data. Another important aspect in the development of models that can be applied on a national scale is the need for a broad and representative database that takes into account the diversity of the main soil classes, textural classes, biomes, climatic zones, and different forms of land use and cover, and where possible, the length of time the land has been used, especially for structured clay soils that tend to become compacted with agricultural use.

Innovative solutions for monitoring greenhouse gas flows in agriculture

Quantifying GHG emissions in agriculture is essential to understand the environmental impacts of agricultural activities and develop mitigation strategies. In the context of Embrapa's research networks (Fluxus, Saltus, and Pecus) and other research initiatives, the use of manual static collection chambers has been the main technical solution available to date for monitoring the flow of nitrous oxide (N_2O) and ammonia volatilization (NH_3), following international criteria and ensuring comparability between data obtained in Brazil and global studies.

During the process of directly determining GHG flows, sampling is performed using closed static chambers, a method accepted by the international scientific community as long as technical criteria are observed. These chambers are installed in the soil and capture the gases emitted over time. Samples are taken from the chambers at regular intervals, permitting analysis of variations in gas concentration. The GHG samples collected are usually analyzed by gas chromatography, using specific detectors for each gas.

More recently, techniques for measuring GHG concentrations using laser spectroscopy have been applied to measure carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). This method is based on absorption spectroscopy, namely the interaction between laser light and gas molecules, considering that different gases absorb radiation at specific wavelengths. The technique itself is commercial; the approach here will be to adapt these techniques for the continuous monitoring of GHG flows in agriculture.

Adapting static chambers to monitor direct emissions under national conditions

The main aspects of static chamber design have already been detailed in national (Zanatta et al., 2014; Alves et al., 2017) and international protocols (Parkin; Venterea, 2010; Zaman et al., 2021). The main models of static chambers adapted for use in studies in Brazil for direct measurement of GHG can be seen in Figure 4.4.

Figure 4.4. Types of chambers and materials available for fabrication: (A) cylindrical shape with galvanized steel base and PVC top; (B) cylindrical shape with galvanized steel base and polyurethane top covered with thermal insulation; (C, D) cylindrical shape with PVC base and top; (E) rectangular shape with galvanized steel base and polyethylene top; (F) square shape with galvanized steel base and top; (G) rectangular shape with aluminum base and top; (H) rectangular shape with galvanized steel base and polypropylene top covered with thermal insulation; (I) rectangular shape with galvanized steel base and top; and (J) rectangular shape with galvanized steel base and polyethylene top.

Photos: Josiléia Acordi Zanatta (A, B, J e L), Falberni De Souza Costa (C), Bruno José Rodrigues Alves (D, E, F e K), Cimélio Bayer (G) e Michely Tomazi (H e I).

Source: Adapted from Zanatta et al. (2014).

Determining the shape of the chamber and the material to build it with tends to be connected, since the goal is to adapt industrialized materials to make them easier to build and handle in the field, and reduce costs while simultaneously meeting the technical specifications for the chamber as well as the crop to be monitored. Inexpensive materials make it possible to increase the number of repetitions in the field; in contrast, very heavy chambers are difficult to handle in the field and may require large teams for sampling, depending on the frequency retired.

The criteria to be observed when developing projects with static chambers are as follows:

Dimensions and materials: Chambers must be made of materials like PVC or aluminum that are inert to the gases being measured, to avoid reactions that might alter the results. Height and internal volume are optimized to minimize environmental changes inside the chamber.

Controlled ventilation: Small vents ensure balanced internal pressure without altering the concentration of gases.

Proper sealing: The seal between base and top can be made of channels filled with water or inert rubber to prevent leakage.

Sampling system: Includes collection ports connected to sealed syringes or vials for subsequent analysis in the lab.

Although this method is widely used, it has limitations, such as the need for manual sampling and the possibility of distortions due to the influence of environmental conditions inside the chamber. With this difficulty in mind, researchers from Embrapa Forestry, in partnership with the Technological University of Paraná, developed a prototype of semi-automatic equipment (Figure 4.5) capable of taking samples directly from vials that were emptied after the chambers were closed. The prototype was developed based on an embedded system to control pumps and pneumatic valves for sample collection via a remote app interface, for remote interactions via Bluetooth and easy sharing of the data obtained. The technical functionalities of the complete system have been tested on the lab bench and in the field (Figure 4.5), with successful results described in Libel et al. (2021).

Collection chambers have been the main technical solution available up to this point to measure GHG flows in agriculture, guaranteeing the standardization and comparability of the results obtained. Despite the operational and

Photos: Josiléia Zanatta

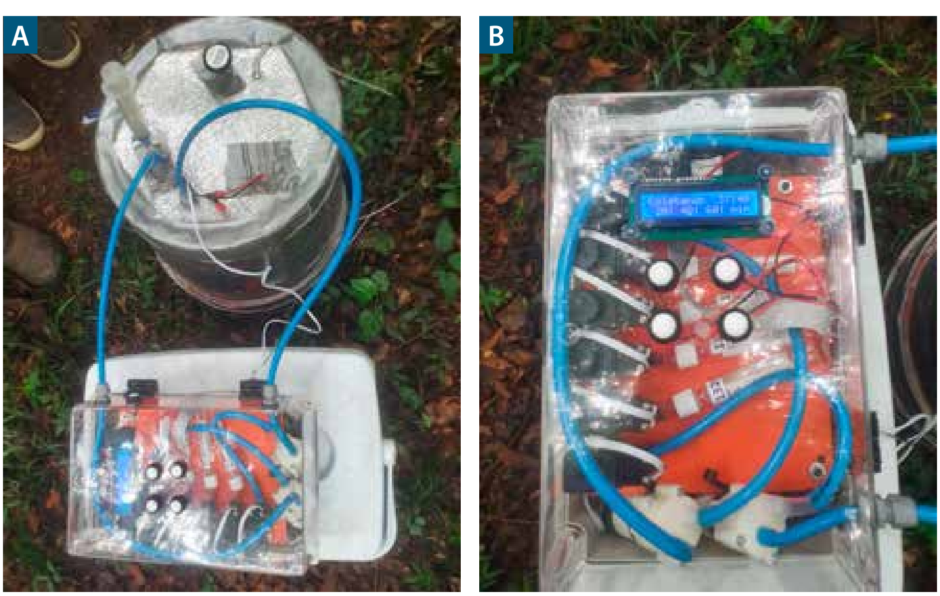


Figure 4.5. Prototype of a semi-automatic system for collecting air samples via static chambers to monitor the flow of greenhouse gases.

methodological limitations, their use has followed internationally established scientific protocols, ensuring the reliability of the data generated. Recent technological advances are already pointing towards more automated and efficient solutions, bringing with them new possibilities for innovation in agricultural GHG monitoring.

Adaptation of the laser spectroscopy technique to measure soil greenhouse gas flows

The measuring equipment incorporates different techniques based on direct absorption spectroscopy, which quantifies the attenuation of a laser beam with a wavelength specific to the gas being monitored. Configurations may vary, such as cavity ring-down spectroscopy (CRDS), cavity attenuated phase shift spectroscopy (CAPS), and off-axis integrated cavity output spectroscopy (OA-ICOS), in which detection of the attenuation rate occurs through the loss of energy from a laser pulse confined within a highly reflective optical cavity, where the gas aspirated from the environment is present. The equipment records the intensity of light before and after it passes through the gas. The difference in intensity (attenuation) is proportional to the concentration of the gas in the optical path.

One major advantage of laser spectroscopy over gas chromatography is its high precision, even at very low concentrations of the GHG, such as nitrous oxide (N_2O). In addition to highly precise measurements, it offers rapid response time. The ability to operate in portable mode is especially useful for studies in remote areas, since there is no need to store or transport samples (Figure 4.6), or even in experiments that require very frequent measurements (Figure 4.7). In this case, the incubation chamber works in closed dynamic mode; in other words, the air circulates through the chamber past the equipment, which records the increase in GHG concentration over time. The angular coefficient of the line, adjusted to the time and concentration data, results in the flow of the gas emitted into the atmosphere.

Multi-channel models can be used to monitor a large number of treatments simultaneously. In the system depicted in Figure 4.7, 15 sampling points are monitored every 2 hours (Ibarr et al., 2021). In addition to spatial coverage, the

Photos: Bruno Alves

Figure 4.6. Off-axis integrated cavity output spectroscopy (OA-ICOS) analyzer for monitoring nitrous oxide (N_2O) and methane (CH_4) flows in soil planted with soybeans, in a greenhouse (A) and in the field (B), both at Embrapa Agrobiology.

Photo: Mariana Ibarr

Photo: Josiléia Zanatta

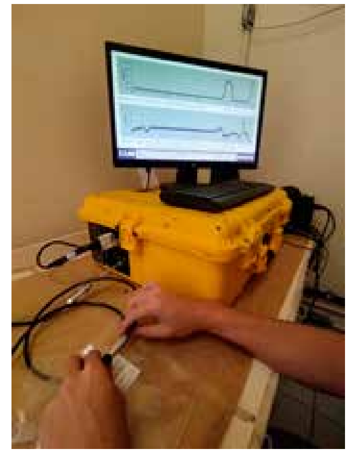
Figure 4.7. Cavity ring-down spectroscopy (CRDS) analyzer for monitoring greenhouse gas flows in soil planted with forest species in a greenhouse (A) and in the field (B), both at Embrapa Forestry.

robustness of the concentration values obtained is undoubtedly the greatest advantage of these laser systems, since gas concentration is measured every 2 seconds and the average concentration of the gas of interest derived from at least 30 measurements. This robustness makes it possible to estimate the flow with fewer collection times (Ibarr et al., 2021).

