Info Note

Soil carbon stocks in tropical pasture systems in Colombia's Orinoquía region: supporting readiness for climate finance

Daniel M. Villegas, Mike Bastidas, Natalia Matiz-Rubio, Alejandro Ruden, Idupulapati Rao, Glenn Hyman, Jacobo Arango, Tobias Baedeker, Lee Cando, Mariangela Ramirez Diaz, Felix Teillard, and Ciniro Costa Jr.

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Key messages

- Using field measurements, it was found that pastures in clay soils in the Orinoquía region can store as more than 200 $tCha^{-1}$ (0-100 cm). Results are 40% higher than the IPCC default values (0-30cm).
- Close to 30% of the total SOC stock were found in the top 0-20 cm soil layer, highlighting the importance of evaluating deeper soil layers in SOC assessments.
- Improving pasture systems have the potential to accumulate SOC, especially in the topsoil layer. This may be a consequence of higher forage production in improved pastures and cattle waste depositions.
- Clay soils in Orinoquía shows a large potential for SOC sequestration through pasture improvement (~2.0 $tCha^{-1}y^{-1}$; 0-20 cm). This rate should be reduced overtime once SOC stocks approach a new steady-state. Therefore, future monitoring is critical to validating findings and better understanding SOC changes in the region.
- This info note reports high sequestration potential for grassland in Colombia's Orinoquía region, which can be attractive for climate finance. Information is also provided to improve SOC estimation and implement SOC monitoring systems.

Cattle farms are multifunctional systems by nature. They provide tangible products like meat, milk, and hide, valuable services like draught power, and manure for organic fertilization or biogas production (FAO 2016). Moreover, through the implementation of improved technologies and management practices (i.e., rotational grazing, silvopastoral and grass-legume mixtures), cattle ranching can deliver further ecosystem services like carbon (C) accumulation in pasture soils (Gerber et al., 2013; Herrero et al., 2013). The livestock sector plays an important role in global greenhouse gas emissions and offers mitigation options whereby climate finance can accelerate the transformation towards low emissions development practices (World Bank, 2021).

Yet actions and investments to foster soil organic carbon (SOC) accumulation are not currently taking place and largely miss the opportunity because of a series of barriers. Some are specific to the livestock sector. One major constraint has been the need for cost-effective methods for measurement, reporting and verification (MRV) of SOC stock changes. Promising approaches combine practical, user-friendly tools with site-specific modelling and the use of geospatial data sources and technology (Costa Jr et al., 2020).

In this context, soil sampling is key to improving the understanding of regional-specific SOC dynamics and enhancing project capabilities to estimate and monitor SOC changes over time more accurately (i.e., moving to higher IPCC methodological *Tiers,* improving IPCC default *Tier 1* values, setting baselines and initiating models).

This study aims to estimate SOC stocks from two different rangeland systems (native savanna and improved pasture) in a beef cattle farm located in the Orinoquía region, Colombia. The ultimate goal of this work is to support the readiness of livestock production to access climate finance.

Material and methods

Area of study

This study was conducted at the Hacienda San Jose (HSJ), located in Vichada, Colombia (Figure 1; Table 1). The region is dominated by native savanna mainly used for extensive cattle raising. HSJ started operations in 2014 as a cattle farm with two productive orientations: high-quality animal genetics (short-cycle Nelore breed) and cow-calf production. HSJ has since then implemented several management practices pursuing a sustainable intensification, such as a rotational grazing system with improved pastures (IP) of high forage quality avoiding savanna burning.

Pasture improvement was mostly achieved through the introduction of four forage grass cultivars, i.e. *Brachiaria humidicola* cv. Humidicola, *Brachiaria brizantha* cv. Marandú, *Brachiaria humidicola* cv. Llanero, *Brachiaria* hybrid cv. Cayman, and *Panicum maximum* cv. Mombasa. The area of improved pastures went from 0 ha in 2014 to approximately 7,200 in 2021 covering more than 80% of the total 8,670 ha of the farm.

