Article

Carbon Storage Potential of Silvopastoral Systems of Colombia

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Abstract: Nine Latin American countries plan to use silvopastoral practices—incorporating trees into grazing lands—to mitigate climate change. However, the cumulative potential of scaling up silvopastoral systems at national levels is not well quantified. Here, we combined previously published tree cover data based on 250 m resolution MODIS satellite remote sensing imagery for 2000–2017 with ecofloristic zone carbon stock estimates to calculate historical and potential future tree biomass carbon storage in Colombian grasslands. Between 2000 and 2017, tree cover across all Colombian grasslands increased from 15% to 18%, with total biomass carbon (TBC) stocks increasing from 0.41 to 0.48 Pg. The range in 2017 carbon stock values in grasslands based on ecofloristic zones (5 to 122 Mg ha^{-1}) suggests a potential for further increase. Increasing all carbon stocks to the current median and 75th percentile levels for the respective eco-floristic zone would increase TBC stocks by about 0.06 and 0.15 Pg, respectively. Incorporated into national C accounting, such Tier 2 estimates can set realistic targets for silvopastoral systems in nationally determined contributions (NDCs) and nationally appropriate mitigation actions (NAMAs) implementation plans in Colombia and other Latin American countries with similar contexts.

Keywords: agroforestry; carbon sequestration; climate change mitigation; grazing management; land restoration; nationally determined contribution; silvopastoral; tree cover

1. Introduction

The ability to limit global warming below 2 °C, the target set by the Paris Climate Agreement, is predicated on significant greenhouse gas (GHG) emission reductions in the agriculture and land use sector (AFOLU) [1,2]. While land use accounts for nearly 25% of net annual anthropogenic GHG emissions [3], it also offers many options to mitigate climate change. Estimates suggest that land use interventions could generate up to 30% of the emission reductions and carbon sequestration needed to meet the Paris Agreement's ambition [4,5]. Most agriculture and land use mitigation interventions target the reduction of emissions from livestock systems, rice systems, deforestation, and nitrogen fertilizer. However, the integration of trees in crop and pasture lands, also known as agroforestry, is another potentially significant intervention option [6].

Nine Latin American countries have identified silvopastoral systems (SPS), agroforestry systems where trees are managed or planted in pasturelands, as a priority action to mitigate climate change within their nationally determined contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC) [7,8] and the Nationally Appropriate Mitigation Actions (NAMAs),

two documents that prescribe national climate response priorities. The focus on livestock in Latin American countries is due to the economic importance of the sector and its leverage on national emissions. Indeed, the livestock sector accounts for 58–70% of the overall agricultural emissions in Latin America [9], making greening milk and meat production a critical aspect of meeting national goals.

Silvopastoral systems sequester carbon in biomass increasing the amount of carbon in the landscape. Silvopastoral systems accumulate more than 2 Mg C per ha per year above and below ground biomass and additional 0.5 Mg C per ha per year in the soil [10]. Grazing grasslands occupy more than 550 million hectares of land in Latin America. Therefore, scaling up silvopastoral systems would seemingly have the potential to increase carbon in the landscape despite the modest change per unit of land. Estimates of the climate change mitigation benefits of scaling up silvopastoral systems at the national level, however, are largely unavailable. Zomer et al. [11,12] provided a first estimate of t C stocks in tree biomass in crop lands at global scale but did not specifically consider trees in grasslands (i.e., silvopastoral systems). Griscom et al. [5], on the other hand, estimate silvopastoral C but mix these estimates together with other land management options to estimate a total mitigation potential of land restoration. However, countries need estimates of silvopastoral potential to set targets for climate action [13].

This study estimated the climate change mitigation benefits of expanding silvopastoral systems in Colombia to inform realistic inclusion of silvopastoral systems in NDC and NAMA planning options for Colombia and other Latin American countries with similar contexts. Expanding on the earlier analysis for agricultural lands [11,12], we explored historical C stocks for Columbian grassing lands in 2000 and 2017, before considering options to increase C stock density with the silvopastoral systems in the local context. Specific questions were: (i) What changes in tree cover in Columbian pastureland are evident from satellite imagery? (ii) What changes in C stock do such changes in tree cover imply, using ecofloristic-zone-specific C density estimates? (iii) Evaluating the existing statistical distribution, which further changes may be feasible?

Colombia was selected because of its active promotion of silvopastoral systems. For example, the Colombian government and National Livestock Federation (FEDEGAN) have a strategy to reduce GHG emissions from the agricultural sector by 13.46 Mt CO_2e yr^{-1} by 2030. The conversion of current grasslands to SPS is among the priority mitigation activities [14]. Importantly, Tapasco et al. [15] also identified SPS as the most promising policy option for achieving this goal, and Lerner et al. [16] notes that the country is in an ideal position to create integrated plans for sustainable cattle intensification, including SPS, conservation, and restoration initiatives.

2. Methods

2.1. Conceptual Approach

For this analysis, a methodology earlier applied to agricultural lands [8] was adapted to spatially quantify carbon sequestration from tree cover in grasslands and estimate potential carbon stocks under widespread implementation of SPS. The steps were to define the extent of grasslands in the target area; derive the current level of tree cover; estimate the carbon stocks in above and belowground biomass; estimate the potential increase with shifts in tree cover from the current to the 25th percentile, median, and 75th percentile of 2017 biomass carbon stocks; and quantify the difference between current and potential tree cover and carbon sequestration ("silvopastoral carbon gap"). A detailed description of the methodology used for this analysis is found in Zomer et al. [11,12].