In general, equipment using this technique operates in dynamic systems. In static mode, the chamber volume must be greater than 50 L to avoid significant negative pressure effects, since one disadvantage of this technique is that it requires samples with larger volume: up to 50 times larger than those used in gas chromatography. Sensitivity to high temperatures presents a problem in tropical environments, which during long routines in the field and especially in summer can mean frequent interruptions due to overheating and the need to shut down. Humidity in the air can also be a problem, but can be avoided by using filters at the external air intake. The equipment is expensive (over USD 180,000), which may limit more widespread use in the country. On the other hand, the robustness of the equipment, which requires practically no maintenance and also does not need calibration gases, greatly reduces the operating costs for research. Technical assistance in this area is still in its infancy in Brazil.

Benchtop mode is an interesting option where the equipment can be operated similar to a gas chromatograph, avoiding exposure to dust, and high humidity and temperatures. It has been used at Embrapa Agrobiology to study flows of N_2O and CH_4 in the soil with the closed static chamber technique. In this case, the sample inside the chamber is removed at every incubation time via a 200 mL syringe attached to a Tedlar-type sample bag (made of highly impermeable plastic material specifically for environmental samples), which provides a volume sufficient for the OA-ICOS laser analyzer (Figure 4.8). The bags replace the syringes and chromatography vials typically used for chromatography sampling and analysis; they are expensive, however (~USD 50.00 per unit), even though they can be reused.

Experience using laser spectroscopy equipment shows that a great deal more sensitivity and precision can be attained, and that even very small soil gas flows can easily be measured. This makes it possible to reduce the number of samples during incubation, and even the time between samples, making the experiment more efficient.



Photos: Bruno Alves

Figure 4.8. Transferring air from the chamber to the Tedlar bag using a 200 mL syringe. Note that an initial aspiration of 10 mL is carried out for flushing, followed by aspiration and transfer of 200 mL of air from the chamber into the bag. The bags are then taken to the laboratory and individually connected to the laser analyzer, where nitrous oxide (N_2O) and methane (CH_4) concentrations are analyzed in approximately 1.5 minutes

Innovative solutions for monitoring greenhouse gas emissions from animals

Livestock farming has been associated with high greenhouse gas (GHG) emissions. At times during discussions on GHG mitigation in ruminant production systems, the relationship between feed efficiency, adequate animal performance, and GHG emissions seems incompatible. However, there are different possibilities for creating sustainable production systems while simultaneously making a profit and producing meat and milk that meet consumer demands and ensure profitability for the farmer, depending on the animal type and species.

Two technologies are particularly important from this perspective: CH_4 emission proficiency testing for cattle, and GHG measurement services for small ruminants using respirometry chambers.

Bovine enteric methane emission proficiency test

This technology called Prova de Emissão de Gases (Proof of Gas Emission, PEG), was launched by Embrapa Southern Livestock and is used to measure the methane gas emitted by European breeds of cattle. The goal is for livestock farmers to be able to use this information to help select breeding stock, combining weight gain and production with lower GHG emissions. PEG testing serves as a tool to improve the efficiency of livestock farming and reduce GHG emissions, and is part of a larger effort to understand and reduce the impact of livestock farming on the climate, solving one of livestock farming's sustainability challenges. It is used to identify animals with lower methane emissions, which can be an important factor in genetic selection, indirectly contributing to the establishment of herds with greater production efficiency and less environmental impact.

The methodology for evaluating enteric methane emissions is now part of the service offered by Embrapa Southern Livestock to assess performance and feed efficiency. The evaluation is conducted on breeding stock of European breeds such as Angus, Charolais, Braford, and Hereford, which are sent to the research unit every year. The process uses the sulfur hexafluoride (SF6) tracer gas technique, as described in a protocol previously established by Embrapa (Berndt et al., 2014). The test seeks to identify the animals with the lowest methane emissions for each kilo of food consumed and per kilo of live weight produced. Enteric methane is one of the main GHGs emitted by livestock farming, and research is working to reduce this environmental impact (Genro et al., 2023).

In addition to combining methane emissions with field tests of feed efficiency, Embrapa Southern Livestock intends to conduct genetic validation of this trait, contributing to a greater understanding of methane production by animals. Livestock production is the main source of methane emissions in Brazil; from the viewpoint of national competitiveness, reducing methane emissions in livestock production and improving feed efficiency rates directly improves the country's image. Preliminary results indicate lower emissions per animal per year than those recommended by the IPCC guidelines (Genro et al., 2023), creating a qualification for these animals and making direct contributions to the decarbonization of Brazilian livestock.

Greenhouse gas measurement service in small ruminants at the Semi-Arid Respirometry Laboratory (LARESA)

In the context of climate change, tests to assess ruminant metabolism using respirometry also help measure GHG emissions, making it possible to develop efficient feed management techniques to mitigate these gases in livestock production systems and supporting development of feed and supplements that provide maximum feed efficiency.

These emissions are measured in respirometry chambers over periods of 21-24 hours per animal. This technique is the gold standard that even can be used to calibrate other equipment, with a view to using other techniques that are also accessible and scalable for field data collection. At Embrapa Goats & Sheep, this technique has been studied and improved for over 16 years. Initial efforts were directed towards equipment calibration to ensure adequate measurements, especially of enteric methane and carbon dioxide. Appropriate models are continually being developed, making it possible to evaluate small ruminants on pasture. Another approach includes the use of portable respirometry chambers that can be transported to the field, as well as the strategy of moving the animals at specific times of day to the locations where the respirometry chambers are installed, allowing measurements to be taken in short periods of time (30 to 60 minutes).

From an economic perspective, this technology has the potential to transform the sector by enabling new feeding practices, providing financial benefits to producers by reducing costs and increasing production efficiency. GHG mitigating diets in association with breed selection for feed efficiency and lower GHG emissions, for example, can be applied in practice by small ruminant producers, field technicians, and nutritionists. An experimental trial at Embrapa Goats & Sheep was able to determine that the use of diets with bioadditives that manipulate rumen fermentation led to a 52% reduction in CH_4 emissions compared to traditional diets. It is therefore possible, based on the assessments made using this methodology, to develop more productive and sustainable livestock systems that help maintain ecosystems in a way that is adaptable to climate change and which progressively improve the efficiency of land and soil use. The research carried out at the Laboratório de Respirometria do Semiárido (Semi-Arid Respirometry Laboratory, LARESA) has resulted in groundbreaking publications and filing of a specific patent on the use of GHG mitigating bioadditives, providing opportunities to interact with both domestic and international companies that produce food inputs and GHG mitigating bioadditives for ruminants (Rogério et al., 2019a, 2019b, 2022; Costa et al., 2020, 2021; Oliveira et al., 2020; Alves et al., 2024).

The resulting instrumentation and methods have been applied in long-term field experiments at Embrapa and in privately owned areas, yielding highly promising results. Advances in research and the growing market demand for GHG (enteric methane and CO_2) analysis have driven the official launch of the service, which will take place at VICTAM LatAm 2025,[3] the largest international trade fair and congress for technology, equipment, ingredients, and additives in this production chain, with a focus on the animal nutrition and grain processing industries. There may be some limitations to the use of the technique in relation to individual variations, but these can be overcome by the need for more numerous repetitions, depending on the variability between readings.

The GHG measurement service for small ruminants has made a significant contribution to national competitiveness in the agricultural sector. In Brazil, there are few structures and services that carry out this type of measurement. By offering this service, Embrapa is making its qualified research environment available to serve as the conduit for measuring the real emissions from livestock farming, adopting sustainable production practices, achieving maximum feed and production efficiency, and reducing risks for producers and industry.

The development of specific mathematical models for quantifying emissions provides greater security and decreases risk for this activity, resulting in added value and increased competitiveness. For the industry, it is a guarantee that the products are more sustainable. For producers, it allows them to have more knowledge about their production, generating additional income and permitting them to enter new markets that value sustainable agricultural practices, strengthening Brazil's position in the global market.

The service can be perceived by those involved as an innovation capable of providing robust data and supported by qualified research which can clarify that Brazilian livestock systems involve environmental sustainability, based on management strategies aimed at maximum efficiency and GHG mitigation. This translates notably into the generation of specific GHG mitigation indices per animal product produced (kilo of carcass or liter of milk, for example), allowing traceability of sustainable production initiatives.

Innovative solutions for monitoring carbon in trees

Traditional forest inventories involve measuring the biophysical parameters of trees in sample plots, such as diameter at breast height (DBH) and total height (Corte et al., 2020). This data is then used in specific allometric equations for species or groups of species to estimate the

3 www.embrapa.br/caprinos-e-ovinos/sead.

biomass of each tree, which is then extrapolated to the total area (Machado et al., 2025). Although field inventories can provide highly accurate estimates at local scales, they are expensive, time-consuming, and laborious, especially for studies that cover large areas or regions that are difficult to access (Corte et al., 2020; Costa et al., 2021). In Brazil, the Inventário Florestal Nacional (National Forest Inventory, IFN) uses this methodology to obtain information on forest resources at a national level. Studies such as Machado et al. (2025) established biomass equations and quantified biomass and carbon stocks in subtropical forests in Paraná, using allometric data collected in the field and preexisting equations for larger trees.

The quantification of carbon stocks is often derived from biomass estimates. For example, aboveground biomass (AGB) in forest ecosystems and agroforestry systems is fundamental for understanding the global carbon cycle, assessing ecosystem health, determining primary productivity, and monitoring biodiversity (Sinha et al., 2016; Machado et al., 2025).

Remote sensing techniques for estimating biomass

The dynamics of growth and mortality, along with biomass losses due to fires or deforestation, directly influence GHG concentrations in the atmosphere (Costa et al., 2021; Machado et al., 2025). Estimating aerial biomass, especially repeatedly and on a large scale, is crucial to develop strategies to mitigate and adapt to climate change in the agriculture and forestry sector that include sustainable forest management, reforestation, and implementation of integrated systems like ICLF (Corte et al., 2020; Lima et al., 2022).