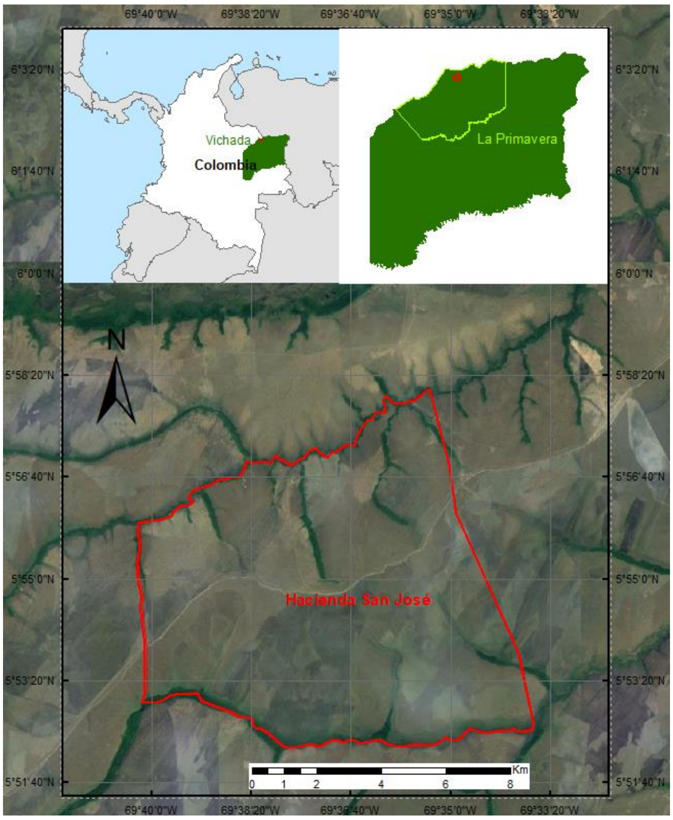

Figure 1. Location of Hacienda San Jose and aerial view of rotational systems at HSJ (taken from HSJ's YouTube channel).

Thereof, around 50% of the total farm is covered by *B. humidicola*, which has shown to be the most adapted to the conditions of the region among the cultivars tested on-site. Dolomitic lime, phosphate rock and gypsum were applied in 2017 to amend soil acidity and to supply nutrients. Pastures were grazed one year after sowing. Subsequently, the area was divided pursuing a system of radial distribution of the paddocks, which converge in the center, equipped with drinking troughs and cattle salting for the welfare of the animals. The entrance and exit of animals from pastures were determined by the height of the pasture, e.g., for *B. humidicola* the entrance height was 30 cm and the exit height was 15 cm. Depending on the paddock area, the animal category and the stocking rate, the duration of the animals in a paddock could take from 5 to 15 days.

Soil sampling and analysis

In August 2021, soil was sampled at HSJ in two pasture areas, unmanaged native savanna (NS) and improved pasture (IP), using a completely randomized design (n=5) for the quantification of total organic carbon, bulk density (BD), and chemical and physical characteristics. These two pasture areas (NS and IP) were located in close proximity (next to each other) and presented similar topographic and edapho-climatic conditions. The IP area was implemented 6.5 years ago (2015) by the conversion of the same native savanna into B. *humidicola*. These areas, therefore, represent a chronosequence, in which NS preceded IP in a land use succession (Table 1).

Table 1. Location and characteristics of native savanna (NS) and improved pasture (IP) soil sampling sites at HSJ, Colombia.

	Native Savanna 	Improved pasture 
Location	Orinoco region (Orinoquia), La Primavera, Colombia	
Lat/Lon	5°54'52.48" N, 69°37'12.54" W	
Climate classification	The climate zone defined by the IPCC (2006) is "Tropical, wet".	
Soil characteristics (0-20cm)	Order: Ultisols and Oxisols (IGAC, 2014); pH: 4.5; Texture: Silty clay loam (8% Sand, 55% Silt, 37% Clay) "Low activity clay (IPCC, 2006)"; Organic matter: 43.8 g kg^{-}1; BrayII-P: 1.3 mg kg^{-1}; Al: 2.9 cmol kg^{-1}	
Pasture details	The unmanaged native savanna (NS) in which the research was carried out has been free of burning and cattle grazing for more than 7 years.	The improved pasture (IP) of *B. humidicola* was established in 2015 (~6.5 years ago). Rotationally grazed with cattle at approximately 1 head per hectare.

In each pasture area (NS and IP) soil samples were collected from five trenches (replicates; n=5) arranged in a random transect along the pasture area, ~250-400 meters apart from each other. Soil samples were collected at 0–5, 5–20, 20–60 and 60–100 cm soil depth. In each sampling location and soil depth, two sub-samples were collected on two sides of the trench (which were further analyzed and combined in an attempt to account for SOC spatial variability). A total of 40 soil samples per area were collected. Samples from the 5–20, 20–60 and 60–100 cm soil layers were taken from the middle part of the corresponding soil layer.

