REPORT 2025

ATN/RF-19787-RG and ATN/RF-19788-RG

Satellite monitoring of forage biomass quantity and quality in grazing livestock systems of Latin America and the Caribbean

MINISTRY FOR PRIMARY INDUSTRIES (MPI) OF NEW ZEALAND

GLOBAL RESEARCH ALLIANCE ON AGRICULTURAL GREENHOUSE GASES (GRA)

REGIONAL FUND FOR AGRICULTURAL TECHNOLOGY (FONTAGRO)

Te Kāwanatanga o Aotearoa
New Zealand Government

GLOBAL RESEARCH ALLIANCE ON AGRICULTURAL GREENHOUSE GASES

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CAI: Cellulose Absorption Index

Executive Summary

This project aims to reduce the cost of estimating, in real time and with adequate accuracy, the quantity and quality of forage biomass available in grazing livestock systems in Latin America and the Caribbean through the use of satellite information. The central strategy of the project is the development of a large, standardized ground-truth database compatible with satellite observation scales, enabling the calibration and validation of robust models across a diversity of environments and management systems.

During the first phase of the project, a unified field sampling protocol and a set of open-access digital tools were developed to support coordinated field measurements across countries. These tools include applications for characterizing landscape heterogeneity, recording field data, and monitoring the progress of sampling activities. As a result, a regional monitoring network involving more than 79 researchers and technicians was established.

By 2025, the project database surpassed 2,500 georeferenced field records of forage biomass, covering temperate and tropical pastures, natural grasslands, and annual forage crops. Preliminary analyses of this dataset enabled the calibration of initial biomass estimation models using Sentinel-1 and Sentinel-2 imagery. These models achieved average prediction errors ranging from 650 to 1,100 kg DM/ha, while the integration of field observations with satellite data reduced prediction errors by up to 50% compared with remote sensing-only approaches.

Building on these advances, two operational tools were developed during 2025 to facilitate biomass estimation at the grazing system scale: a spatial simplification tool, which allows biomass estimation across grazing platforms using a reduced number of field measurements, and a temporal simplification tool, which integrates residual biomass observations, satellite data, and weather information to estimate forage availability during pasture regrowth periods. These tools are currently being validated in demonstration modules and commercial farms.

In parallel, the project strengthened knowledge exchange and technical capacity across the region, reaching more than 1,100 technicians, producers, and students through training activities and technical dissemination. Together, these advances establish the foundation for a regional forage monitoring infrastructure based on open and traceable data, supporting the development of scalable tools for more efficient and sustainable grazing systems in Latin America and the Caribbean.

FONTAGRO-MPI-GRA: Partnering for Innovation and Sustainability

We gratefully acknowledge the Ministry for Primary Industries (MPI) of New Zealand and the Global Research Alliance on Agricultural Greenhouse Gases (GRA) for their support of the project “Satellite monitoring of forage biomass quantity and quality in grazing livestock systems of Latin America and the Caribbean (ATN/RF-19787-RG and ATN/RF-19788-RG)”. MPI–GRA support has been instrumental in building the project’s core assets during the first implementation phase: (i) a unified, satellite-compatible field sampling protocol; (ii) a suite of open-access digital tools to plan field campaigns, capture data, and characterize landscape heterogeneity; and (iii) the consolidation of a regional monitoring network and a large ground-truth database that now exceeds 2,500 georeferenced records spanning multiple forage resources and management contexts. These foundations are enabling the calibration and validation of scalable biomass and forage-quality models, and the development of operational “spatial” and “temporal simplification” tools that reduce field effort while providing real-time, decision-relevant estimates at paddock and grazing-platform scale.

This project benefits New Zealand by strengthening the global evidence base and the practical toolbox for pasture-based livestock systems—an area that is central to New Zealand agriculture. New Zealand dairy and beef farms depend on frequent, accurate pasture measurements for feed budgeting and grazing decisions (for example, rising plate meter assessments). Tools that cut labour and cost, while providing more timely information, fit these needs well. This is especially true for satellite-based, near real-time estimates of pasture biomass and, increasingly, forage quality. The project’s approach also matches current directions in New Zealand. It combines large, standardized ground-truth datasets with machine-learning calibration using Sentinel imagery. It also delivers user-facing tools that integrate field observations with satellite and weather data. Remote sensing and ML-based pasture biomass mapping is already seen in New Zealand as proven and commercially relevant, and there is strong interest in pushing performance beyond simpler lowland settings. Finally, better and more traceable pasture/forage monitoring strengthens measurement, reporting, and verification, which helps support credible claims about mitigation and efficiency in grazing systems. It also complements New Zealand’s ongoing work on agricultural greenhouse-gas reporting and inventory science.

I. Introduction

Pasture-based livestock production accounts for approximately 46% of the agricultural GDP in Latin America and the Caribbean and plays a key role in regional food security and rural livelihoods (FAO, 2023). However, these systems operate under increasing economic pressure and growing concerns regarding their environmental impacts, creating the challenge of improving profitability while reducing their contribution to global warming.