Remote sensing makes it possible to acquire vegetation data on much larger spatial and temporal scales, overcoming some of the limitations of field inventories (Costa et al., 2021; Lima et al., 2022). Different types of sensors and platforms can be used to estimate aerial biomass; these include passive optical sensors like those used on the Landsat and Sentinel-2 satellites, and active sensors such as light detection and ranging (LiDAR) and radio detection and ranging (RADAR). Multispectral optical data makes it possible to calculate vegetation indices (such as NDVI, SAVI, and EVI) that are related to vegetation density, canopy cover, and biomass (Ceddia et al., 2017; Zhou et al., 2022; Bartsch et al., 2025). Minhoni et al. (2021), in a study carried out in agricultural areas in southeastern Brazil, demonstrated that multitemporal analysis of spectral indices derived from Sentinel-2 images can be used to assess soil organic carbon and indirectly provide information on vegetation biomass. However, direct estimation of aerial biomass using optical data alone can be limited by signal saturation in areas of high biomass and sensitivity to atmospheric conditions (Corte et al., 2020). While LiDAR and RADAR involve a similar basic principle (sending and receiving energy pulses), they use different technologies and have different characteristics.

LiDAR can provide detailed information on tree height, canopy structure, vegetation density, and wood volume, parameters that are strongly correlated with biomass (Costa et al., 2021). Studies conducted in Brazil, such as D'Oliveira et al. (2020) in the Amazon and Machado et al. (2025) in subtropical forests, show the potential of airborne LiDAR on board unmanned aerial vehicles (UAVs, popularly known as drones) to estimate aerial biomass with high precision. Machado et al. (2025) used allometric equations and forest inventory data to validate biomass estimates obtained with LiDAR. In tropical savanna ecosystems (Cerrado), Costa et al. (2021) and Machado et al. (2025) demonstrated the ability of UAV-borne LiDAR to estimate total aerial biomass (including trees, shrubs, and undergrowth), highlighting the importance of this technology for carbon monitoring.

The combination of optical remote sensing and LiDAR data can overcome the limitations these individual techniques present, providing more accurate and robust aerial biomass estimates (Zhang et al., 2019; Petropoulos et al., 2025). The integration of canopy surface information obtained by optical sensors with vegetation structural data provided by LiDAR allows for a more complete characterization of biomass (Zhang et al., 2019). Kulawardhana et al. (2014) and Zhang et al. (2019) demonstrated that multiple regression models using combined variables from LiDAR and multispectral vegetation indices perform better in predicting plant biomass than models based on just one of these data sources.

Embrapa has made consistent contributions to the estimation of aerial biomass in Amazonian tropical forests using aerial LiDAR and UAV data, involving innovative methodologies for forest inventory in the Amazon (D'Oliveira et al., 2020) as well as other biomes (Dalla Corte et al., 2022). One example is Embrapa's Netflora, which uses AI algorithms trained on a database of 40,000 hectares mapped by drones to semi-automate the planning and execution of precision forest inventories and spatialize carbon emissions from different land uses in the Amazon. Netflora provides a protocol for acquiring drone data to detect forest species and training AI algorithms according to the phenological calendar to recognize forest species using orthophotos. In this way, it strengthens automation in initial inventories and expands monitoring capabilities for aerial biomass and carbon stocks (Cunha et al., 2019; Queiroz et al., 2023) in precision forest management systems.

To convert aerial biomass into carbon stocks, it is generally assumed that a fixed proportion of the dry biomass (typically around 50%) is composed of carbon (Machado et al., 2025). In this way, estimates of AGB (in tons per hectare or gigagrams) can be multiplied by a conversion factor to obtain equivalent carbon stocks. Machado et al. (2025) estimated carbon stocks in subtropical forests in Paraná using this approach.

Estimating root biomass (below-ground biomass, or BGB) is more challenging, due to the difficulty of directly observing the subsoil. Traditionally, BGB is estimated using root-to-shoot ratio factors (R), which are multiplied by AGB to obtain an estimate of underground biomass (Costa et al., 2021). These R factors can vary widely depending on the species, plant age, environmental conditions, and type of ecosystem (Costa et al., 2021). As a result, the accuracy of BGB estimates based on R factors strongly depends on the availability of specific and representative factors for the study area. Some studies have sought to establish empirical relationships between parameters for aerial components such as DBH, height, crown area, and root biomass using destructive methods or techniques like GPR (Adão et al., 2025), but generalizing these relationships still remains a challenge. Basuki et al. (2009) and Machado et al. (2025) developed allometric equations to estimate AGB and BGB in low-altitude tropical forests, demonstrating the complexity of the relationship between the aerial and subterranean components.

Notable advantages of remote sensing and combined approaches (optical and LiDAR) over traditional forest inventories include:

Extensive spatial coverage: contributes to assessment of biomass over large areas, including remote and difficult-to-access regions.

Repeatability and temporal monitoring: make it possible to monitor changes in biomass over time in response to natural events (growth, fires, storms) or human activities (management, deforestation).

Reduced costs and time: may be more efficient in terms of time and cost compared to intensive field data collection over large areas.

Detailed structural information (LiDAR): provides data on vegetation height and vertical structure, which are strongly related to biomass.

There are also limitations and difficulties associated with the use of remote sensing to estimate aerial biomass, which will be dealt with in the section on future prospects.

The use of remote sensing techniques, especially LiDAR and the combination of optical and LiDAR data, represents a significant advance in data collection for estimating aerial biomass and, in turn, carbon stocks in tree components. These approaches offer the scalability and repeatability needed for large-scale carbon monitoring, contributing to the development of effective climate change adaptation and mitigation strategies in agriculture and forest ecosystems, including the Brazilian context (Costa et al., 2021; Minhoni et al., 2021; Machado et al., 2025). However, it is essential to recognize the limitations and invest in the development of robust methodologies to calibrate, validate, and integrate these techniques with field data in order to obtain increasingly accurate and reliable estimates of aerial and underground biomass.

The SIS family

The SIS family is a set of software programs to support forest management of introduced or exotic species. Embrapa has been developing forest management software since 1988, initially for monocultures, and since 2016 also for ICLF systems. There are currently 25 software applications that are widely used by the Brazilian forestry sector. With these programs it is possible to make forecasts of wood production under present and future conditions, for each climate and soil condition, carry out economic analyses, and then implement the best planting alternative in the field. They permit simulation of how the forest plantation will grow and produce according to the management regimes indicated by the user, and also calculate the carbon captured by the trees.

The models were created using data from continuous inventories and experiments conducted by Embrapa itself and by forestry companies, which provided their forest growth and production inventory databases and tested the software. The software uses the Delphi programming language and is called SIS plus the common name of each specific genus or species in question. The software includes species of *Pinus* and *Eucalyptus*, as well as black acacia, Paraná pine (*Araucaria angustifolia*), bracatinga (*Mimosa scabrella*), Australian cedar, African mahogany, and teak. These solutions provide information to optimize production and expand the producer's income.

Unlike agricultural crops, each individual stand requires specific management to optimize forest production. Thinning practices of different types, intensities, and times and variations in the age at final harvest can affect production. The effect of thinning can also vary, depending on factors such as the industrial use of the wood, site quality (in terms of soil and climate), genetic material, spacing, and plant density. Altering one of these factors changes the ideal management regime and, in turn, the productive potential of the forest. Thinning is one of the most important practices in forest production. Its importance stems from its direct relationship with tree growth. As trees grow in reforestation, competition between them for water, light and nutrients increases, and thinning is conducted to reduce excess competition. The SIS programs make it possible to simulate the effects of thinning and to test any management regime in the stands. To operate the SIS simulators, the user provides the forest inventory data and the software predicts growth and production, indicating how much wood the forest will produce at any given age.

The technology helps define silvicultural treatments such as pruning, immediate or future thinning, or continuing until the final harvest, and considers factors and parameters that lead to optimized forest production and income, depending on the objective. This is a clear example of how technology boosts the efficiency of forestry production, ensuring competitiveness in producing wood products from the forest. The use of software to optimize forest management contributes to the sustainability of the sector, avoiding the waste of resources and promoting efficient management of natural resources.

Another important aspect is that this technology helps reduce agricultural risk, since the simulation makes it possible to create scenarios while considering soil type and climate. This allows users to connect forest production and investments in silvicultural techniques and treatments in line with the site's carrying capacity. Precision forestry makes it possible to manage the forest based on science, making the best use of the site and maximizing income.

The SIS have been well-received by the public, especially in terms of usefulness in strategic planning and forest management. The SIS software helps producers make decisions about planting, thinning, and harvesting, optimizing production and increasing income. Every year there are 4,000 downloads of SIS family software. Embrapa, which is responsible for these products, emphasizes the importance of its ease of use and the ability to simulate various scenarios, allowing producers to analyze different forest management strategies.

Future prospects

Considering the challenges posed by climate change and intensified by GHG emissions, it is crucial for Brazil and the productive sector to monitor and quantify these emissions, along with the carbon stored in different compartments of the environment. Brazil, with its vast territory and strong agricultural sector, plays an important role in both GHG emissions and mitigation. In order to fulfill its international commitments (such as the Paris Agreement) and so that companies and farmers can improve their practices and even be rewarded for sustainable actions, it is essential to be able to measure and monitor carbon storage in the soil and forests and the quantity of GHG emissions and removals, especially in agriculture.

Collecting field data for this purpose, in a country of Brazil's size, is an enormous task. To meet this challenge, Embrapa and its partners have been working to develop and adapt techniques and tools that are more accessible and can be applied on a large scale. The goal is to collect data more efficiently and at a lower cost than traditional methods, which often require significant effort and qualifications and may be invasive. While progress has been significant, there are still challenges to overcome, and areas that need improvement.

Although these new techniques have advanced significantly, there are still aspects that must be refined or improved so that monitoring of carbon stocks and GHG flows in the field (along with other essential variables) can become completely scalable, efficient, and reproducible, permitting the generation of accurate metrics throughout the country.