For SOC analysis, soil samples were air-dried and then sieved at 2 mm. From each sample, 10 g were ground and sieved at 0.25 mm for determination of total C content that was determined by dry combustion through a Carbon Analyzer - LECO CN-2000. For the determination of soil bulk density (BD), samples of undisturbed areas were collected using a steel cylinder (5 x 5 cm) for subsequent evaluation of dry soil weight (at 110 °C) and determination of soil bulk density.

The soil sampling approach used in this work has been applied in several agricultural SOC evaluations (e.g., Carvalho et al., 2010; Costa Jr et al., 2013). For better assessment of changes, defining the number of samples may require pre-analysis of the SOC variation of the area (World Bank, 2021). Although this condition is not always possible due to time and financial constraints, it should be pursued in future assessments.

Soil C stock calculation

For each soil layer, we calculated the C stocks by multiplying the concentration of the soil C (g kg^{-1}) by the soil density (g cm^{-3}) and the soil layer thickness (cm). As samples were collected from fixed layers, the stock calculation needed to be adjusted for variations in BD after the conversion of NS (reference area) into IP. Therefore, the methodology described in Ellert and Bettany (1996) was used to adjust soil C stocks to an equivalent soil mass. For that, the depth of the IP area was adjusted for the same soil mass as the corresponding layer (0–100cm) in the NS.

Statistical analysis

The statistical analysis of data was run considering a completely randomized design with five pseudo-replicates in each evaluated area. The use of pseudo-replicates is a procedure commonly applied in ecological studies and it is described in detail by Hurlbert (1984). Two-way Analysis of variance (ANOVA) was applied to the results regarding SOC stocks considering pasture type and soil depth as fixed factors. The Tukey HSD test (α = 0.05) was applied to the comparison of mean values between the areas evaluated in each case study. All statistical analyses were run using the "r-companion" package of the R software.

Results and discussion

Soil bulk density, carbon content and carbon stocks

Both NS and IP areas showed the same pattern of soil C distribution over the different soil layers. The highest soil C content was found in the upper 0–5 cm soil layer with a decrease in the deeper layers. These values were higher under IP compared to NS. Soil bulk densities showed an opposite tendency, with results showing an increase with soil depth and it was lower under IP compared to NS (Figure 2).

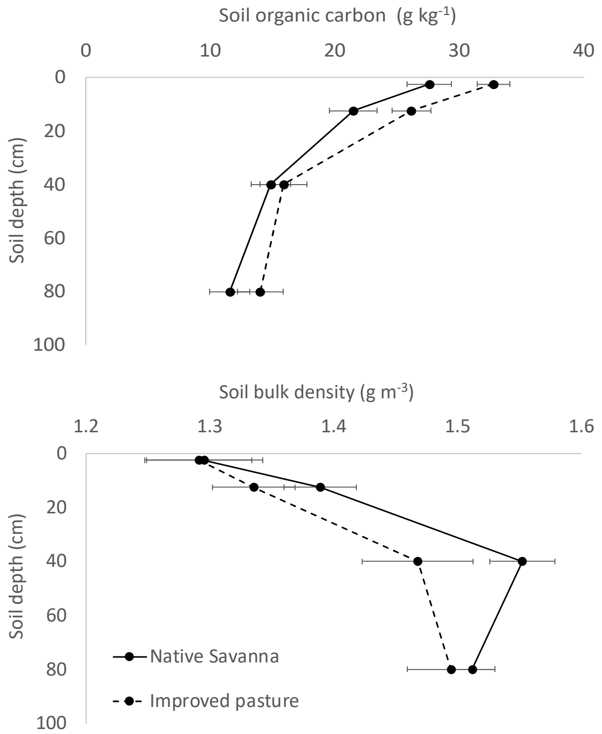

Figure 2. Soil carbon content (g kg^{-1}) and soil bulk density (g cm^{-3}) of soil layers in HSJ.