Accurate knowledge of the quantity and quality of available forage biomass is essential for making management decisions that improve the productivity and profitability of grazing systems (Beukes et al., 2019). In addition, this information is necessary to monitor, report, and verify the effects of greenhouse gas mitigation strategies. However, conducting frequent field surveys covering entire farms is costly and often impractical (Ortega et al., 2023).

In recent years, the availability of satellite data with spatial and temporal resolution compatible with weekly grazing management decisions has increased substantially. As a result, predictive models of forage biomass quantity and quality based on remote sensing have begun to emerge (Punalekar et al., 2018; Chen et al., 2021). For these technologies to effectively support management decisions, reliable models validated under local conditions are required (Correa-Luna et al., 2024), as well as mechanisms that make the information accessible to different users.

The main objective of this project is therefore to reduce the cost of estimating, in real time and with adequate accuracy, the quantity and quality of forage biomass available in grazing livestock systems through satellite-based tools. During the first years of the project, a standardized sampling protocol, a field data recording application, and a web platform for metadata visualization and management were developed. These actions enabled the consolidation of a regional monitoring network composed of more than 79 researchers and technicians and the creation of a database that currently includes more than 2,500 georeferenced ground-truth records associated with different forage resources and management conditions.

The analysis of this database allowed preliminary calibration of biomass estimation models and highlighted the importance of integrating field measurements with satellite information to improve prediction accuracy. Based on these results, new tools have been developed to provide biomass estimates at the grazing system scale, which are currently being validated in demonstration modules and commercial farms within the network.

Finally, the project includes a strategy for training, dissemination, and institutional collaboration aimed at promoting the adoption of the developed tools by technicians, advisors, and producers. The monitored sites not only play a key role in model validation but also provide the foundation for continuously expanding the field database over time, progressively strengthening the robustness, applicability, and scalability of the solutions developed within the framework of this project.

II. Project Portfolio Execution and Results

Satellite monitoring of forage biomass quantity and quality in grazing livestock systems of Latin America and the Caribbean (ATN/RF-19787-RG and ATN/RF-19788-RG)

II.1 Objective

To reduce the cost of estimating, in real time and with adequate accuracy, the quantity and quality of forage biomass available in grazing livestock systems in Latin America and the Caribbean through satellite-based tools.

II.2 Summary of Project Activities

The project is structured into three components that represent sequential stages. The first focuses on calibrating models to estimate forage quantity and quality at the pixel scale using medium-resolution satellite imagery (~900 m^2 pixels) within experimental and commercial farms. The second component focuses on validating these models at the grazing management unit scale (paddocks). The third component aims to promote knowledge exchange through training and dissemination activities targeted at technicians, advisors, and producers.

During the implementation of the project, progress has been made across all components. Initial efforts focused on developing standardized sampling protocols, building the regional ground-truth database, and calibrating preliminary satellite-based biomass estimation models. More recently, the project has progressed toward validating these models in demonstration modules and commercial farms, as well as strengthening training and knowledge transfer activities across the regional network.

Table 1: Project components and activities

Component	Activities	Results	Current Status
1) Generate and calibrate forage quantity and quality prediction models from remote sensors	1.1 Generation of a common ground truth data measurement protocol compatible with satellite data	Product 1. Technical note with sampling protocol	Completed
	1.2 Ground truth metadata base generation	Product 2. Technical note with database metadata	Execution
	1.3 Calibration of forage quantity and quality estimation models using satellite data	Product 3. Technical note with calibration of forage quantity and quality estimation models published	Execution
2) Validate the models generated in demonstration units and commercial properties	2.1 Validation of prediction models for the quantity and quality of biomass available at the system level in demonstration units and commercial properties	Product 4. Biomass and forage quality estimation tool implemented in validation sites and disseminated through technical note	Execution
	2.2 Evaluation of the cost of remotely predicting the quantity and quality of biomass available in demonstration units and commercial properties	Product 5. Technical note with validation of prediction models at system scale published	Execution
	2.3 Evaluation of the cost of remotely predicting the quantity and quality of biomass available on a regional or national scale	Product 6. Technical note with evaluation of the cost of remotely predicting the quantity and quality of biomass available at system scale published	Execution
		Product 7. Technical note with evaluation of the cost of remotely predicting the quantity and quality of biomass available in regions or countries published	Execution
3) Knowledge management, transfer and communication	3.1 Training workshops and dissemination products	Product 8. Training and dissemination workshops carried out	Execution
		Product 9. Videos disseminating results published	Execution

III. Project Implementation and Results

III.1 Component 1. Generation and calibration of real-time prediction models for forage biomass quantity and quality using remote sensing

Significant progress was achieved across all activities within this component. In 2023, a standardized protocol for sampling both forage biomass quantity and quality under field conditions was developed. The protocol was designed to be compatible with satellite data and adaptable to different forage resources. It includes guidelines for field sampling procedures and integrates digital tools that facilitate the recording of field data. The protocol was initially implemented at three sites in Argentina.