As for monitoring soil carbon, which is just as important a component as carbon in vegetation, innovative techniques such as the AgLIBS AI and SpecSolo platforms represent a major step forward. They promise faster and cheaper analysis, without the use of chemical reagents and with less waste, making it easier to create carbon and nutrient maps. The acceptance of these techniques to certify carbon credits in voluntary markets is an important step, but standardization and validation on a large scale remain an ongoing task. Integration with other systems to generate real-time information (especially in the case of AgLIBS AI), such as the concept of an autonomous "agricultural rover," is still a prospect to be consolidated in the future.

The "agricultural rover" would be able to roam the countryside, monitoring the soil in real time and connecting this information directly to agricultural operations. This will lead to more intelligent input use, providing economic and environmental benefits.

Remote sensing techniques such as RADAR/SAR and ground penetrating radar (GPR) are also important future prospects for monitoring soil carbon and root biomass. RADAR/SAR makes it possible to cover large areas and operate in adverse weather conditions, while GPR is useful for investigating subsoil structure and roots in a non-destructive manner. However, the relationship between the signal from these technologies and soil carbon is not direct and can be influenced by other factors, requiring complex models. GPR has penetration depth limitations in clayey or wet soils, and specialized knowledge is required to interpret the data. Estimation of root biomass with GPR is still under development. Using machine learning to integrate this data with other information is seen as one way to improve accuracy.

Another crucial point for quantifying carbon stocks in the soil is determining its density. Traditional methods for measuring soil density are laborious, and limit application over large areas. One promising alternative lies in pedotransfer equations (PTFs), which allow density to be estimated from other soil characteristics that are easier to obtain, such as granulometry (sand, silt, clay) and carbon content. Although models based on machine learning perform well, one aspect that requires improvement is the incorporation of variables that better capture the effects of soil structure and landscape conditions (such as relief and climate), which also influence density. Furthermore, developing accurate PTFs at a national level, considering the enormous diversity of soils in Brazil, is a complex challenge that requires large databases and advanced processing methods. Automated probes for collecting undeformed soil samples are also being tested as a way to hasten soil density diagnostics, avoiding the need to dig trenches. While these probes offer great potential to replace traditional methods and permit large-scale collection, systematic studies are still required to validate their accuracy and correspondence with standard methods in different soil types, moisture conditions, and agricultural uses.

Static chambers are the most widely used technique around the world to monitor the flows of GHG released by soils in agriculture. But they involve complex and labor-intensive field collection, which limits the number of measurements and the frequency of monitoring, and makes it difficult to carry out more comprehensive studies over space and time. Semi-automatic sample collection systems have been developed to expand collection capacity in the field. The laser spectroscopy technique for measuring GHGs in soil permits quick responses and portable operations, but is sensitive to high temperatures and requires larger sample volumes than gas chromatography. Furthermore, technical assistance for equipment based on laser spectroscopy is still nascent in Brazil.

Measuring GHG emissions from animals (such as enteric methane from cattle and small ruminants) also presents challenges in terms of scale. Although respirometry chambers are considered the "gold standard" for precise measurements, they are laborious and restricted to a small scale. Making this measurement accessible and scalable for large numbers of animals and direct use on farms still remains an obstacle. Qualified services for this measurement are starting to become available in Brazil, using the SF6 tracer gas technique. This type of service and the environments in which it is offered need to be expanded in order to cover the main conditions involved in the production systems present in the country, and for different categories of animals, breeds, age, etc.

Finally, quantifying the carbon stored in tree components, which is essential for understanding the carbon cycle, also faces challenges of scale. While traditional forest inventories are locally accurate, they are expensive and slow for large areas. Remote sensing, including LiDAR and satellite imagery, offers a more time- and cost-efficient alternative for monitoring biomass on a large scale, but has some limitations, such as signal saturation in dense areas (in optical data) and the cost of acquiring and processing LiDAR data. The creation of techniques like Netflora, which are based on artificial intelligence and sensors, to support forest inventories and map emissions requires collection of specific data, such as drone images. It is also essential to train models using representative, robust databases in order to ensure accuracy in the analyses.

All in all, while Brazil is making progress in developing and adapting innovative techniques and tools to collect and monitor field data for climate and environmental management in agriculture and forestry, much work still remains to make these solutions fully accessible, scalable, and validated in all of the country's diverse conditions. Improving the accuracy of predictions, validating new methodologies (such as automated probes), and overcoming the scale limitations of methods including GHG chambers and animal respirometry are ongoing challenges. Furthermore, the use of remote sensing data must be refined and integrated with other information. Tackling these issues will require continuous investments in research and infrastructure. Overcoming these barriers is fundamental if Brazil is to effectively monitor its carbon stocks and GHG emissions on a large scale, supporting both national commitments and the needs of the productive sector for increasingly sustainable and competitive production. The aim is to have accessible, accurate, and reliable monitoring tools that support the climate goals of the country, the productive sector, and sustainable management of natural resources.

References

ABDELBAKI, A. M. Evaluation of pedotransfer functions for predicting soil bulk density for U.S. soils. **Ain Shams Engineering Journal**, v. 9, n. 4, p. 1611-1619, 2018. DOI: http://dx.doi.org/10.1016/j.asej.2016.11.008.

ADÃO, F.; PÁDUA, L.; SOUSA, J. J. Evaluating Soil Degradation in Agricultural Soil with Ground-Penetrating Radar: A Systematic Review of Applications and Challenges. **Agriculture**, v. 15, n. 8, p. 852, 2025. DOI: http://dx.doi.org/10.3390/agriculture15080852.

AL-QINNA, M. I.; JABER, S. M. Predicting soil bulk density using advanced pedotransfer functions in an arid environment. **Transactions of the ASABE**, v. 56, n. 3, p. 963-976, 2013. DOI: https://doi.org/10.13031/trans.56.9922.

ALVES, B. J. R.; SCIVITTARO, W. B.; JANTALIA, C. P.; SOUSA, R. O. de; BAYER, C.; RODRIGUES, R. de A. R.; BODDEY, R. M.; URQUIAGA, S.; MADARI, B. E. **Protocolo para medições de fluxos de gases de efeito estufa em sistemas aeróbicos e alagados de produção de grãos - Rede Fluxus**. Seropédica: Embrapa Agrobiologia, 2017. (Embrapa Agrobiologia. Documentos, 306). Available at: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/161925/1/DOC306-PROTOCOLO-MEDICOES-DE-FLUXOS-DE-GASES.pdf. Accessed: 10 Oct. 2023.

ALVES, F. G. da S.; CARNEIRO, M. S. de S.; COSTA, C. dos S.; GUEDES, L. F.; OLIVEIRA, D. de S.; MARTINS, E. C.; POMPEU, R. C. F. F.; ROGERIO, M. C. P. Economic and financial viability of the production of Brazilian somalis sheep fed with different nutritional plans. **Tropical Animal Health and Production**, v. 56, p. 231, 2024. DOI: http://dx.doi.org/10.1007/s11250-024-04014-w.

BABOS, D. V.; GUEDES, W. N.; FREITAS, V. S.; SILVA, F. S.; TOZO, M. L. L.; VILLAS-BOAS, P.; MARTIN-NETO, L.; MILORI, D. M. B. P. Laser-induced breakdown spectroscopy as an analytical tool for total carbon quantification in tropical and subtropical soils: evaluation of calibration algorithms. **Frontiers in Soil Science**, v. 3 (1242647), p. 1-14, 2024a. DOI: http://dx.doi.org/10.3389/fsoil.2023.1242647.

BARROS, H. S.; FEARNSIDE, P. M. Pedo-transfer functions for estimating soil bulk density in central Amazonia. **Revista Brasileira Ciência do Solo**, v. 39, p. 397-407, 2015. }DOI: http://dx.doi.org/10.1590/01000683rbcs20140358.

BARTSCH, B. D. A.; ROSIN, N. A.; ROSAS, J. T. F.; POPPIEL, R. R.; MAKINO, F. Y.; VOGEL, L. G.; NOVAIS, J. J. M.; FALCIONI, R.; ALVES, M. R.; DEMATTÊ, J. A. M. Space-time mapping of soil organic carbon through remote sensing and machine learning. **Soil and Tillage Research**, v. 248, art. 106428, p. 1-14, 2025. DOI: http://dx.doi.org/10.1016/j.still.2024.106295.

BASUKI, T. M.; VAN LAAKE, P. E.; SKIDMORE, A. K.; HUSSIN, Y. A. Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. **Forest Ecology and Management**, v. 257, n. 8, p. 1684-1694, 2009. DOI: https://doi.org/10.1016/j.foreco.2009.01.027.

BENITES, V. M.; MACHADO, P. L. O. A; FIDALGO, E. C. C; COELHO, M. R.; MADARI, B. E. Pedotransfer functions for estimating soil bulk density from existing soil survey reports in Brazil. **Geoderma**, v. 139, n. 1-2, p. 90-97, 2007. DOI: https://doi.org/10.1016/j.geoderma.2007.01.005.

BERNDT, A.; PEDROSO, A. de F.; PEREIRA, L. G. R.; RODRIGUES, P. H. M.; ALMEIDA, R. G. de; GUIMARAES JUNIOR, R.; FRIGHETTO, R. T. S.; OLIVEIRA, P. P. A. **Diretrizes para avaliação da emissão de metano entérico com a técnica do gás traçador SF6**. São Carlos, SP: Embrapa Pecuária Sudeste, 2014. 19 p. (Embrapa Pecuária Sudeste. Documentos, 117). Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1024608/1/Diretrizesparaavaliacaodaemissaodemetano.pdf. Accessed: 10 Oct. 2023.

BERNOUX, M.; CERRI, C.; ARROUAYS, D.; JOLIVET, C.; VOLKOFF, B. Bulk densities of Brazilian Amazon Soils related to other soil properties. **Soil Science Society American Journal**, v. 62, n. 3, p. 743-9, 1998. DOI: https://doi.org/10.2136/sssaj1998.03615995006200030029x.