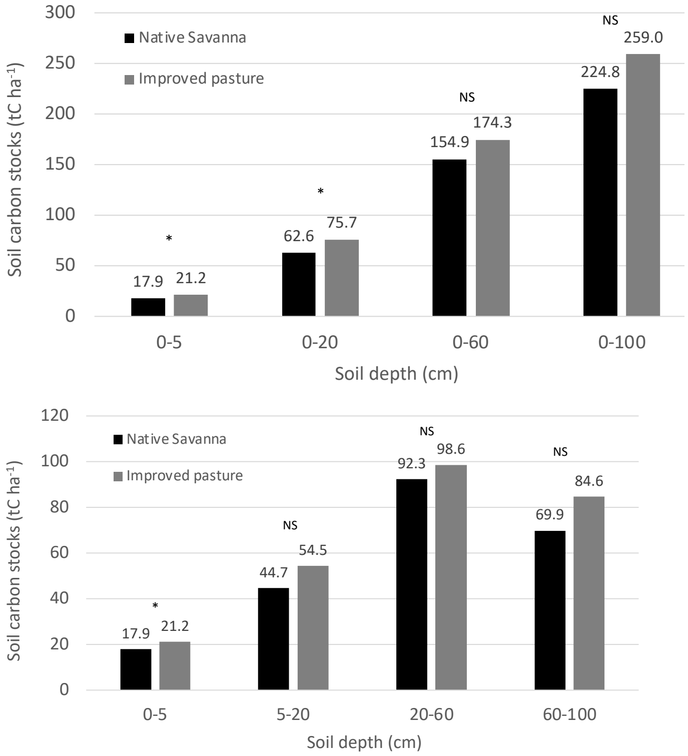

Figure 3. Soil carbon stocks (tCha^{-1}) of soil layers in HSJ. Asterisk (*) represent significant differences according to the Tukey HSD test at 5% level. 'ns' represent no significant differences.

The estimated total SOC stocks of the 0-100 cm layer were 224.8 and 259.0 t C ha^{-1} for the NS and IP, respectively (Figure 3). In both NS and IP areas, close to 10% and 30% of the total SOC stock (0-100 cm) was concentrated in the top 0-5 cm and 0-20 cm soil layers, respectively (Figure 3). The SOC stock (0-100 cm) was 15% higher in IP compared to the NS, however, significant differences were only found in the upper layers, 0–5 and 0-20 cm. Differences between treatments suggested an accumulation of 3.3 and 13.1 t C ha^{-1} or 0.5 and 2.0 t C $ha^{-1}y^{-1}$ in the 0–5 and 0-20 cm soil depths, respectively, over ~6.5 years.

The introduction of *B. humidicola* in previous NS areas influenced the SOC accumulation and soil quality of the improved pasture area probably through its abundant root system and its turnover, which may be influenced by pasture productivity and management (i.e., rotational grazing). Field evaluations at HSJ show that forage dry matter (DM) production in IP is 14% higher annually than NS (7.2 vs. 6.3 t DM ha^{-1} y^{-1}) and almost 8 times higher in the dry season (2.5 vs. 0.3 t DM ha^{-1}) compared to the published values for native savanna vegetation. The higher plant biomass productivity in IP, together with the introduction of grazing animals depositing urine and dung have likely increased the deposition of organic residues, especially on the soil surface, with subsequent percolation into the soil profile.

Therefore, we can expect significant changes in SOC stocks occurring in deeper soil layers in the coming years (below 20 cm soil depth) if the current management continues or improves. Otherwise, accumulated SOC could decline over time in the absence of adequate management (Fisher et al., 2007).

Comparison with other studies

The magnitude of C stocks found in this work (>200 t C ha^{-1}) was higher when compared to other studies for the same land use, management and soil depth (0-100 cm). For example, Fisher et al. (1994) measured approximately 200 t C ha^{-1} researching in the same region as this work. Corazza et al. (1999) found 150 Mg C ha^{-1} in soils cultivated with *Brachiaria decumbens* pasture in the Brazilian savanna and Battle-Bayer et al. (2010) reported SOC stocks of 123-209 t C ha^{-1} in different types of Brazilian savannas.

The rates of SOC accumulation (~2.0 t C ha^{-1} y^{-1} for the 0-20 cm and ~5.5 t C ha^{-1} y^{-1} for the 0-100 cm), were also in the high-end values found in the literature, including those in the Orinoquía region. Discrepancies may be attributed to differences in soil texture, pasture management, forage grass type and time of implementation as well as soil sampling design and SOC stock calculation (e.g., correction for the same soil mass).