2.2. Study Area

Given that both the Colombian government and independent researchers have identified SPS as a priority in achieving Colombia's agricultural emission reduction goals [15], we focused on Colombia as a case study. As of 2015, Colombia had more than 12 million ha of grassland (13% of the national land area) scattered throughout tropical moist deciduous forests (77% of grassland), tropical rainforest

(12%), and other ecofloristic zones (Figure 1). The largest grazing areas are found in the sparsely populated Llanos Orientales and Orinoquia regions of the Orinoco River basin. In other regions of the country, smaller grassland areas are interspersed with various land uses, including croplands and settlements.
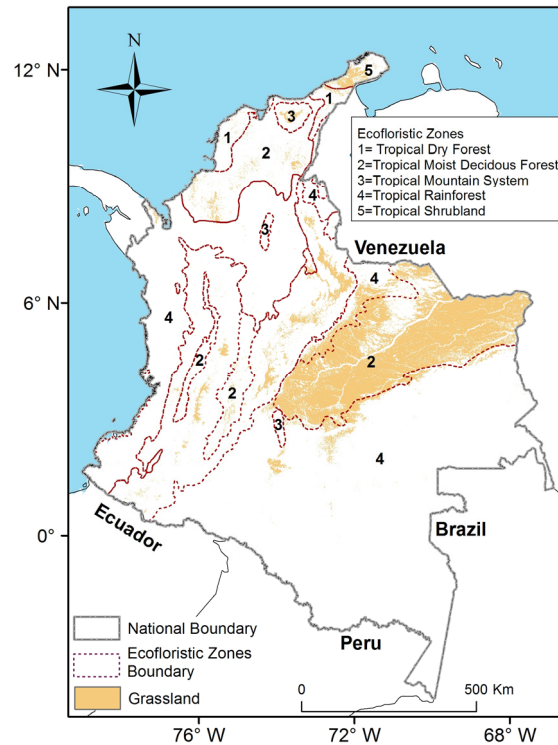
Figure 1. Grassland cover in 2015 (source: European Space Agency, 2017a) and ecofloristic zones of Colombia.

2.3. Data Collection and Analysis

Grassland area was derived at 300 m spatial resolution from the European Space Agency's (ESA) annual global land cover data. Per ESA recommendations, the ESA land use classes grass land, mosaic herbaceous cover > 50% and tree and shrub < 50% were combined to produce the grassland designation used in this analysis [17]. Percent tree cover was derived from previously published tree cover data based on the 250 m resolution Moderate-Resolution Imaging Spectroradiometer (MODIS) 44B Version 6 Vegetation Continuous Field remote sensing product [18]. This product is a continuous, quantitative representation of global land surface cover at 250 m spatial resolution. Ground cover gradations are based on percent tree cover, percent non-tree cover, and percent non-vegetated (bare) [18]. A detailed description of the methodology used for this analysis is found in Zomer et al. [11,12].

We used the default Intergovernmental Panel on Climate Change (IPCC) Tier 1 total carbon stock values for each ecofloristic zone as the minimum potential carbon stock values for 0% tree cover [19] (Table 1). We then estimated the total carbon sequestration potential of SPS by ecofloristic zone using the methodology recommended by IPCC Tier 1 and detailed in Zomer et al. [12]. The biomass carbon value of the equivalent (or most similar) Global Land Cover (GLC) 2000 Mixed Forest class [19] was used as a surrogate aboveground biomass carbon value for each ecofloristic zone to simulate full tree cover (100%). Belowground carbon sequestration potential was calculated using aboveground sequestration potential values and the root/shoot ratio for each of the ecofloristic zones as per IPCC Tier 1 values (Table 1) [19]. Below and aboveground C sequestration potential values were then summed to determine total potential carbon stock values for 100% tree cover. A carbon fraction value of 0.47 was uniformly applied to determine the carbon content of dry woody biomass. We then assumed a linear

increase in biomass carbon from 0% to 100% tree cover for each ecofloristic zone. We used the Tier 1 value when tree cover was 0% and the maximum value for Mixed Forest when tree cover was 100%.

Table 1. IPCC Tier 1 values of above ground carbon stocks in grassland under different ecofloristic zones.

Ecofloristic Zone	Area		Above Ground Carbon Stocks Mg ha^{-1}		Root to Shoot Ratio
	ha	%	Minimum	Maximum	
Tropical dry forest	67,758	0.6	4	126	0.28
Tropical Moist deciduous forest	9,487,070	77	8	128	0.24
Tropical mountain system	1,076,967	8.8	6	87	0.27
Tropical rainforest	1,469,597	12	8	193	0.37
Tropical shrubland	206,495	1.7	4	126	0.28
Total	12,307,887	100			

We used the 2015 grassland area as a basis for 2000, 2008, and 2017 tree cover and biomass assessments to control for any change in grassland area over time. We used the 2017 25th, median, and 75th percentile carbon stock values in each ecofloristic zone to calculate carbon gaps and the current carbon sequestration potential. We identified areas with carbon stock values below the 25th percentile in each ecofloristic zone as those with the greatest potential to increase carbon stock. Similarly, we considered areas with carbon stock values between the 25th percentiles and medium values as having medium potential and areas between the median and 75th percentile values as having low potential to increase carbon stocks. Areas with greater than the 75th percentile tree cover values were considered as not suitable for increasing carbon stocks. This approach is particularly useful for spatially targeting SPS-based mitigation actions [20].

3. Results

3.1. Estimates of Tree Cover on Grassland in 2000, 2008, and 2017

Tree cover increased between 2000 and 2017. For presentation purposes, we classified these results into tree cover classes (Table 2). Land area with tree cover greater than 10% increased from 55% in 2000 to 74% in 2008 and 73% in 2017. The percentage of grasslands with tree cover > 30% increased with time, from 10% in 2000 to 12% in 2008 and 13% in 2017. Total tree cover across all grasslands increased by about 20% from 2000 to 2017.

Table 2. Grassland (ha) tree cover (%) in 2000, 2008, and 2017.