BEUTLER, S. J.; PEREIRA, M. G.; TASSINARI, W. D. S.; MENEZES, M. D.; VALLADARES, G. S.; ANJOS, L. H. C. Bulk density prediction for histosols and soil horizons with high organic matter content. **Revista Brasileira Ciência do Solo**, v. 41, e0160158, p. 1-13, 2017. DOI: https://doi.org/10.1590/18069657rbcs20160158.

BOSCHI, R. S.; LOPES-ASSAD, M. L. R. C.; SOUZA, G. P. S.; CIDIN, A. C. M.; ASSAD, E. D. Efeito de estimativa de densidade do solo no cálculo de estoque de carbono. **Revista Ciência, Tecnologia e Ambiente**, v. 2, n. 1, p. 8-16, 2015.

BOTULA, Y. D.; NEMES, A.; VAN RANST, E.; MAFUKA, P.; PUE. J.; CORNELIS, W. M. Hierarchical pedotransfer functions to predict bulk density of highly weathered soils in Central Africa. **Soil Science Society American Journal**, v. 79, n. 2, p. 476-86, 2015. DOI: https://doi.org/10.2136/sssaj2014.06.0238.

BRASIL. Ministério da Agricultura e Pecuária. **Coletânea de fatores de emissão e remoção de gases efeito estufa da pecuária brasileira**. In: SOTTA, E. D.; SAMPAIO, F. G.; COSTA, M. S. N. (org.). Brasília, DF: Mapa/Senar, 2020. Available at: https://www.gov.br/agricultura/pt-br/assuntos/sustentabilidade/planoabc-abcmais/publicacoes/coletanea-gee-pecuaria_web.pdf/view. Accessed: 10 Oct. 2023.

BRASIL. Ministério da Ciência, Tecnologia e Inovações. **Brazil´s national inventory report of anthropogenic emissions by sources and removals by sinks of greenhouse gases**: Brazil's National Inventory Report 1990-2022. Brasília, DF: MCTI, 2024a. Available at: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/publicacoes/relatorios-bienais-de-transparencia-btrs/BRA_NIR_2024_ENG.pdf. Accessed: 15 Jan. 2025.

BRASIL. Ministério da Ciência, Tecnologia e Inovações. **Quarta Comunicação Nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima**. Brasília, DF: MCTI, 2021. Disponível em: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/publicacoes/comunicacoes-nacionais-do-brasil-a-unfccc/arquivos/4comunicacao/4_com_nac_brasil_web.pdf. Accessed: 10 Oct. 2023.

BRASIL. Ministério da Ciência, Tecnologia e Inovações. **Sistema de Registro Nacional de Emissões (SIRENE)**. Brasília, DF: MCTI, 2024b. Available at: https://sirene.mcti.gov.br/. Accessed: 10 Jul. 2024.

BUBLITZ, J.; DÖLLE, C.; SCHADE, W.; HARTMANN, A.; HORN, R. Laser-induced breakdown spectroscopy for soil diagnostics. **European Journal of Soil Science**, v. 52, n. 2, p. 305-312, 2001. DOI: https://doi.org/10.1046/j.1365-2389.2001.00375.x.

CÁSSARO, F. A. M.; TOMINAGA, T. T.; BACCHI, O. O. S.; REICHARDT, K.; OLIVEIRA J. C. M.; TIMM, L. C. Improved laboratory calibration of a single-probe surface gamma-neutron gauge. **Australian Journal of Soil Research**, v. 38, n. 5, p. 937-946, 2000a.

CÁSSARO, F. A. M.; TOMINAGA, T. T.; BACCHI, O. O. S.; REICHARDT, K.; OLIVEIRA J. C. M.; TIMM, L. C. The use of a surface gamma-neutron gauge to explore compacted layers. **Soil Science**, v. 165, n. 8, p. 665-676, 2000b. DOI: https://doi.org/10.1097/00010694-200008000-0000.8.

CEDDIA, M.; GOMES, A.; VASQUES, G.; PINHEIRO, É. Soil Carbon Stock and Particle Size Fractions in the Central Amazon Predicted from Remotely Sensed Relief, Multispectral and Radar Data. **Remote Sensing**, v. 9, n. 2, p. 1-19, 2017. DOI: https://doi.org/10.3390/rs9020124.

CHEN, S.; CHEN, Z.; ZHANG, X.; LUO, Z.; SCHILLACI, C.; ARROUAYS, D.; RICHER-DE-FORGES, A. N.; SHI, Z. European topsoil bulk density and organic carbon stock database (0-20 cm) using machine-learning-based pedotransfer functions. **Earth System Science Data**, v. 16, n. 5, p. 2367-2383, 2024. DOI: https://doi.org/10.5194/essd-16-2367-2024.

CHOUDHURY, B. U.; SANTRA, P.; SINGH, N.; CHAKRABORTY, P. Development of land-use-specific pedotransfer functions for predicting bulk density of acidic topsoil in eastern Himalayas (India). **Geoderma Regional**, v. 34, e00671, p. 1-13, 2023. DOI: https://doi.org/10.1016/J.GEODRS.2023.E00671.

COELHO, M. R.; DEMATTÊ, J. A. M.; PEREIRA, G. E.; LIESENBERG, V. Espectroscopia de Visível e Infravermelho Próximo (Vis-NIR) para predição de atributos de solos. **Revista Brasileira de Ciência do Solo**, v. 42, e0170068, 2018. DOI: https://doi.org/10.1590/S0100-29452011000500038.

CORTE, A. P. D.; SOUZA, D. V.; REX, F. E.; SANQUETTA, C. R.; MOHAN, M.; SILVA, C. A.; ZAMBRANO, A. M. A.; PRATA, G.; ALVES DE ALMEIDA, D. R.; TRAUTENMÜLLER, J. W.; KLAUBERG, C.; MORAES, A. de; SANQUETTA, M. N.; WILKINSON, B.; BROADBENT, E. N. Forest inventory with high-density UAV-Lidar: Machine learning approaches for predicting individual tree attributes. **Computers and Electronics in Agriculture**, v. 179, 105815, p. 1-14, 2020. DOI: https://doi.org/10.1016/j.compag.2020.105815.

COSTA, C. dos S.; ROGÉRIO, M. C. P.; ALVES, F. G. da S.; GUEDES, L. F.; POMPEU, R. C. F. F.; FERREIRA, A. L.; VASCONCELOS, A. M. de; MUIR, J. P.; NEIVA, J. J. M. Dietary nutrient restrictions in the post-weaning period change feed efficiency and productivity of Santa Inês ewe lambs. **Animal Production Science**, v. 60, n. 17, p. 1978-1986, 2020. DOI: https://doi.org/10.1071/AN19300.

COSTA, C. dos S.; ROGÉRIO, M. C. P.; FERREIRA, A. L.; MACHADO, F. S.; POMPEU, R. C. F. F.; ALVES, F. G. da S.; RÊGO,

J. P. A. do; PIMENTEL, P. G.; MUIR, J. P.; NEIVA, J. J. M. Dietary nutrient restrictions in the post-weaning period change Santa Inês ewe lamb nutritional metabolic profile. **Tropical Animal Health and Production**, v. 53, n. 3, article number 359, 2021. DOI: https://doi.org/10.1007/s11250-021-02767-3.

COSTA, M. B. T. da; SILVA, C. A.; BROADBENT, E. N.; LEITE, R. V.; MOHAN, M.; LIESENBERG, V.; STODDART, J.; DO AMARAL, C. H.; DE ALMEIDA, D. R. A.; DA SILVA, A. L.; RÉ Y. GOYA, L. R.; CORDEIRO, V. A.; REX, F.; HIRSCH, A.; MARCATTI, G. E.; CARDIL, A.; MENDONÇA, B. A. F. de; HAMAMURA, C.; CORTE, A. P. D.; KLAUBERG, C. Beyond trees: Mapping total aboveground biomass density in the Brazilian savanna using high-density UAV-lidar data. **Forest Ecology and Management**, v. 491, 1151195, p. 1-15, 2021. DOI: https://doi.org/10.1016/j.foreco.2021.119155.

COSTA, M. G.; REX, F. E.; SANQUETTA, C. R.; DALLA CORTE, A. P.; MELO, L. C.; ROCHA, M. P.; ALMEIDA, J. R. V. de. Mapeamento de biomassa florestal utilizando LiDAR embarcado em VANT: estudo de caso em plantio de *Pinus*. **Revista Árvore**, v. 47, e470404, 2023.

CREMERS, D. A.; RADZIEMSKI, L. J. **Handbook of laser induced breakdown spectroscopy**. Oxford, England: John Wiley & Sons, 2013. 418 p. DOI: https://doi.org.10.1002/9781118567371.

CUNHA, J. M.; GAIO, D. C.; CAMPOS, M. C. C.; SOARES, M. D. R.; SILVA, D. M. P.; LIMA, A. F. L. Atributos físicos e estoque de carbono do solo em áreas de terra preta arqueológica da Amazônia. **Revista. Ambiente e Água**, v. 12, n. 2, p. 263-281, 2017. DOI: https://doi.org/10.4136/ambi-agua.1890.

CUNHA, R. M. da; ORFANÓ, E. F.; D'OLIVEIRA, M. V. N.; PAPA, D. de A. Estimativa da perda de biomassa em área de manejo florestal sustentável na Amazônia por meio da combinação de dados lidar e câmeras RGB a bordo de aeronave remotamente pilotada (ARP). In: SIMPÓSIO BRASILEIRO DE SENSORIAMENTO REMOTO, 19., Santos. **Anais** [...] Santos: Galoá Procedings, 2019. Available at: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/198851/1/26805.pdf. Accessed: 24 Apr. 2025.

DALAL, R. C.; WANG W.; ROBERTSON G. P.; PARTON W. J. Nitrous oxide emission from Australian agricultural lands and mitigation options, a review. **Australian Journal Soil Research**, v. 41, n. 2, p.165-195, 2003. DOI: https://doi.org/10.1071/SR02064.