During the early phase of the project, criteria for field sampling were defined through a series of virtual meetings involving technical leaders from the participating institutions (Figure 1). These meetings facilitated discussions on the most relevant forage resources in each participating country and on the technical capacities available within each institution. In addition, an in-person workshop was held in Argentina with the participation of 29 technicians from different regions. Over two days, participants defined specific sampling criteria for different forage resources and received training on the use of the digital tools developed within the project.

Figure 1. Workshop on forage resources held on 9/27/23.

Based on the discussions held during these workshops, a decision tree was developed to guide field sampling according to vegetation characteristics (Figure 2). This decision tree operates at multiple levels. At the regional level, eligible forage resources are identified according to their relevance for livestock production systems. At the site level, factors such as paddock size, accessibility, and landscape heterogeneity determine the sampling strategy. Finally, at a finer scale, variability in vegetation structure among patches determines the number of sampling repetitions required.

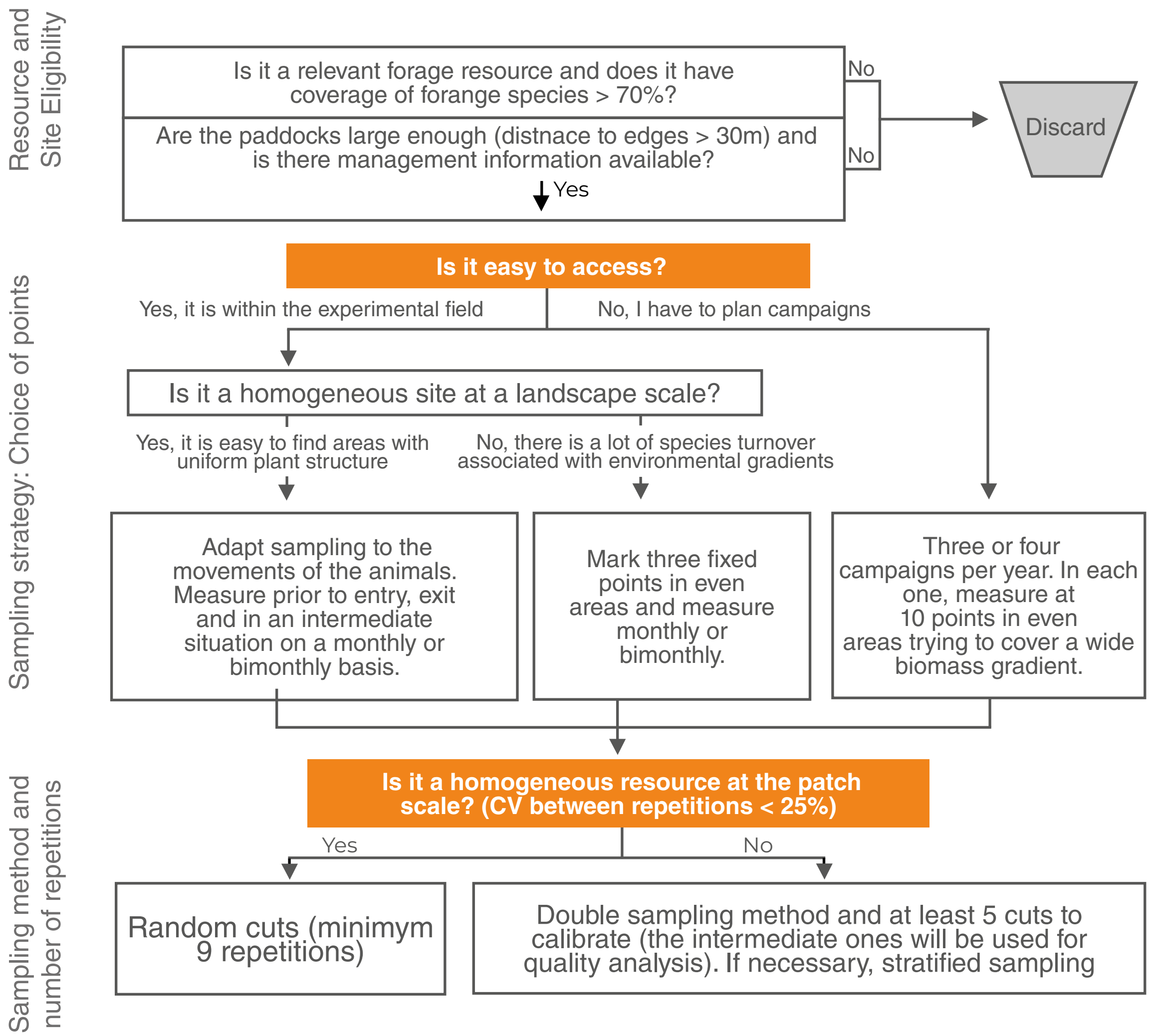


Figure 2. Decision tree to define forage sampling.