Tree Cover (%)	2000		2008		2017	
	ha	(%)	ha	%	ha	%
≤10	5,507,090	45	3,210,585	26	3,319,775	27
11–20	3,883,571	32	4,861,344	39	4,700,027	38
21–30	1,715,737	14	2,708,461	22	2,709,611	22
>30	1,201,488	10	1,527,496	12	1,578,474	13
Total	12,307,887	100	12,307,887	100	12,307,887	100

Tree cover increased on grassing lands between 2000 and 2017, but tree cover dynamics and the relative increase or decrease depended on the location. Colombian grassing lands show between 0% and 84% tree cover (Figure 2). The relative change on any given parcel increased up to 76% over this period while others decreased by 80%.
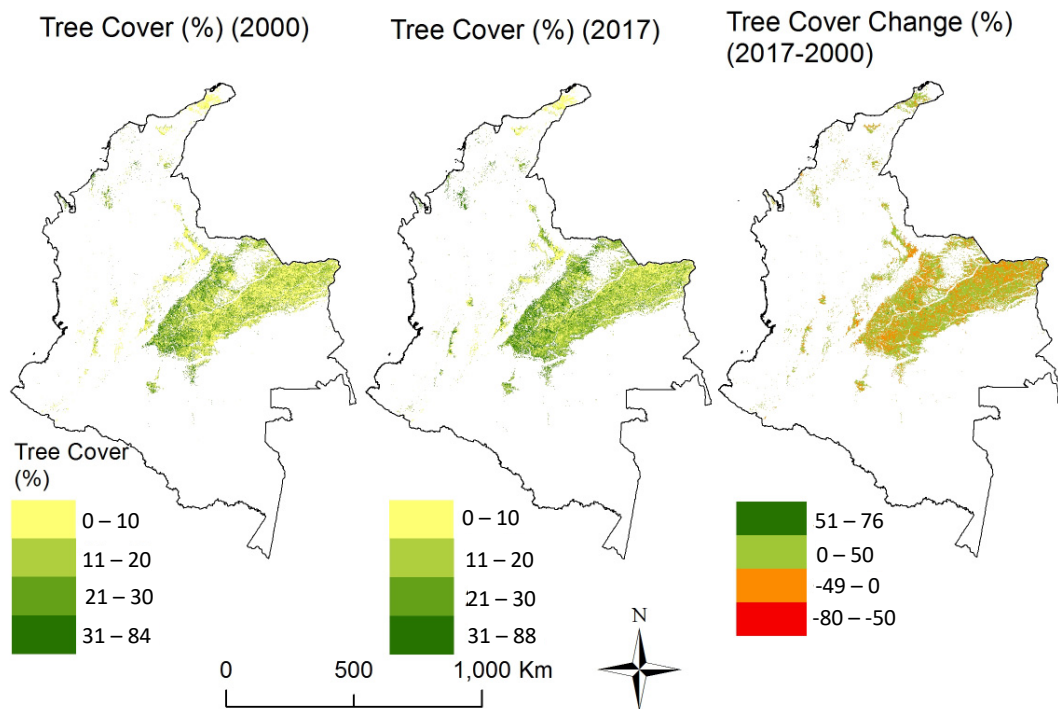
Figure 2. Tree cover change from 2000 to 2017 in grasslands.

3.2. Biomass Carbon Stocks

The TBC stock increased by 17% from 2000 to 2017 (Table 3). TBC stocks in Colombian grassland were 0.41 and 0.48 petagrams (Pg) C in 2000 and 2017, respectively (Table 3).

Table 3. Average and total biomass carbon stocks on Colombian grassland in 2000 and 2017.

Biomass Carbon	Average (SD) (Mg ha^{-1})			Total (Pg C)		
	2000	2017	Change	2000	2017	Change
Above ground	27 (14)	31 (14)	4	0.33	0.38	0.05
Total biomass	34 (18)	39 (18)	5	0.41	0.48	0.07

Land area with a C stock < 10 Mg ha^{-1} decreased from 2000 to 2017, and land area with C stocks of 26–100 Mg ha^{-1} increased (Table 4).

Table 4. Land area carbon stocks in 2000 and 2017.

Total Carbon Stocks (Mg ha^{-1})	2000		2008		2017	
	ha	%	ha	%	ha	%
≤10	489,333	4	610,508	5	355,760	3
11–25	4,967,851	40	2,715,698	22	3,063,775	25
26–50	4,937,931	40	6,199,358	50	6,207,735	50
51–75	1,185,878	10	1,968,009	16	1,796,833	15
76–100	514,348	4	575,421	5	643,622	5
>100	212,545	2	238,892	2	240,161	2
Total	12,307,887	100	12,307,887	100	12,307,887	100