DALLA CORTE, A. P. SANQUETTA, C. R.; MENDONÇA, A. R. Tecnologia LiDAR aplicada a inventários florestais: métodos e estudos de caso. In: SILVA, J. R. M.; MARTINS, F. B. (org.). **Inovações em Inventário e Manejo Florestal**. Curitiba: Ed da UFPR, 2022. p. 45-78.

DENG, O.; LI, X.; DENG, L.; ZHANG, S.; GAO, X.; LAN, T.; ZHOU, W.; TIAN, D.; XIAO, Y.; YANG, J.; OU, D.; LUO, L. Emission of CO2 and CH4 from a multi-ditches system in rice cultivation region: Flux, temporal-spatial variation and effect factors. **Journal of Environmental Management**, v. 270, 110918, 2020. DOI: https://doi.org/10.1016/j.jenvman.2020.110918.

D'OLIVEIRA, M. V. N.; BROADBENT, E.; OLIVEIRA, L. C.; ALMEIDA, D. R. A.; PAPA, D. A.; FERREIRA, M. E.; ZAMBRANO, A. M. A.; SILVA, C. A.; AVINO, F. S.; PRATA, G. A.; MELLO, R. A.; FIGUEIREDO, E. O.; JORGE, L. A. de C.; LEOMAR JUNIOR; ALBUQUERQUE, R.; BRANCALION, P. H. S.; WILKINSON, B.; OLIVEIRA-DA-COSTA, M. Aboveground Biomass Estimation in Amazonian Tropical Forests: A Comparison of Aircraft- and GatorEye UAV-borne LIDAR Data in the Chico Mendes Extractive Reserve in Acre, Brazil. **Remote Sensing**, v. 12, n. 11, p. 754, 2020. DOI: https://doi.org/10.3390/rs12111754.

DORICH, C. D.; VARADARAJAN, S.; PANTOJA, J. L.; HRISTOV, A. N. Short communication: Use of a portable automated open-circuit gas quantification system and the sulfur hexafluoride tracer technique for measuring enteric methane emissions in Holstein cows fed ad libitum or restricted. **Journal of Dairy Science**, v. 98, n. 4, p. 2676-2681, 2015. DOI: https://doi.org/10.3168/jds.2014-8468.

EL-JAMAOUI, I.; DELGADO-INIESTA, M. J.; MARTÍNEZ SÁNCHEZ, M. J.; PÉREZ SIRVENT, C.; MARTÍNEZ LÓPEZ, S. Assessing Soil Organic Carbon in Semi-Arid Agricultural Soils Using UAVs and Machine Learning: A Pathway to Sustainable Water and Soil Resource Management. **Sustainability**, v. 17, n. 8, p. 3440, 2025. DOI: https://doi.org/10.3390/su17083440.

FAO. **A protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes**: GSOC-MRV protocol. Rome, 2020. 140 p. Available at: https://doi.org/10.4060/cb0509en. Accessed: 25 Mar. 2025.

FERREIRA, F. A. GIONGO, M., KOEHLER, H. S.; MACHADO, S. A.; KIRCHNER, F. F.; MARCHETTI, M. Aplicação de VANTs e LiDAR para a caracterização da estrutura de florestas nativas no Cerrado. **Pesquisa Florestal Brasileira**, v. 42, n. 172, e202202214, 2022.

FONTANA, A.; BIANCHI, S. R. Carbono e nitrogênio total: analisador elementar. In: TEIXEIRA, P. C.; DONAGEMMA, G. K.; FONTANA, A.; TEIXEIRA, W. G. (ed.). **Manual de métodos de análise de solo.** 3. ed. rev. e ampl. Brasília, DF: Embrapa, 2017. p. 393-396. Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1107200/1/Pt3Cap4Carbonoenitrogeniototal.pdf. Accessed: 10 Jul. 2024.

FONTANA, A.; CAMPOS, D. V. B. de. Carbono orgânico. In: TEIXEIRA, P. C.; DONAGEMMA, G. K.; FONTANA, A.; TEIXEIRA, W. G. (ed.). **Manual de métodos de análise de solo**. 3. ed. rev. e ampl. Brasília, DF: Embrapa, 2017. p. 360-367. Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1107196/1/Pt3Cap1Carbonoorganico.pdf. Accessed: 10 Jul. 2024.

FONTANA, A.; MACEDO, M. C. M.; TEIXEIRA, W. G.; BALIEIRO, F. de C. (ed.). **Protocolo para coleta de amostras e quantificação do carbono no solo da agricultura de baixo carbono**. Rio de Janeiro: Embrapa Solos, 2024. 30 p. (Embrapa Solos. Documentos, 243). Documentos. Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1169442/1/CNPS-DOC-243-2024.pdf. Accessed: 22 Feb. 2025.

GENRO, T. C. M.; LARA, D. M. de; LAMPERT, V. do N. **Análise das emissões de metano entérico do rebanho de bovinos de corte do Rio Grande do Sul**. Bagé: Embrapa Pecuária Sul, 2023. 12 p. (Embrapa Pecuária Sul. Comunicado técnico, 109). Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1158126/1/CT-109-Online.pdf. Accessed: 22 Feb. 2025.

GOMES, A. S.; FERREIRA, A. C. S.; PINHEIRO, E. F. M.; MENEZES, M. D.; CEDDIA, M. B. The use of Pedotransfer functions and the estimation of carbon stock in the Central Amazon region. **Scientia Agricola**, v. 74, n. 6, p. 450-460, 2017. DOI: https://doi.org/10.1590/1678-992X-2016-0310.

HAMMOND, K. J.; BURKE, J. L.; KOOLAARD, J. P.; MUETZEL, S.; PINARES-PATIÑO, C. S.; WAGHORN, G. C. The GreenFeed system for measurement of enteric methane emissions from cattle. **Animal Production Science**, v. 56, n. 3, p. 181-189, 2015. DOI: https://doi.org/10.1071/AN15631.

HAN, G. Z.; ZHANG, G. L.; GONG, Z. T.; WANG, G. F. Pedotransfer functions for estimating soil bulk density in China. **Soil Science**, v. 177, n. 3, p. 158-164, 2012. DOI: https://doi.org/10.1097/SS.0b013e31823fd493.

HAYNES, R. J. Labile organic matter fractions as central components of the quality of agricultural soils: An overview. **Advances in Agronomy,** v. 85, p. 221-268, 2005. DOI: https://doi.org/10.1016/S0065-2113(04)85005-3.

HEUSCHER, S. A.; BRANDT, C. C.; JARDINE, P. M. Using soil physical and chemical properties to estimate bulk density. **Soil Science Society American Journal**, v. 69, n. 1, p. 51-56, 2014. DOI: https://doi.org/10.2136/sssaj2005.0051a.

HUNGRIA, M.; VARGAS, M. A. T. Environmental factors affecting N_2 fixation in grain legumes in the tropics, with an emphasis on Brazil. **Field Crops Research**, v. 65, n. 2-3, p. 151-164, 2000. DOI: https://doi.org/10.1016/S0378-4290(99)00084-2.

HUTCHINSON, G. L.; ROCHETTE, P. Non-flow-through steady-state chambers for measuring soil respiration. numerical evaluation of their performance. **Soil Science Society of America Journal**, v. 67, n. 1, p. 166-180, 2003. DOI: https://doi.org/10.2136/sssaj2003.1660.

IBARR, M. A.; ZANATTA, J. A.; DIECKOW, J.; RIBEIRO, R. H.; RACHWAL, M. F. G.; STAHL, J. Nitrous oxide and methane emissions from soil and nitrogen uptake by eucalyptus fertilized with enhanced efficiency fertilizers. **Plant and Soil**, v. 463, n. 1-2, p. 615-630, 2021. DOI: https://doi.org/10.1007/s11104-021-04938-5.

JANTALIA, C. P.; SANTOS, H. P. dos; URQUIAGA, S.; BODDEY, R. M.; ALVES, B. J. R. Fluxes of nitrous oxide from soil under different crop rotations and tillage systems in the South of Brazil. **Nutrient Cycling in Agroecosystems**, v. 82, n. 2, p. 161-173, 2008. DOI: https://doi.org/10.1007/s10705-008-9178-y.

JOL, H. M. **Ground penetrating radar**: Theory and applications. . [S.l.]: Elsevier Science, 2009. 524 p. DOI: https://doi.org/10.1016/B978-0-444-53348-7.X0001-4.

KULAWARDHANA, R. W.; POPESCU, S. C.; FEAGIN, R. A. Fusion of lidar and multispectral data to quantify salt marsh carbon stocks. **Remote Sensing of Environment**, v. 154, p. 345-357, 2014. DOI: http://dx.doi.org/10.1016/j.rse.2013.10.036.

LA SCALA, N.; MARQUES JÚNIOR, J.; PEREIRA, G. T.; CORÁ, J. E. Short-term temporal changes in the spatial variability model of CO2 emissions from a Brazilian bare soil. **Soil Biology and Biochemistry**, v. 32, n. 10, p. 1537-1542, 2000. DOI: 10.1016/S0038-0717(00)00051-1.

LIBEL, G.; LATINI, I. P.; HERCULES, M. C. **Sistema de coleta automatizada de amostras de ar para análise da concentração de gases de efeito estufa do solo**. 2021. 93 f. Trabalho de Conclusão de Curso (Bacharelado em Engenharia da Computação) – Universidade Tecnológica Federal do Paraná, Curitiba.

LIMA, A. A. J.; LOPES, J. C.; LOPES, R. P.; DE FIGUEIREDO, T.; VIDAL-VÁZQUEZ, E.; HERNÁNDEZ, Z. Soil Organic Carbon Assessment Using Remote-Sensing Data and Machine Learning: A Systematic Literature Review. **Remote Sensing**, v. 17, n. 5, 882, 2025. DOI: https://doi.org/10.3390/rs17050882.