To support the decision-making process described in the decision tree and facilitate data collection, several digital tools were developed and evaluated. These include a web platform for planning and monitoring field sampling activities hosted in a GitHub repository (Figure 3). The platform allows users to access the most recent version of the sampling protocol, visualize satellite overpass calendars, and consult weather forecasts for sampling locations. The platform also serves as a central access point for the digital tools and metadata generated within the project.

Figure 3. Screenshots of the web platform used to plan and monitor field sampling activities (https://fontagrobiomasa.github.io/Muestreos/). Left: access to the sampling protocol and digital tools. Top right: satellite overpass calendar for one sampling site, showing cloud cover for recent acquisitions and rainfall probability for upcoming passes. Bottom right: map displaying metadata associated with sampled locations.

Another tool developed within the project is an application designed to characterize landscape heterogeneity. The application was developed in Google Earth Engine and is based on a previously developed approach (Durante and Jaurena, 2022). It generates maps representing areas with similar vegetation characteristics using vegetation indices derived from Sentinel-2 imagery. Within the sampling protocol, the application is used to assist in the selection of sampling points. Beyond its use within the protocol, the ability to rapidly generate landscape classifications can also support other management decisions such as paddock subdivision or identifying areas that require closer inspection during field visits.

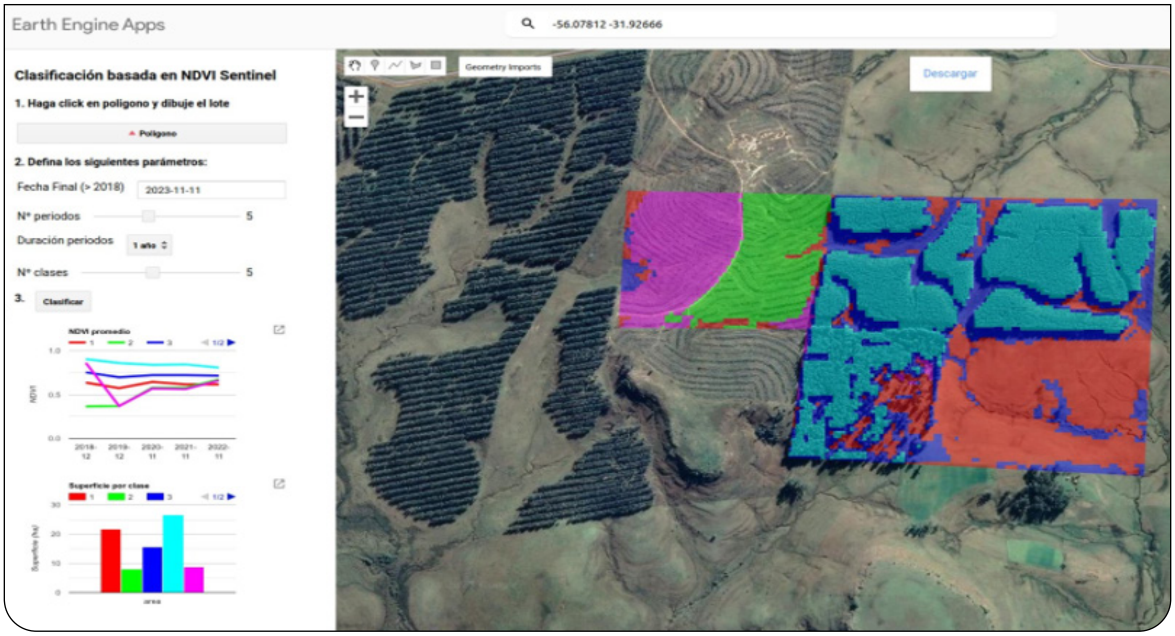


Figure 4. Screenshot of the application developed to characterize landscape heterogeneity (https://ee-fontagrobiomasa.projects.earthengine.app/view/clasificacion).

An indirect method for biomass estimation, referred to as “PhenoPhoto”, was also evaluated. This method is based on oblique photographs taken against a white background (Figure 5). The method was tested in natural grasslands in Entre Ríos (Argentina) and Uruguay, which are highly diverse grasslands containing approximately 40 species per square meter and dominated by both C3 and C4 grasses. When compared with direct clipping measurements, the method showed good agreement ($R^2 = 0.88$; N = 60 samples) and slightly lower relative error than other double-sampling approaches such as visual estimation or height measurements.

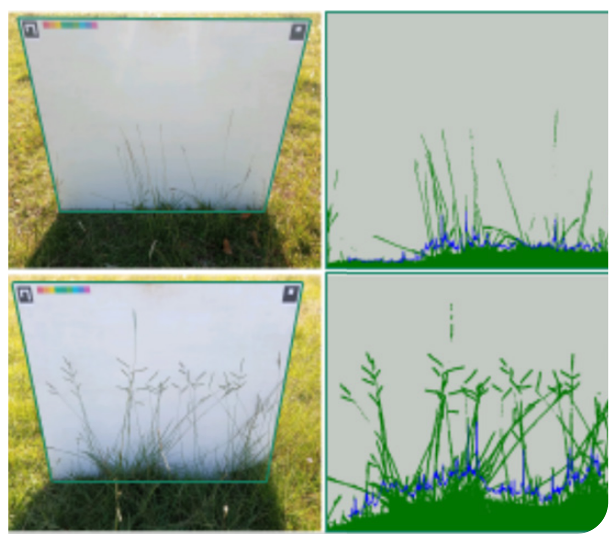


Figure 5. Oblique photographs taken with a smartphone (left) and the resulting processed image (right). Biomass estimators include vegetation cover (green) and vegetation height distribution (blue line) derived from the processed image.