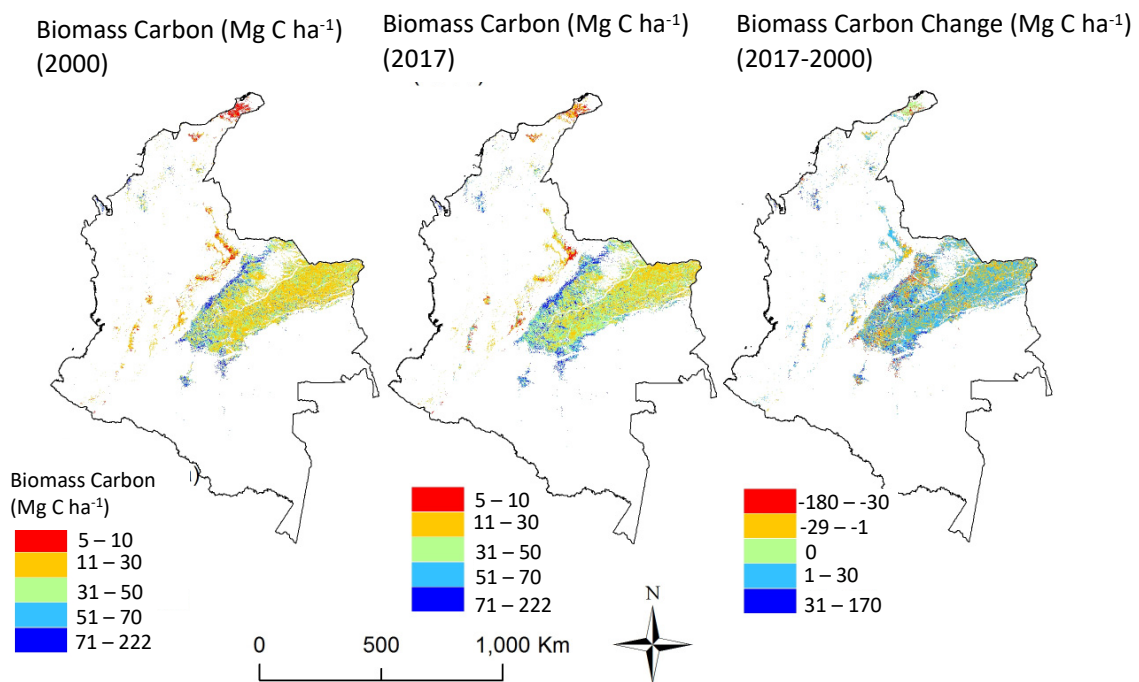The grassland biomass carbon stock maps are indicated in Figure 3.

Figure 3. Biomass carbon stocks change (Mg ha^{-1}) from 2000 to 2017.

3.3. Carbon Stock Gaps by Ecofloristic Zones

Average 2017 carbon stock values ranged from 5 and 122 Mg ha^{-1}. The highest average stock per hectare was recorded in the tropical rainforest ecofloristic zone, which accounts for 12% of total grassland. The highest carbon stock density and variation occurred in tropical rainforest, while the lowest carbon stock per hectare and the lowest variation were found in shrubland ecofloristic zones (Figure 4). About 73% of the total grassland had carbon stocks less than the < 75th percentile. Increasing these stocks to the current 75th percentile level would increase total stocks by approximately 0.15 Pg C (0.57 Pg CO_2e). By the same token, about 46% of grasslands have carbon stocks lower than the median (Figure 4). Increasing these carbon stocks to the median value would increase total stocks by 0.06 Pg C (0.2 Pg CO_2e).
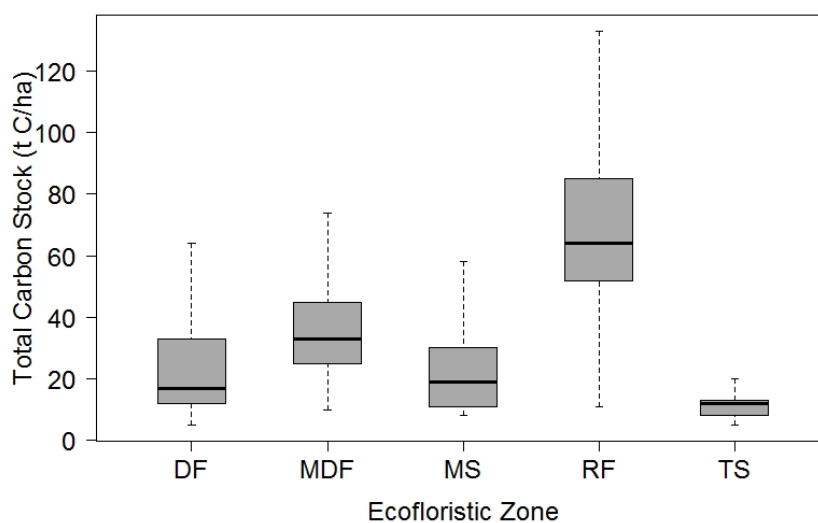

Figure 4. Variation in percentile carbon stocks in tropical dry forest (DF), moist deciduous forest (MDF), mountain system (MS), rain forest (RF), and tropical shrubland (TS).

Figure 5 indicates the spatial distribution of grazing lands with different levels of biomass carbon gaps. This helps identify priority areas for silvopastoral system interventions in Colombia.
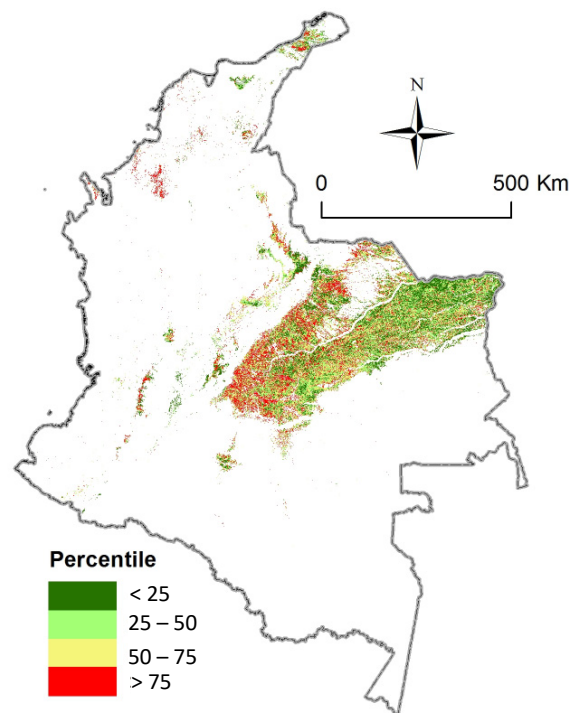

Figure 5. Priority areas for increasing Colombian grassland carbon stocks.