After ~7 years of *B. humidicola* implementation over native savanna on the same eastern plains of the Colombia's Orinoquía region, Fisher et al. (1994) estimated a lower SOC accumulation of ~1.0 t C ha^{-1} y^{-1} for the 0-20 cm soil layer, but a similar rate when considering deeper soil layers (~4.0 t C $ha^{-1}y^{-1}$ for 0-80 cm). Another similar study evaluating 9 farms in the Orinoquía region reported much lower rates of ~0.4 (0-20 cm) and ~1.0 t C ha^{-1} y^{-1} (0-100 cm), but after ~29 years of implementation of *B. humidicola* over native savanna (CIAT-Agrosavia; unpublished data). The authors suggested the higher SOC sequestration in the first study (Fisher et al.,1994) was related to adequate management of the introduced pasture under experimental condition (e.g., with fertilization and rotational grazing), which did not have the same status in the second case (CIAT-Agrosavia; unpublished data). This situation has probably prevented the proper forage development and, therefore, the amount of below and aboveground organic residues going back into soil. In addition, after almost 30 years, the SOC stock could be just reaching a new-steady state after peaking its accumulation in the first decade of the pasture implementation.

In the Brazilian savanna (Cerrado region), SOC accumulation rates with the introduction of pastures were also more conservative than the level observed in this study. Bustamante et al. (2006), reported that the conversion of native vegetation to pasture showed a mean SOC accumulation of 1.23 t C ha^{-1} y^{-1} (from -0.9 to 3.0 t C ha^{-1} y^{-1}). Maia et al. (2009) observed variations in SOC after conversion of native vegetation (Cerrado and Amazon Forest) into pasture of -0.28 t C ha^{-1} y^{-1} (degraded pastures), 0.03 t C ha^{-1} y^{-1} (non-degraded pastures) and 0.61-0.72 t C ha^{-1} y^{-1} (improved pasture) (0-20 cm). Modeling (DayCent) impacts on SOC by improving and diversifying pasture management in Brazil (e.g., integrated crop-livestock and forest-livestock systems), Damian et al. (2021) estimated an increase in SOC of 0.04-0.95 t C ha^{-1} y^{-1}. Out of 115 studies evaluating SOC stock changes in introduced pasturelands globally, Conant et al. (2001) found in 74% of the cases an increase in SOC between 0.11-3.04 t C ha^{-1} y^{-1}, but just 35% of those cases showed significant differences.

Although the improved pastures evaluated in this work did not receive any maintenance fertilization after establishment, the higher SOC sequestration rate found in this work could have also been favored by the higher clay content of the sampled area (~40% of clay content; Table 1), which represents less than 50% of the Orinoquía region area only. The majority would have around 25% content of clay (mid texture soil), and therefore less potential to accumulate SOC. The relationship between SOC and soil texture have been attributed to a chemical stabilization of SOC by soil clay/mineral surface (Feller and Beare, 1997). These relations suggest that clayey soils have more potential for SOC storage than sandy soils and, therefore, the percentage of clay content is a good predictor of SOC content and its potential accumulation (Nichols et al., 1984).

Differences in SOC accumulation rate can be further associated with climatic differences, where high temperatures and rainfall evenly distributed in Colombia favor *B. humidicola* to root deeply and, consequently, accumulate more SOC (Fisher et al., 2007). Furthermore, the conversion to IP is relatively recent (6.5 years) and, therefore, the soil is likely to be still developing its SOC accumulation curve and this rate is expected to reduce overtime as suggested by other studies in the same region.

Finally, the errors associated with non-identical initial soil conditions in the NS and IP chronosequence (e.g., land history) of fields make this approach less accurate for the determination of rates of SOC accumulation compared to a diachronic approach (Costa Jr et al., 2013).

Comparison to the IPCC default values

The SOC stock found in NS represents 79.9 t C ha^{-1} for the 0-30 cm soil depth (linear regression analysis not shown), which is almost 40% and 50% higher than the reference default value for this climate zone and soil type provided by the IPCC (52 ±6% t C ha^{-1}; IPCC, 2019) and FAO-GSP-GloSIS Global (42.7 ±5.8 t C ha^{-1}; 29.3 Min - 56.2 Max).

Using the IPCC Tier 2 SOC stock change method to estimate SOC sequestration with improved practices, using an adjusted reference SOC stock (from 52 to 79.9 t C ha^{-1}) (IPCC, 2019), we estimated a total SOC accumulation of 13.6 t C ha^{-1} for the 0-30 cm, which is similar to the value found in this work (12.7 t C ha^{-1} for the 0-30 cm). However, according to the IPCC (2019), this level of SOC accumulation would be expected in 20-year time (equivalent to a new steady-state for this stock). Here we estimated that this change was achieved just after six years. These results underscore the importance of field measurements to improve local-specific SOC data, but especially the necessity of SOC monitoring for better understanding and validating SOC stock variations over time.