Finally, a mobile application was developed to record field information in a systematic manner using smartphones or computers (Figure 6). The application was developed using the AppSheet platform and allows project participants to upload and visualize data stored in a shared Google Sheets database. Its main objective is to reduce recording errors, streamline field data collection, and facilitate the registration of metadata associated with each sampling event

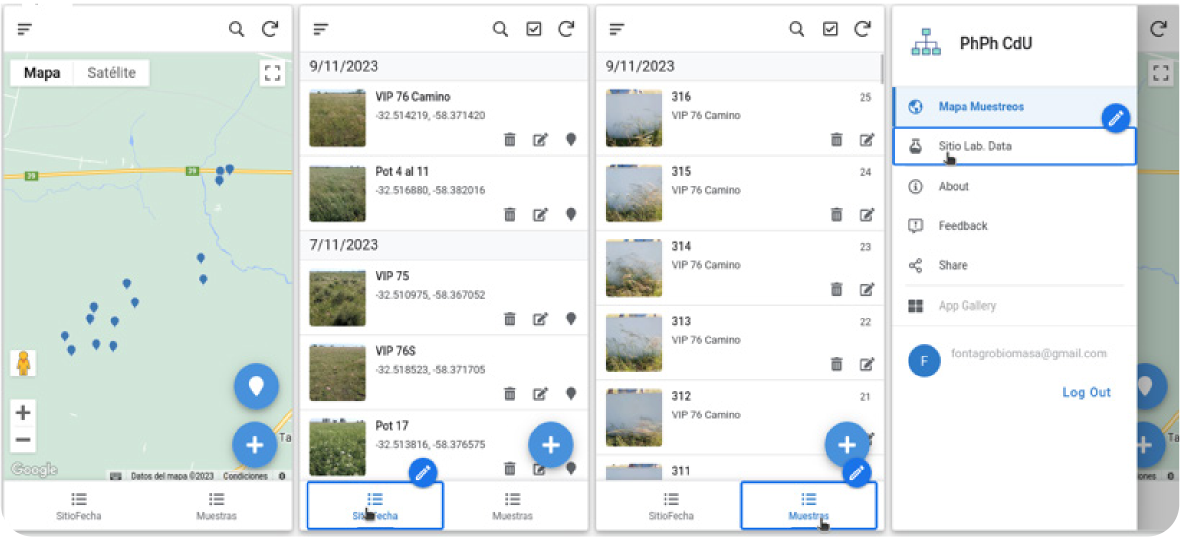


Figure 6. Screenshots of the application used to record field data. From left to right: sampling point map; interface for viewing and adding new sampling points; interface for viewing and adding repetitions within a sampling point; and data entry for a sampling point; and data entry for a sampling point after sample processing.

During 2024 and 2025, efforts focused on strengthening the technical capacity of the project network and expanding field sampling activities. Fourteen training and discussion workshops were conducted on sampling methodologies and field data collection. Meetings held during 2024 focused on harmonizing measurement criteria across sites, including methodological details such as the use of two cutting heights in tropical pastures (recommended grazing height and ground level). In 2025, activities increasingly focused on integrating field sampling with system-level validation activities under Component 2. Training workshops on drone image processing were conducted, and field campaigns were implemented to evaluate the scalability of point-based sampling to larger grazing areas.

As a result of these coordinated efforts, the project database currently contains more than 2,500 field measurements of forage biomass collected at spatial scales compatible with satellite observations. Argentina, Colombia, Uruguay, and Costa Rica currently contribute 1,970, 263, 115, and 51 biomass records respectively, with additional data expected to be incorporated in the near future. Temperate pastures represent the largest share of the dataset, followed by natural grasslands, tropical pastures, and annual forage crops.

Regarding forage quality analysis, 395 samples have been analyzed using wet chemistry and NIRS methods. A subset of 177 samples collected in Argentina was used to evaluate NIRS factory calibrations using a FOSS DS2500 instrument (Figure 7). The comparison between Kjeldahl protein measurements and NIRS predictions showed a coefficient of determination of $R^2 = 0.88$, although the average absolute error remained relatively high (5.6%) due to bias. The dataset generated within the project will be used to refine calibrations and improve prediction accuracy for the evaluated forage resources.