4. Discussion

Tree cover across all grasslands showed an increasing trend between 2000 and 2017. Trends in tree cover in grasslands found here support the same conclusions of more general studies on tree cover change, e.g., Sánchez-Cuervo et al. [21], who found that woody vegetation showed an increasing trend from 2001 to 2010 at the national scale in Colombia. This was mainly attributed to woody regrowth of trees following land abandonment resulting from armed conflicts, economic development, and increase in rainfall [21,22]. However, Sánchez-Cuervo et al. [21] reported that woody cover decreased by about 5% between 2000 and 2010, which was mainly due to intensive management of grasslands. The difference between these earlier results and ours may simply be a result of our study analyzing a longer time period, and the inconsistency in trends may be a function of changing management dynamics.

Zomer et al. [11,12] reported that the contribution of trees on global arable land was over 4 times higher than when estimated with IPCC default values [19]. Chapman et al. [23] also reported that trees in the global crop and pasture lands store about 3.07 and 3.86 Pg carbon in their aboveground biomass, respectively. Similarly, this study found that carbon stocks in the grassland of Colombia has likely also been underestimated. We found mean values of 34 Mg C ha^{-1} in 2000 and 39 Mg C ha^{-1} in 2017, which is more than four times larger than the IPCC Tier 1 global estimate of 8 Mg C ha^{-1} [19]. On the contrary, the global study by Liu et al. [24] reported that the TBC in grasslands and croplands did not show significant change during 1993–2010. Liu et al. [24] used harmonized Vegetation Optical Depth (VOD) data for 1993 onwards derived from a series of passive microwave satellite sensors to estimate above ground canopy in forest and non-forest land use types [25].

Zomer et al. [11,12] reported an average biomass carbon stock of 53 Mg ha^{-1} in Colombian arable land in 2000, demonstrating that trees in productive systems can significantly increase carbon stocks in Colombia. In a meta-analysis, Feliciano et al. [26] found that SPS that use controlled grazing practices and appropriate pasture species can increase average aboveground carbon sequestration

by 2.29–6.54 Mg ha^{-1} yr^{-1}. López-Santiago et al. [27] reported that *Leucaena leucocephala* (shrub legume) and *Panicum maximum* grass based SPS contain higher aboveground (19.6 ± 1.6 Mg ha^{-1}) and belowground (7.7 ± 0.90 Mg ha^{-1}) biomass compared with deciduous tropical forest and grass monoculture systems in Mexico. This led to a rapid expansion of SPS in Mexico. Our study showed that average Colombian grasslands contained 34 Mg ha^{-1} in the same year. While 36% less than that of arable land, these significant levels of carbon in silvopastoral systems suggest a large opportunity for climate change mitigation, especially when considering the existing and planned areal extent of silvopastoral systems in Colombia. About 13% and 12% of the total area of Colombia was grazing and cultivated lands, respectively, in 2015 [28].

The potential carbon stock of SPS is notable for its ability to accumulate carbon over relatively short time frames. Increasing soil carbon in Colombian grasslands could take decades [29]. In contrast, carbon stocks in tree biomass can be accumulated in less than a decade. Trees have the additional benefit in that they help maintain and increase soil carbon stocks. Given the swift action necessary to limit global warming below the <2° climate change goal (by 2030 according to the IPCC), integrating trees into multi-use landscapes like SPS is an important pathway to meeting mitigation goals in a timely manner. Importantly, trees also regulate soil conditions, including organic matter content, fertility, structure, erosion resistance, and moisture content, during extreme events such as heavy precipitation and drought. Maintaining a hospitable soil environment has a dramatic effect on the presence of N-fixing bacteria, which are crucial in cropping systems with little or no N fertilizer inputs [12]. In turn, all of these mechanisms extend and improve productivity, both in terms of quality and quantity.

Silvopastoral system grasslands go beyond carbon stock potential to offer myriad co-benefits. SPS have direct positive impacts on the livelihoods of producers and environmental quality [30]. Trees create micro-climates that help protect crops and livestock from sun, wind, and extreme temperatures [31,32]. SPS have also been shown to reduce plant and animal production seasonality, reduce ruminal methane production, and increase biodiversity and natural pest control mechanisms as compared to conventional systems [7]. It is important to note that there may be significant trade-offs associated with integrating trees into some production systems. Smallholders rely on these systems as their source of livelihood. As such, increasing tree cover in SPS must be tested locally as one of the suites of potential climate-smart agricultural solutions with the aim of developing a project portfolio that minimizes tradeoffs and maximizes co-benefits.

The management of silvopastoral system trees can minimize trade-offs through complementary uses that augment climate resiliency and diversify household income. Complementary uses may include, timber plantations, living fences, tree alleys, windbreaks, fuelwood, perennial crops, and fodder banks [30,33]. For example, *Albizia saman* (syn. *Samanea saman*) trees improved forage production under their canopy [34], and their palatable pods are suitable as a dry season feed supplement [35]. Smallholder agroforestry systems can continue to increase their carbon stocks while also producing timber through select harvesting of high economic value tree species [36]. Colombian pastoral systems face serious complications because of climate change. The country is well poised to create national initiatives around SPS and other mitigation initiatives [16]. Indeed, the Colombian livestock sector will need to increase carbon efficiency in order to remain competitive on the international market. Our study reveals significant potential for addressing climate change mitigation and an array of co-benefits through implementation of SPS in Colombian grasslands. This suggests that SPS can significantly contribute to the NDCs and NAMAs of Colombia and other Latin American countries, as well as addressing other national commitments such as the United Nations 2030 Sustainable Development Goals and national regulatory targets.