LIMA, G. S. A. de; FERREIRA, M. E.; MADARI, B. E.; CARVALHO, M. T. D. M. Carbon estimation in an integrated crop-livestock system with imaging sensors aboard unmanned aerial platforms. Remote Sensing Applications: **Society and Environment**, v. 28, e100867, 2022. DOI: https://doi.org/10.1016/j.rsase.2022.100867.

MACHADO, H. A.; MALLMANN, A. A.; ENGEL, K.; FAVARIN, J. A. S.; MODESTO, J. L. C.; SANQUETTA, C. R.; DALLA CORTE, A. P.; KOEHLER, H. S.; PÉLLICO NETTO, S.; BEHLING, A.; TRAUTENMÜLLER, J. W. Aboveground biomass and carbon stocks in subtropical forests. **Ecological Indicators**, v. 172, 113294, p. 1-14, 2025. DOI: https://doi.org/10.1016/j.ecolind.2025.113294.

MAPBIOMAS. **Coleção 9 do MapBiomas da Série Anual de Mapas de Cobertura e Uso da Terra do Brasil**. 2024. Available at: https://plataforma.brasil.mapbiomas.org/cobertura. Accessed: 6 May 2025.

MILORI, D. M. B. P.; SEGNINI, A.; SILVA, W. T. L. da; POSADAS, A.; MARES, V.; QUIROZ, R.; MARTIN-NETO, L. **Emerging techniques for soil carbon measurements**. Copenhagen, Denmark: CCAFS, 2011. 30 p. DOI: http://hdl.handle.net/10568/10279.

MINHONI, R. T. D. A.; SCUDIERO, E.; ZACCARIA, D.; SAAD, J. C. C. Multitemporal satellite imagery analysis for soil organic carbon assessment in an agricultural farm in southeastern Brazil. **Science of The Total Environment**, v. 784, 147216, p. 1-12, 2021. DOI: https://doi.org/10.1016/j.scitotenv.2021.147216.

NANKO, K.; UGAWA, S.; HASHIMOTO, S.; IMAYA, A.; KOBAYASHI, M.; SAKAI, H.; ISHIZUKA, S.; MIURA, S.; TANAKA, N.; TAKAHASHI, M.; KANEKO, S. A pedotransfer function for estimating bulk density of forest soil in Japan affected by volcanic ash. **Geoderma**, v. 213, p. 36-45, 2014. DOI: https://doi.org10.1016/j.geoderma.2013.07.025.

NELSON, D. W.; SOMMERS, L. E. Total carbon, organic carbon, and organic matter. In: SPARKS, L.; PAGE, A. L.; HELMKE, P. A.; LOEPPERT, R. H.; SOLTANPOUR, P. N.; TABATABAI, M. A.; JOHNSTON, C. T.; SUMNER, M. E. (ed.). **Methods of soil analysis**: part 3 chemical methods. Madison: American Society of Agronomy, 1996. p. 961-1010.

NICOLODELLI, G.; MARANGONI, B. S.; CABRAL, J. S.; VILLAS-BOAS, P. R.; SENESI, G. S.; SANTOS, C. H.; ROMANO, R. A.; SEGNINI, A.; LUCAS, Y.; MONTES, C. R.; MILORI, D. M. B. P. Quantification of total carbon in soil using laser-induced breakdown spectroscopy: a method to correct interference lines. **Applied Optics**, v. 53, n. 10, p. 2170-2176, 2014. DOI: https://doi.org10.1364/ao.53.002170.

OBIDIKE-UGWU, E. O.; OGUNWOLE, J. O.; EZE, P. N. Derivation and validation of a pedotransfer function for estimating the bulk density of tropical forest soils. Modeling **Earth Systems and Environment**, v. 9, n. 1, p. 801-809, 2023. DOI: https://doi.org10.1007/s40808-022-01531-2.

OLIVEIRA, D. S.; ALVES, A. A.; ROGÉRIO, M. C. P.; POMPEU, R. C. F. F.; PEREIRA, E. S.; AZEVEDO, D. M. M. R.; GUEDES, L. F.; COSTA, C. dos S.; MUIR, J. P. Influence of nutrient restriction on finishing Morada Nova lambs. **Tropical Animal Health and Production**, v. 52, n. 6, p. 3509-3518, 2020. DOI: https://doi.org10.1007/s11250-020-02385-5.

OLIVEIRA, P. P. A. (ed.). **Protocolo para quantificação dos estoques de carbono do solo da Rede de Pesquisa Pecus**. São Carlos, SP: Embrapa Pecuária Sudeste, 2014. 20 p. (Embrapa Pecuária Sudeste. Documento, 116). Available at: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/117416/1/Documentos116.pdf. Accessed: 25 Feb. 2025.

PALLADINO, M.; ROMANO, M.; PASOLLI, E.; NASTA, P. Developing pedotransfer functions for predicting soil bulk density in Campania. **Geoderma**, v. 412, 115726, p. 1-14, 2022. DOI: https://doi.org/10.1016/j.geoderma.2022.115726.

PARKIN, T. B.; VENTEREA, R. T. Chamber-based Trace Gas Flux Measurements. In: FOLLETT, R.F. (ed.). **Sampling Protocols. USDA**, 2010. p. 3-39. Available at: http://www.ars.usda.gov/SP2UserFiles/Program/212/Chapter%203.%20GRACEnet%20Trace%20Gas%20Sampling%20Protocols.pdf. Accessed: 21 May 2015.

PETROPOULOS, T.; BENOS, L.; BUSATO, P.; KYRIAKARAKOS, G.; KATERIS, D.; AIDONIS, D.; BOCHTIS, D. Soil Organic Carbon Assessment for Carbon Farming: A Review. **Agriculture**, v. 15, n. 5, 567, 2025. DOI: https://doi.org/10.3390/agriculture15050567.

PIRES, L. F.; BORGES, J. A. R.; BACCHI, O. O. S.; REICHARDT, K. Twenty-five years of computed tomography in soil physics: A literature review of the Brazilian contribution. **Soil and Tillage Research**, v. 110, n. 2, p. 197-210, 2010. DOI: https://doi.org/10.1016/j.still.2010.07.013.

QUEIROZ, R. F. P. de; D'OLIVEIRA, M. V. N.; REZENDE, A. V.; ALENCAR, P. A. L. de. Estimation of Aboveground Biomass Stock in Tropical Savannas Using Photogrammetric Imaging. **Drones**, v. 7, n. 8, 423, 2023. DOI: https://doi.org/10.3390/drones7080493.

RAMCHARAN, A.; HENGL, T.; BEAUDETTE, D.; WILLS, S. A soil bulk density pedotransfer function based on machine learning: A case study with the NCSS Soil characterization database. **Soil Science Society of America Journal**, v. 81, p. 1279-1287, 2017. DOI: https://doi.org/10.2136/sssaj2016.12.0421.

REIS, A. M. H.; TEIXEIRA, W. G. T.; FONTANA, A.; BARROS, A. H. C.; VICTORIA, D. C.; VASQUES, G. M.; SAMUEL-ROSA, A.; OTTONI, M. V.; MONTEIRO, J. E. B. A. Hierarchical pedotransfer functions for predicting bulk density in Brazilian. **Scientia Agricola**, v. 81, e20220255, 2024. DOI: https://doi.org/10.1590/1678-992X-2022-0255.

ROGÉRIO, M. C. P.; BORGES, I.; FERREIRA, A. L.; MACHADO, F. S.; POMPEU, R. C. F. F.; GUEDES, L. F.; COSTA, C. dos S.; GUEDES, F. L.; GALVANI, D. B. **Especificações padrões para mensurações de gases de efeito estufa e metabolismo de pequenos ruminantes no bioma Caatinga**. Sobral: Embrapa Caprinos e Ovinos, 2019a. 24 p. (Embrapa Caprinos e Ovinos. Boletim de Pesquisa e Desenvolvimento, 13).

ROGÉRIO, M. C. P.; GUEDES, L. F.; ALVES, A. A.; POMPEU, R. C. F. F.; FERREIRA, M. I. C.; ALVES, F. G. da S.; COSTA, C. dos S.; BOMFIM, M. A. D.; GUEDES, F. L. **Estratégias nutricionais para grupos genéticos localmente adaptados ao Semiárido brasileiro visando a mitigação de gases de efeito estufa**. Sobral: Embrapa Caprinos e Ovinos, 2019b. 18 p. (Embrapa Caprinos e Ovinos. Comunicado técnico, 196). Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1117108/1/CNPC2019Cot196.pdf. Accessed: 22 Feb. 2025.

ROGÉRIO, M. C. P.; SOUSA, M. G. C. de; PIMENTEL. P. G.; POMPEU, R. C. F. F.; TEIXEIRA, M.; OLIVEIRA, D. de S.; BARROSO, M. R. C.; VIEIRA, L. da S. **Dietas para incremento da resiliência à verminose e mitigação de gases do efeito estufa**. Sobral: Embrapa Caprinos e Ovinos, 2022. 17 p. (Embrapa Caprinos e Ovinos. Boletim de Pesquisa e Desenvolvimento, 19). Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1148937/1/CNPC-2022-Art45.pdf. Accessed: 22 Feb. 2025.

SANTOS, L. S.; SOUZA, A. P. D.; LIMA, R. C. S.; NEVES, J. C. L.; LEITE, H. G.; SOARES, C. P. B.; LEITE, V. G.; GOMES. Estimativa de altura e volume de árvores em floresta de Mata Atlântica utilizando dados LiDAR de drone. **Cerne**, v. 27, n. 4, e104990, 2021.

SANTOS, W. P.; VAZ, C. M. P.; MARTIN-NETO, L.; ANSELMI, A.; TOMASELLA, J.; COSTA, F. S.; ALBUQUERQUE, J. A.; VAN LIER, Q. J.; GALBIERI, R.; PERINA, F. J. Predicting bulk density in Brazilian soils for carbon stocks calculation: a comparative study of multiple linear regression and Random Forest models using continuous and categorical variables. **Discover Soil**, v. 2, n. 7, 2025. DOI: https://doi.org/10.1007/s44378-025-00035-6.