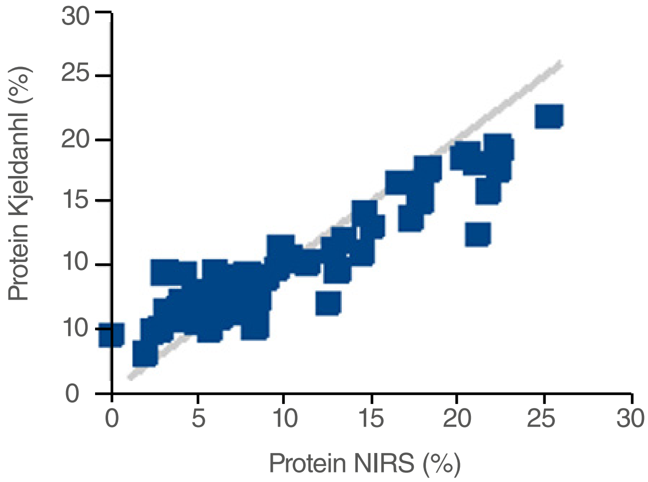


Figure 7. Crude protein measured by the Kjeldahl method versus NIRS predictions using the factory calibration for pasture silage, based on 177 forage samples collected in the field.

Using the available dataset, preliminary biomass estimation models were calibrated using spectral indices derived from Sentinel-1 and Sentinel-2 imagery and machine learning techniques (random forest). The general model showed an average prediction error of 1,100 kg DM/ha, which decreased to 450 kg DM/ha when models were calibrated specifically for temperate pastures in Balcarce. Simple regression models using the Cellulose Absorption Index (CAI = B11 − 0.5 x (B8 + B12)) calibrated separately for each date produced even lower errors (299 kg DM/ha). These results highlight the importance of expanding the ground-truth database and developing methods that allow field observations to be integrated into biomass estimation workflows in a simple and practical way for end users.

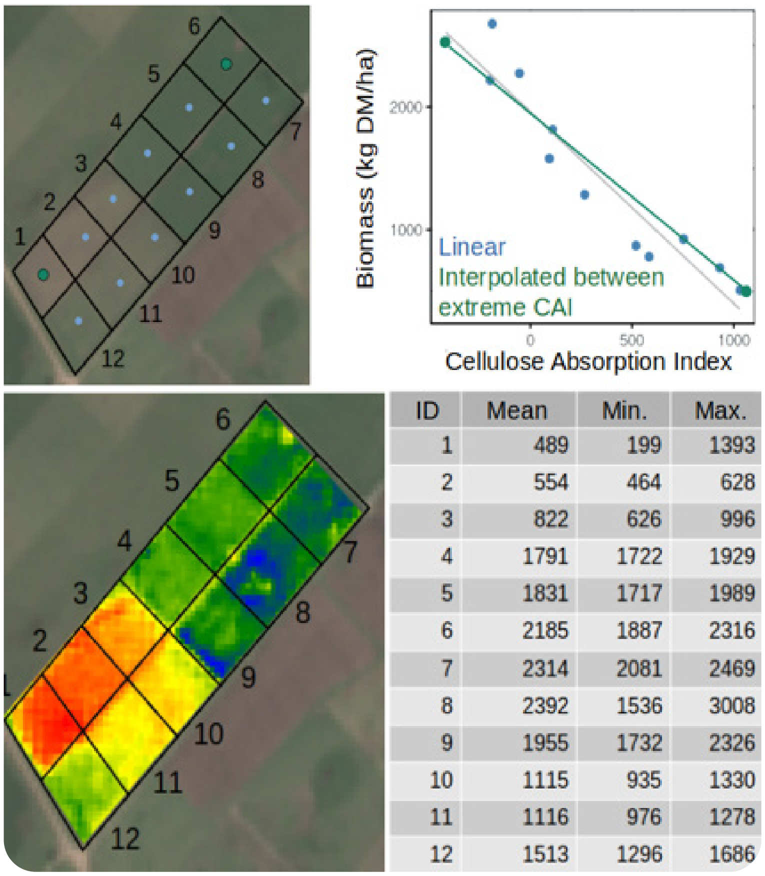
In parallel, the project strengthened institutional collaboration through agreements with the Argentine National Commission on Space Activities (CONAE) for the use of SAOCOM satellite data, and through collaborations with AgTech companies such as Planet and Cibolabs to evaluate biomass estimation algorithms. The project also contributed to human capacity development through doctoral research projects focused on the analysis and modeling of the generated dataset.

III.2 Component 2. Validation of the generated models in demonstration units and commercial farms

Progress was made in the development and implementation of two digital tools that integrate field measurements with satellite and meteorological information: spatial simplification and temporal simplification. These tools emerged from the preliminary analysis of the regional sampling database, which showed that incorporating field observations of biomass consistently improves the accuracy of satellite-based estimations compared with approaches based exclusively on remote sensing.

Both tools aim to provide real-time biomass estimates at the grazing system scale while reducing the effort required for traditional field sampling, thereby facilitating adoption by technicians and producers. In this sense, they represent the conceptual and operational basis for Products 4 to 7 of the project. Product 4, already submitted, documents the design and functioning of the tools, while Products 5 to 7 currently focus on their validation under real management conditions.