However, scaling up SPS will not be straightforward. Calle et al. [37] demonstrated the importance of adequate technical assistance to farmer adoption of SPS in Colombia. Similarly, it is equally important to consider the quality and source of genetic material when promoting tree planting programs [38]. Market incentives including factors related to lower costs and/or higher benefits are important for silvopastoral system technology adoption [39]. In spite of the growing international

demand for carbon-efficient and environmentally friendly animal products [16], very few producers will plant trees in grasslands just for the sake of climate change mitigation [40]. However, awareness of the implications of land use decisions and the increased productivity and resiliency of SPS over conventional systems, in conjunction with adequate technical and policy support [15], has been shown to incentivize adoption [41].

The MODIS data are low-resolution and may overestimate carbon stock estimates in grasslands by including different land uses like wooded areas and forest patches into grazing land pixels [23]. However, our study showed the potential of SPS to mitigate climate by sequestering more carbon in woody biomass. We assumed a linear increase in biomass carbon stocks with increasing tree cover, which may not be accurate in all cases. For example, species functional traits play a role in carbon dynamics by influencing species productivity [42].

We considered grasslands as proxy for silvopastoral systems as maps detailing silvopastoral systems were not identified. It is important to considered trade-offs across expected ecosystem services from increasing tree cover in grassland biomes. For example, a study on the effects of increased woody vegetation following fire suppression in Brazilian Cerrado reported a decline in plant and ant species by 27% and 35%, respectively [43]. Bond et al. [44] and Parr et al. [45] also reported that a large-scale increase in tree cover in grasslands could impact African grassland biomes. Several similar comments [46,47] were generated by the optimistic analysis of the global tree restoration potential by Bastin et al. [48].

As discussed in Lusiana et al. [49], however, common measures of pixel-level uncertainty in both classification and assigned C stock do not stand in the way of fairly narrow confidence intervals for aggregated data as used in national GHG accounting. The specific reduction of uncertainty with aggregation depends on the spatial structure of land cover change. For an Indonesian forest margin landscape, the study concluded that for the 1 km^2 scale of aggregation error was reduced below a defined tolerance. Further studies of this type on SPS in Columbia would be relevant.

The study is not without limitations. Data used in this study were generated on a global scale and thus may have some inaccuracies when down-scaled to a national analysis. Tree cover was measured via remote sensing and interpreted from MODIS Vegetation Continuous Fields (VCF) product; as such, it is an estimate of percentage crown cover, not tree density or tree biomass per se, and is likely to underestimate or overestimate tree cover [11]. Remotely sensed data should be validated with ground-level measurements [10], but this was not possible for logistical reasons during this study. We assumed a linear increase in biomass carbon stocks with increasing tree cover, which provides an approximation of biomass. We considered grasslands as proxy for silvopastoral systems as silvopastoral systems are a type of grazing system. Our estimates can inform the potential for further increase in C storage in SPS, but do not indicate yet what types of policy change and farmer innovation will be needed to achieve this.

5. Conclusions

We estimated carbon stocks in Colombian grasslands using remotely sensed tree cover data from MODIS and IPCC Tier 1 values. The results help clarify current and potential grassland carbon stocks at a national scale. Tree cover and carbon stocks increased significantly from 2000 to 2017. There remains high spatial variability, and regions with low tree cover have significant potential for increasing carbon stocks. This approach, along with ground-level data validation, could be useful in creating targets for planning NDCs and NAMAs in Latin American countries. Co-benefits include improved productivity and socioeconomic outcomes, climate resilience, and environmental conservation. Moving forward, it will be essential to create an enabling environment for the implementation of SPS in terms of policy, land governance, investment, capacity development, and international cooperation.

References

1. Wollenberg, E.; Richards, M.; Smith, P.; Havlík, P.; Obersteiner, M.; Tubiello, F.N.; Herold, M.; Gerber, P.; Carter, S.; Reisinger, A.; et al. Reducing emissions from agriculture to meet the 2 °C target. *Glob. Chang. Biol.* **2016**, *22*, 3859–3864. [CrossRef] [PubMed]

2. Smith, P. Soil carbon sequestration and biochar as negative emission technologies. *Glob. Chang. Biol.* **2016**, *22*, 1315–1324. [CrossRef]

3. Roe, S.; Streck, C.; Obersteiner, M.; Frank, S.; Griscom, B.; Drouet, L.; Fricko, O.; Gusti, M.; Harris, N.; Hasegawa, T.; et al. Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Chang.* **2019**, *9*, 817–828. [CrossRef]

4. Witkowski, K.; Medina, D. *Agriculture in the New Climate Action Plans of Latin America (Intended Nationally Determined Contributions)*; Inter-American Institute for Cooperation on Agriculture: San Jose, Costa Rica, 2016.

5. Griscom, B.W.; Adams, J.; Ellis, P.W.; Houghton, R.A.; Lomax, G.; Miteva, D.A.; Schlesinger, W.H.; Shoch, D.; Siikamäki, J.V.; Smith, P.; et al. Natural climate solutions. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 11645–11650. [CrossRef] [PubMed]

6. IPCC. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*; Shukla, P.R., Skea, J., Buendia, E.C., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., et al., Eds.; IPCC: Geneva, Switzerland, 2019.

7. Cardona, C.A.C.; Naranjo Ramírez, J.F.; Tarazona Morales, A.M.; Murgueitio Restrepo, E.; Charaá Orozco, J.D.; Ku Vera, J.; Solorio Saánchez, F.J.; Flores Estrada, M.X.; Solorio Saánchez, B.; Barahona Rosales, R. Contribution of intensive silvopastoral systems to animal performance and to adaptation and mitigation of climate change. *Rev. Colomb. Cienc. Pecu.* **2014**, *27*, 76–94.

8. Calle, Z.; Murgueitio, E.; Chará, J.; Molina, C.H.; Zuluaga, A.F.; Calle, A. A Strategy for Scaling-Up Intensive Silvopastoral Systems in Colombia. *J. Sustain. For.* **2013**, *32*, 677–693.