SCHILLACI, C.; PEREGO, A.; VALKAMA, E.; MÄRKER, M.; SAIA, S.; VERONESI, F.; LIPANI, A.; LOMBARDO, L.; TADIELLO, T.; GAMPER, H.A.; TEDONE, L.; MOSS, C.; PAREJA-SERRANO, E.; AMATO, G.; KÜHL, K.; DĂMĂTÎRCĂ, C.; COGATO, A.; MZID, N.; EESWARAN, R.; RABELO, M.; SPERANDIO, G.; BOSINO, A.; BUFALINI, M.; TUNÇAY, T.; DING, J.; FIORENTINI, M.; TISCORNIA, G.; CONRADT, S.; BOTTA, M.; ACUTIS, M. New pedotransfer approaches to predict soil bulk density using WoSIS soil data and environmental covariates in Mediterranean agro-ecosystems. **Science of the Total Environment**, v. 780, 146609, 2021. DOI: https://doi.org/10.1016/j.scitotenv.2021.146609.

SEGNINI, A.; XAVIER, A. A. P.; OTAVIANI-JUNIOR, P. L.; FERREIRA, E. C.; WATANABE, SPERANÇA, M. A.; NICOLODELLI, G.; VILLAS-BOAS, P. R.; OLIVEIRA, P. P. A.; MILORI, D. M. B. P. Physical and chemical matrix effects in soil carbon quantification using laser-induced breakdown spectroscopy. **American Journal of Analytical Chemistry**, v. 5, n. 11, p. 722-729, 2014.

SEVASTAS, S.; GASPARATOS, D.; BOTSIS, D.; SIARKOS, I.; DIAMANTARAS, K. I.; BILAS, G. Predicting bulk density using pedotransfer functions for soils in the Upper Anthemountas basin, Greece. **Geoderma Regional**, v. 14, e00169, 2018. DOI: https://doi.org/10.1016/j.GEODRS.2018.e00169.

SINHA, S.; JEGANATHAN, C.; SHARMA, L. K.; NATHAWAT, M. S.; DAS, A. K.; MOHAN, S. Developing synergy regression models with space-borne ALOS PALSAR and Landsat TM sensors for retrieving tropical forest biomass. **Earth System Science**, v. 125, n. 4, p. 725-735, 2016. DOI: https://doi.org/10.1007/s12040-016-0692-z.

SOUSA, K. A.; OLIVEIRA, A. L. de; CARVALHO, L. M. T. de; LEITE, H. G.; SOARES, C. P. B.; LEITE, V. G.; NEVES, J. C. L. Desempenho de dados LiDAR aerotransportados no inventário florestal de áreas de plantio de eucalipto. **Floresta**, v. 50, n. 4, p. 1928-1936, 2020.

SOUZA, B. Q.; BRITO, L. R.; CARVALHO, H. P.; PINHEIRO, R. M.; FERREIRA, E. J. L.; SILVA, V. E. P. Utilização de drones estudos florestais: uma revisão sistemática. **Diversitas Journal**, v. 9, n. 3, p. 1091-1104, 2024. DOI: https://doi.org/10.48017/dj.v9i3.2887.

SOUZA, E.; FERNANDES-FILHO, E. I.; SCHAEFER, C. E. G. R.; BATJES, N. H.; SANTOS, G. R.; PONTES, L. M. Pedotransfer functions to estimate bulk density from soil properties and environmental covariates: Rio Doce basin. **Scientia Agricola**, v. 73, n. 6, p. 525-534, 2016. DOI: http://dx.doi.org/10.1590/0103-9016-2015-0485.

TIMM, L. C.; PIRES, L. F.; REICHARDT, K.; ROVERATTI, R.; OLIVEIRA, J. C. M.; BACCHI, O. O. S. Soil bulk density evaluation by conventional and nuclear methods. **Australian Journal of Soil Research**, v. 43, n. 1, p. 97-103, 2005. DOI: https://doi.org10.1071/SR04054.

TOMASELLA, J.; HODNETT, M.G. Estimating soil water retention characteristics from limited data in Brazilian Amazonia. **Soil Science**, v. 163, n. 3, p. 190-202, 1998. DOI: https://doi.org/10.1097/00010694-199803000-00003.

VASQUES, G. M.; COELHO, M. R.; DART, R. de O.; MANSILLA BACA, J. F.; SANTOS, M. de L. M. **Mapas de estoque de carbono orgânico do solo do Brasil na resolução espacial de 1 km - Versão 2021 [CNPS]**. Rio de Janeiro: Embrapa Solos, 2021. Available at: https://geoinfo.dados.embrapa.br/maps/4735/metadata_detail. Accessed: 3 Jun. 2025.

VELOSO, M. G.; DIECKOW, J.; ZANATTA, J. A.; PERGHER, M.; BAYER, C.; HIGA, R. C. V. Long-term loblolly pine land use reduces methane and net greenhouse gas emissions in a subtropical Cambisol, despite increasing nitrous oxide. **Annals of Forest Science**, v. 7, n. 3, article number 86, 2019. DOI: https://doi.org/10.1007/s13595-019-0869-0.

VILLAS-BOAS, P. R; FRANCO, M. A.; MARTIN-NETO, L.; GOLLANY, H. T.; MILORI, D. M. B. P. Applications of laser-induced breakdown spectroscopy for soil analysis, part I: Review of fundamentals and chemical and physical properties. **European Journal of Soil Science**, v. 71, n. 5, p. 789-804, 2020a. DOI: https://doi.org/10.1111/ejss.12888.

VILLAS-BOAS, P. R; FRANCO, M. A.; MARTIN-NETO, L.; GOLLANY, H. T.; MILORI, D. M. B. P. Applications of laser-induced breakdown spectroscopy for soil characterization, part II: Review of elemental analysis and soil classification. **European Journal of Soil Science**, v. 71, n. 5, p. 805-818, 2020b. DOI: https://doi.org/10.1111/ejss.12889.

ZAMAN, M.; KLEINEIDAM, K.; BAKKEN, L.; BERENDT, J.; BRACKEN, C.; BUTTERBACH-BAHL, K.; CAI, Z.; CHANG, S. X.; CLOUGH, T.; DAWAR, K.; DING, W. X.; DÖRSCH, P.; REIS MARTINS, M. dos; ECKHARDT, C.; FIEDLER, S.; FROSCH, T.; GOOPY, J.; GÖRRES, C. M.; GUPTA, A.; HENJES, S.; HOFMANN, M. E. G.; HORN, M. A.; JAHANGIR, M. M. R.; JANSEN-WILLEMS, A.; LENHART, K.; HENG, L.; LEWICKA-SZCZEBAK, D.; LUCIC, G.; MERBOLD, L.; MOHN, J.; MOLSTAD, L.; MOSER, G.; MURPHY, P.; SANZ-COBENA, A.; ŠIMEK, M.; URQUIAGA, S.; WELL, R.; WRAGE-MÖNNIG, N.; ZAMAN, S.; ZHANG, J.; MÜLLER, C. Methodology for Measuring Greenhouse Gas Emissions from Agricultural Soils Using Non-isotopic Techniques. In: ZAMAN, M.; HENG, L.; MÜLLER, C. (ed.). **Measuring Emission of Agricultural Greenhouse Gases and Developing Mitigation Options using Nuclear and Related Techniques**. Cham: Springer, 2021. DOI: https://doi.org/10.1007/978-3-030-55396-8_2.

ZANATTA, J. A.; ALVES, B. J. R.; BAYER, C.; TOMAZI, M.; FERNANDES, A. H. B. M.; COSTA, F. de S.; CARVALHO, A. M. de. **Protocolo para medição de fluxos de gases de efeito estufa do solo**. Colombo: Embrapa Florestas, 2014. 53 p. (Embrapa Florestas. Documentos, 265). Available at: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/123470/1/Doc.-265-Protocolo-Josileia.pdf. Accessed: 14 Feb. 2024.

ZANATTA, J. A.; PULROLNIK, K.; VIANA, J. H. M. **Protocolo para avaliação do estoque de carbono e de nitrogênio do solo em sistemas florestais - Projeto Saltus**. Colombo: Embrapa Florestas, 2015. 31 p. (Embrapa Florestas. Documentos, 277). Available at: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/129380/1/Doc.-277-Projeto-Saltus-2.pdf. Accessed: 14 Feb. 2024.

ZHANG, L.; SHAO, Z.; LIU, J.; CHENG, Q. Deep Learning Based Retrieval of Forest Aboveground Biomass from Combined LIDAR and Landsat 8 Data. **Remote Sensing**, v. 11, n. 12, p. 1-16, 2019. DOI: https://doi.org/10.1155/2012/436537.

ZHENG, G.; JIAO, C.; XIE, X.; CUI, X.; SHANG, G.; ZHAO, C.; ZENG, R. Pedotransfer functions for predicting bulk density of coastal soils in East China. **Pedosphere**, v. 33, n. 6, p. 849-856, 2023. DOI: https://doi.org/10.1016/j.pedsph.2023.01.014.

ZHOU, Y.; ZHAO, X.; GUO, X.; LI, Y. Mapping of soil organic carbon using machine learning models: Combination of optical and radar remote sensing data. **Soil Science Society of America Journal**, v. 86, n. 2, p. 293-310, 2022. DOI: https://doi.org/10.1002/saj2.20371.

ZIMMERMAN, P. R.; ZIMMERMAN, R. S**. Method and system for monitoring and reducing ruminant methane production**. US Patents 2011/0192213. 2012. Available at: https://patentimages.storage.googleapis.com/18/5c/08/1b72aaab6616b4/US20090288606A1.pdf. Accessed: 14 Feb. 2024.