The spatial simplification tool allows the generation of biomass estimation models for a specific forage resource and date using a limited number of strategically located field measurements combined with spectral indices derived from satellite imagery. This approach enables biomass estimates to be extrapolated across larger grazing areas within the same platform while maintaining adequate accuracy and significantly reducing sampling effort (Figure 8).



ID	Mean	Min.	Max.
1	489	199	1393
2	554	464	628
3	822	626	996
4	1791	1722	1929
5	1831	1717	1989
6	2185	1887	2316
7	2314	2081	2469
8	2392	1536	3008
9	1955	1732	2326
10	1115	935	1330
11	1116	976	1278
12	1513	1296	1686

Figure 8. Example for the spatial simplification tool. Top left: biomass sampling points in an alfalfa-based pasture in Balcarce (Argentina) overlaid on a true-color Sentinel-2 image from 20/12/2022. The two points with extreme values of the Cellulose Absorption Index (CAI = B11 − 0.5 × (B8 + B12)) are shown in green. Top right: biomass as a function of CAI, showing the fitted linear model using all sampling points (grey line) and an interpolation between the extreme CAI values (green line). Bottom left: map of available biomass estimated from the satellite image and field sampling points. Bottom right: table with summary statistics of available biomass per paddock expressed in kg DM ha^{-1}.

Initial validation of this approach was conducted using data from temperate pastures in Balcarce (–37.79 S, –58.26 W), where weekly biomass measurements were available from 12 plots. A total of 23 sampling dates between October 2021 and April 2023 were analyzed for which good-quality satellite imagery was available within three days of field sampling. The results showed good agreement between field observations and satellite-derived estimates, with an average R^2 of 0.78, indicating that the number of paddocks sampled per date can potentially be reduced without substantially affecting estimation accuracy.

During 2025, additional sampling campaigns were carried out in several regions of Argentina to evaluate the performance of the tool across a broader diversity of forage resources, particularly natural grasslands characterized by higher structural heterogeneity than cultivated pastures (Figure 9). Results showed slightly lower model performance in these systems, especially in situations with shrub presence or when combining paddocks under active grazing with paddocks undergoing long rest periods (more than four months), where a high proportion of senescent biomass was present.

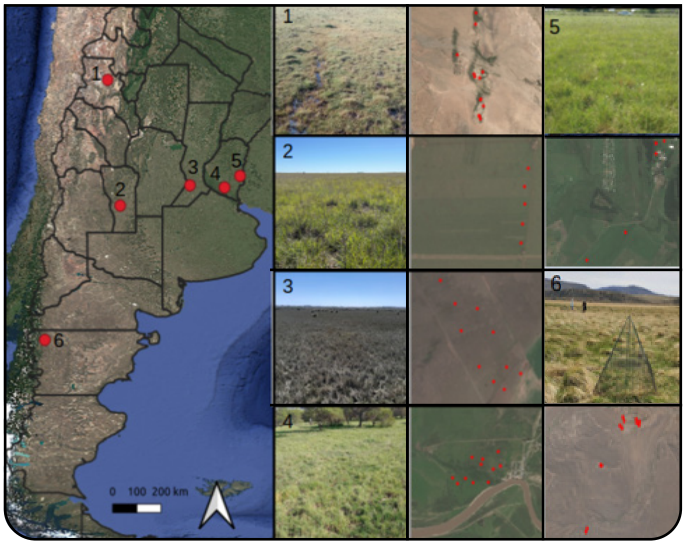


Figure 9. Examples of study sites where the spatial simplification tool was evaluated during 2025. (1) Puna meadow (April 3; R^2 = 0.54). (2) Digitaria pasture (April 3; R^2 = 0.95). (3) Seasonally flooded Pampas grassland (September 11; R^2 = 0.82). (4) Delta grassland (May 3; R^2 = 0.87). (5) Mesopotamian grassland (March 20; R^2 = 0.56). (6) Patagonian meadow (April 21; R^2 = 0.61).

The temporal simplification tool integrates field measurements of residual biomass recorded at the time animals leave a paddock in rotational grazing systems with satellite and meteorological information. Using these inputs, the tool estimates pasture growth and forage availability in real time during the rest periods between grazing events. This approach allows users to dynamically monitor forage availability and supports grazing planning and decision-making.

An example of this tool has been implemented in rotational grazing systems for growing cattle in Balcarce, where users record residual biomass after grazing and the system calculates available biomass during the regrowth period (Figure 10). During 2025, the tool began to be evaluated in additional systems based on different forage resources, including a Buffel grass pasture in the Dry Chaco region, a humid floodplain grassland in the Wet Chaco, and a shallow-soil natural grassland system in Uruguay.