9. Van Dijk, S.; Tennigkeit, T.; Wilkes, A. *Climate-Smart Livestock Sector Development: The State of Play in NAMA Development*; CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS): Copenhagen, Denmark, 2015.

10. Cardinael, R.; Umulisa, V.; Toudert, A.; Olivier, A.; Bockel, L.; Bernoux, M. Revisiting IPCC Tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems. *Environ. Res. Lett.* **2018**, *13*, 12. [CrossRef]

11. Zomer, R.; Trabucco, A.; Coe, R.; Place, F.; van Noordwijk, M.; Xu, J. *Trees on Farms: An Update and Reanalysis of Agroforestry's Global Extent and Socio-Ecological Characteristics*; World Agroforestry Centre (ICRAF): Bogor, Indonesia, 2014.

12. Zomer, R.J.; Neufeldt, H.; Xu, J.; Ahrends, A.; Bossio, D.; Trabucco, A.; Van Noordwijk, M.; Wang, M. Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets. *Sci. Rep.* **2016**, *6*, 29987. [CrossRef]

13. Rosenstock, T.S.; Wilkes, A.; Jallo, C.; Namoi, N.; Bulusu, M.; Suber, M.; Mboi, D.; Mulia, R.; Simelton, E.; Richards, M.; et al. Making trees count: Measurement and reporting of agroforestry in UNFCCC national communications of non-Annex I countries. *Agric. Ecosyst. Environ.* **2019**, *284*, 106569. [CrossRef]

14. FEDEGAN. *Cifras de Referencia del Sector Ganadero Colombiano*; FEDEGAN Federacioún Colombiana de Ganaderos: Bogota, Colombia, 2018.

15. Tapasco, J.; LeCoq, J.F.; Ruden, A.; Rivas, J.S.; Ortiz, J. The Livestock Sector in Colombia: Toward a Program to Facilitate Large-Scale Adoption of Mitigation and Adaptation Practices. *Front. Sustain. Food Syst.* **2019**, *3*, 61. [CrossRef]

16. Lerner, A.M.; Zuluaga, A.F.; Chará, J.; Etter, A.; Searchinger, T. Sustainable Cattle Ranching in Practice: Moving from Theory to Planning in Colombia's Livestock Sector. *Environ. Manag.* **2017**, *60*, 176–184. [CrossRef] [PubMed]

17. ESA. *Land Cover CCI: Product User Guide Version 2.0*; UCL-Geomatics: London, UK, 2017.

18. Dimiceli, C.; Carroll, M.; Sohlberg, R.; Kim, D.H.; Kelly, M.; Townshend, J.R.G. *MOD44B MODIS/Terra Vegetation Continuous Fields Yearly L3 Global 250m SIN Grid V006*; LP DAAC: Sioux Falls, SD, USA, 2020.

19. Ruesch, A.; Gibbs, H.K. *New IPCC Tier-1 Global Biomass Carbon Map For the Year 2000*; Oak Ridge National Laboratory: Oak Ridge, YN, USA, 2008.

20. Heiskanen, J.; Liu, J.; Valbuena, R.; Aynekulu, E.; Packalen, P.; Pellikka, P. Remote sensing approach for spatial planning of land management interventions in West African savannas. *J. Arid Environ.* **2017**, *140*, 29–41. [CrossRef]

21. Sánchez-Cuervo, A.M.; Aide, T.M.; Clark, M.L.; Etter, A. Land Cover Change in Colombia: Surprising Forest Recovery Trends between 2001 and 2010. *PLoS ONE* **2012**, *7*, e43943. [CrossRef]

22. Fagua, J.C.; Baggio, J.A.; Ramsey, R.D. Drivers of forest cover changes in the Chocó-Darien Global Ecoregion of South America. *Ecosphere* **2019**, *10*, e02648. [CrossRef]

23. Chapman, M.; Walker, W.S.; Cook-Patton, S.C.; Ellis, P.W.; Farina, M.; Griscom, B.W.; Baccini, A. Large climate mitigation potential from adding trees to agricultural lands. *Glob. Chang. Biol.* **2020**, *26*, 4357–4365. [CrossRef]

24. Liu, Y.Y.; Van Dijk, A.I.J.M.; De Jeu, R.A.M.; Canadell, J.G.; McCabe, M.F.; Evans, J.P.; Wang, G. Recent reversal in loss of global terrestrial biomass. *Nat. Clim. Chang.* **2015**, *5*, 470–474. [CrossRef]

25. Liu, Y.Y.; De Jeu, R.A.M.; McCabe, M.F.; Evans, J.P.; Van Dijk, A.I.J.M. Global long-term passive microwave satellite-based retrievals of vegetation optical depth. *Geophys. Res. Lett.* **2011**, *38*. [CrossRef]

26. Feliciano, D.; Ledo, A.; Hillier, J.; Nayak, D.R. Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? *Agric. Ecosyst. Environ.* **2018**, *254*, 117–129. [CrossRef]

27. López-Santiago, J.G.; Casanova-Lugo, F.; Villanueva-López, G.; Díaz-Echeverría, V.F.; Solorio-Sánchez, F.J.; Martínez-Zurimendi, P.; Aryal, D.R.; Chay-Canul, A.J. Carbon storage in a silvopastoral system compared to that in a deciduous dry forest in Michoacán, Mexico. *Agrofor. Syst.* **2019**, *93*, 199–211. [CrossRef]

28. ESA. *300 m Annual Global Land Cover Time Series from 1992 to 2015*; ESA Climate Change Initiative: Oxford, UK, 2017.