Final remarks

Limitation

High rates of SOC accumulation found in this work, although in line with previous study in the region (Fisher et al., 1994), may raise the question of the adequacy of the soil sampling design to accurately detect SOC changes as well as how long this situation can be sustained for.

Although the soil sampling approach used in this work has been applied in several other SOC evaluations, as described above, future research could investigate the effect of land stratification in assessing the SOC variation and reducing uncertainties (World Bank, 2021). The soil sampling could be also extended to a NS used under a similar grazing management of the IP in HSJ to decouple the impact of the type of forage from the management practice.

Furthermore, more moderate rates of SOC accumulation are expected to be found when using diachronic sampling (when measurements are made over time on the same location) rather than the chronosequence of fields approach, once it seems to be difficult to eliminate all non-wanted sources of soil C variation (e.g., soil texture, land-use history) by analyzing the soil C accumulation in a chronosequence (synchronic approach) (Costa Jr et al., 2013).

Regarding the capacity of SOC accumulation, accrual potentials remain unclear. The IPCC guidelines assume 20 years as the default period in which new SOC stocks approach a new steady-state - which also enables comparison of results between regions and countries and with other estimation methods (IPCC, 2019). Nevertheless, a meta-analysis of field studies has suggested that SOC sequestration can continue for over 40 years before reaching a new equilibrium (Minasny, et al., 2017), which depends on management practices, soil type and climate conditions (e.g., rainfall and temperature).

Future work

Although subsequent measurements over time are critical to better understanding SOC dynamics in the region, it is worth noting that implementing practices leading to SOC accumulation may also increase the emission of other powerful greenhouse gases (GHG) (Paustian et al., 2019), such as methane (CH_4) and nitrous oxide (N_2O) that have global warming potentials (100-year time horizon) 28 and 265 times higher that of CO_2, respectively (IPCC, 2014). These GHGs are released, for example, during nitrogen fertilizer application to soils and animal enteric fermentation and manure management. Moreover, such practices can lead to additional positive or negative effects on e.g., biodiversity, water use and eutrophication (Griscom et al., 2017).

Therefore, future SOC measurements and the evaluation of environmental trade-offs across different practices are important to accurately determine the net climate and further environmental impacts of farming management strategies.

Conclusions

The conversion of NS into a cultivated pasture under rotational grazing with *B. humidicola* on the eastern plains of the Colombian region increased SOC stocks of the top soil layer (0-20 cm), with a tendency to increment stocks at deeper soil layers (0-100 cm).

The large SOC sequestration capacity in improved pasturelands in clayey soils in the Orinoquía region (~2 t C ha^{-1} y^{-1}), while increasing production of food (i.e., meat and milk), may be attractive for climate finance opportunities. To build the case of beef in the region for climate finance, net emissions will need to be assessed and other safeguards should also be considered (e.g., avoided deforestation, effect of pasture improvement on biodiversity).

This info note reports valuable information for future monitoring of SOC changes under different pasture systems in Colombia that may support climate finance actions for low emissions development in beef cattle production systems.

Further reading

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About the authors

This info note focuses on assessing the implications of improved pastures in Colombia on sequestering soil organic carbon.

Daniel M Villegas *(d.m.villegas@cgiar.org)*, **Mike Bastidas** (m.bastidas@cgiar.org) **and Alejandro Ruden** *(d.ruden@cgiar.org) are Research Associates in the Tropical Forages program at CIAT*

Natalia Matiz-Rubio (natalia.matiz@ier.uni-stuttgart.de) is a Doctoral Researcher at the University of Stuttgart and a visiting researcher at CIAT

Ricardo Gonzalez-Quintero *(ricardo.gonzalezq@udea.edu.co) and* **Alejandra Marin** *(A.marin@cgiar.org)* are post-doctoral Consultants at CIAT

Idupulapati Rao is a Scientist Emeritus with CIAT

Glenn Hyman is an environmental scientist and free-lance geographer

Jacobo Arango *(j.arango@cgiar.org) is a Senior Scientist at the Tropical Forages program of CIAT.*

***Tobias Baedeker, Lee Cando, Felix Teillard** are team members of the World Bank project Livestock Sector Readiness to Access Climate Finance funded by the Forest Carbon Partnership Facility.*

***Mariangela Ramirez Diaz** is a team member of the World Bank project Developing Climate-Smart Agricultural Supply Chains, which is part of the BioCarbon Fund Initiative for Sustainable Forest Landscapes (ISFL) Program.*

***Ciniro Costa Jr** (c.costajr@cgiar.org) is a Science Officer for Low-Emission Development at CCAFS.*

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