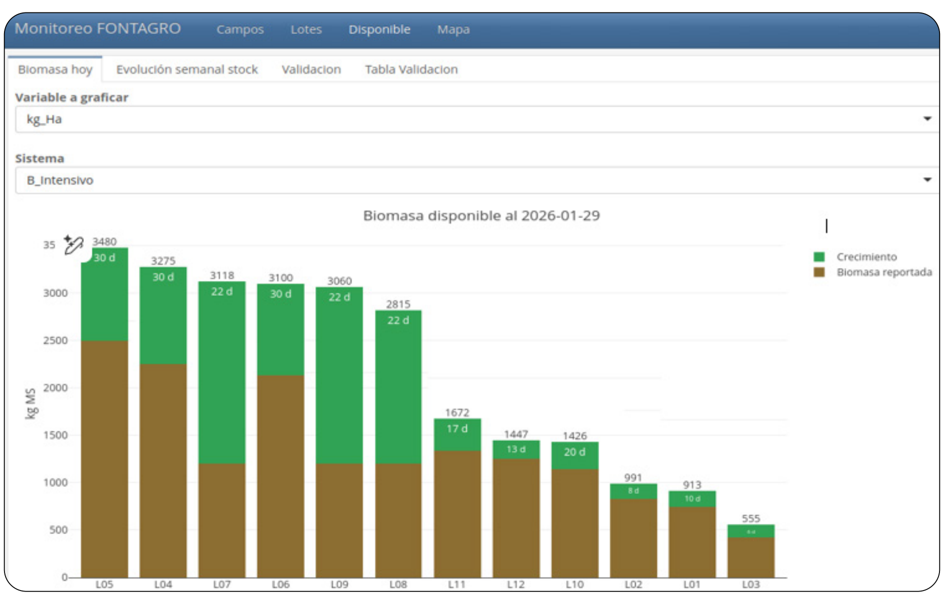


Figure 10. Real-time forage availability in 12 paddocks of a rotational grazing system. Residual biomass measured when animals leave the paddock is shown in brown, and available biomass during the rest period is estimated in green. Numbers above the bars indicate available biomass (kg DM ha^{-1}) and days since residual biomass was recorded; https://fontagrobiomasa.github.io/MonitoreoDR_Balcarce/#disponible.

Both tools are currently being implemented and validated in demonstration modules and commercial farms across different agroecological regions. At this stage, evaluation focuses not only on the accuracy of biomass estimations but also on the usability of the tools for technicians working in real production systems. The spatial simplification tool currently has a prototype application developed in Google Earth Engine, while a new version with user registration and a more user-friendly interface is under development. The temporal simplification tool is implemented through dashboards developed in R using the flexdashboard package and hosted on GitHub, allowing automatic updates so that technicians managing the demonstration modules can visualize forage availability in real time.

III.3 Component 3. Knowledge management, transfer, and communication

The project advanced in several dissemination, training, and institutional collaboration activities alongside the development of the technical tools. Based on the methodological advances and digital applications developed, multiple training and outreach activities were conducted for technicians, producers, and students. The project was presented in 17 dissemination events, including technical workshops, seminars, undergraduate and graduate courses, webinars, and scientific conferences. These activities reached more than 1,100 participants, strengthening technical capacity and raising awareness of the tools developed within the project. In addition to in-person activities, audiovisual materials and digital resources were produced to support knowledge dissemination. These materials accumulated more than 3,000 views, expanding the reach of the project beyond the research network and facilitating access to the methodologies developed. These dissemination activities also contributed to strengthening institutional collaboration with public institutions and technology companies interested in forage monitoring and the use of satellite information in livestock production systems.

Although the original plan included the preparation of a specific technical note linked to a dissemination workshop, the project team decided to prioritize the consolidation of the technical developments before organizing dedicated dissemination events. This strategy will allow future training activities to present more mature tools and validated results. During the next phase of the project, additional training and dissemination events will focus specifically on the spatial and temporal simplification tools. These activities aim to promote their adoption in research and extension initiatives, including the FONTAGRO project "New horizons in AgTech: Scaling innovation in pastoral systems of Latin America and the Caribbean", as well as in collaborative work with producers and technical advisors. The objective is to facilitate the use of these tools under real management conditions and collect feedback from users to support their continued improvement.

IV. Conclusions

During the reporting period, the project progressed from consolidating the regional sampling network and generating a ground-truth database toward the development and initial implementation of tools that use this information to estimate forage biomass at the grazing system scale. These advances contribute directly to the overall objective of reducing the cost and complexity of estimating, in real time and with adequate accuracy, the quantity and quality of forage biomass available in grazing livestock systems in Latin America and the Caribbean.

The integration of field measurements with satellite information enabled the development of two complementary tools—spatial simplification and temporal simplification—designed to facilitate the practical use of satellite-based biomass estimation by technicians and producers. Their initial implementation in demonstration modules and commercial farms has allowed the validation process to begin under real management conditions and provided valuable insights into their operational performance.

Looking forward, the monitoring sites currently operating within the project constitute a strategic foundation for the continued expansion of the ground-truth database. This continuous feedback between field measurements and model development will be essential to improve the robustness and generalization of biomass estimation models and to advance toward scalable and sustainable solutions for forage monitoring across the region.

V. Digital Links

Project's web site: https://fontagro.org/en/proyectos/monitoreosatelital

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