29. Steiner, J.L.; Franzluebbers, A.J.; Neely, C.; Ellis, T.; Aynekulu, E. Enhancing Soil and Landscape Quality in Smallholder Grazing Systems. In *Enhancing Soil and Landscape Quality in Smallholder Grazing Systems*; Lal, R., Stewart, B.A., Eds.; CRC Press: Boca Raton, FL, USA, 2014; pp. 63–112.

30. Montagnini, F.; Ibrahim, M.; Murgueitio Restrepo, E. Silvopastoral Systems and Climate Change Mitigation in Latin America. *Bois For. Trop.* **2013**, *316*, 3–16. [CrossRef]

31. Dinesh, D.; Campbell, B.; Bonilla-Findji, O.; Richards, M. (Eds.) *10 Best Bet Innovations for Adaptation in Agriculture: A Supplement to the UNFCCC NAP Technical Guidelines*; CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS): Wageningen, The Netherlands, 2017.

32. Eekhout, J.; de Vente, J. Assessing the effectiveness of Sustainable Land Management for large-scale climate change adaptation. *Sci. Total Environ.* **2018**, *654*, 85–93. [CrossRef] [PubMed]

33. Chara, J.; Reyes, E.; Peri, P.; Otte, J.; Arce, E.; Schneider, F. *Silvopastoral Systems and Their Contribution to Improved Resource Use and Sustainable Development Goals: Evidence from Latin America*; The Food and Agriculture Organization of the United Nations: Roma, Italy, 2018.

34. Durr, P.; Gangel, J. Enhanced forage production under Samanea saman in a subhumid tropical grassland. *Agrofor. Syst.* **2002**, *54*, 99–102. [CrossRef]

35. Durr, P. The biology, ecology and agroforestry potential of the raintree, Samanea saman (Jacq.) Merr. *Agrofor. Syst.* **2001**, *51*, 223–237. [CrossRef]

36. Roshetko, J.; Lasco, R.; Delos Angeles, M. Smallholder agroforestry systems for carbon storage. *Mitig. Adapt. Strateg. Glob. Chang.* **2007**, *12*, 219–242. [CrossRef]

37. Calle, A.; Montagnini, F.; Zuluaga, A.F. Farmer's perceptions of silvopastoral system promotion in Quindío, Colombia. *Bois For. Trop.* **2009**, *300*, 79–94. [CrossRef]

38. Roshetko, J.; Dawson, I.; Urquiola, J.; Lasco, R.; Leimona, B.; Weber, J.; Bozzano, M.; Lillesø, J.; Graudal, L.; Jamnadass, R. To what extent are genetic resources considered in environmental service provision? A case study based on trees and carbon sequestration. *Clim. Dev.* **2018**, *10*, 755–768. [CrossRef]

39. Iiyama, M.; Derero, A.; Kelemu, K.; Muthuri, C.; Kinuthia, R.; Ayenkulu, E.; Kiptot, E.; Hadgu, K.; Mowo, J.; Sinclair, F.L. Understanding patterns of tree adoption on farms in semi-arid and sub-humid Ethiopia. *Agrofor. Syst.* **2017**, *91*, 271–293. [CrossRef]

40. Mbow, C.; Van Noordwijk, M.; Luedeling, E.; Neufeldt, H.; Minang, P.A.; Kowero, G. Agroforestry solutions to address food security and climate change challenges in Africa. *Curr. Opin. Environ. Sustain.* **2014**, *6*, 61–67. [CrossRef]

41. Murgueitio, E.; Calle, Z.; Uribe, F.; Calle, A.; Solorio, B. Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. *For. Ecol. Manag.* **2011**, *261*, 1654–1663. [CrossRef]

42. Lohbeck, M.; Winowiecki, L.; Aynekulu, E.; Okia, C.; Vågen, T.G. Trait-based approaches for guiding the restoration of degraded agricultural landscapes in East Africa. *J. Appl. Ecol.* **2018**, *55*, 59–68. [CrossRef]

43. Abreu, R.C.R.; Hoffmann, W.A.; Vasconcelos, H.L.; Pilon, N.A.; Rossatto, D.R.; Durigan, G. The biodiversity cost of carbon sequestration in tropical savanna. *Sci. Adv.* **2017**, *3*, e1701284. [CrossRef] [PubMed]

44. Bond, W.J.; Stevens, N.; Midgley, G.F.; Lehmann, C.E.R. The Trouble with Trees: Afforestation Plans for Africa. *Trends Ecol. Evol.* **2019**, *34*, 963–965. [CrossRef] [PubMed]

45. Parr, C.L.; Gray, E.F.; Bond, W.J. Cascading biodiversity and functional consequences of a global change-induced biome switch. *Divers. Distrib.* **2012**, *18*, 493–503. [CrossRef]

46. Friedlingstein, P.; Allen, M.; Canadell, J.G.; Peters, G.P.; Seneviratne, S.I. Comment on "The global tree restoration potential". *Science* **2019**, *366*, eaay8060. [CrossRef]

47. Skidmore, A.K.; Wang, W.; de Bie, K.; Pilesjo, P. Comment on "The global tree restoration potential". *Science* **2019**, *366*, eaaz0111. [CrossRef]

48. Bastin, J.F.; Finegold, Y.; Garcia, C.; Mollicone, D.; Rezende, M.; Routh, D.; Zohner, C.M.; Crowther, T.W. The global tree restoration potential. *Science* **2019**, *364*, 76–79. [CrossRef]

49. Lusiana, B.; van Noordwijk, M.; Johana, F.; Galudra, G.; Suyanto, S.; Cadisch, G. Implications of uncertainty and scale in carbon emission estimates on locally appropriate designs to reduce emissions from deforestation and degradation (REDD+). *Mitig. Adapt. Strateg. Glob. Chang.* **2014**, *19*, 757–772. [CrossRef]