Quantification of climate change mitigation benefits from expansion of silvopastoral systems
An analytical proof of concept for Colombia

Working Paper No. 295

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

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Abstract

Nine Latin American countries have identified silvopastoral practices—trees and livestock systems combined—as a key component of their Nationally Determined Contributions (Paris Climate Accord) or Nationally Appropriate Mitigation Actions (Bali Action Plan). However, the climate change mitigation potential of silvopastoral systems is not well studied. This study estimates the mitigation potential of silvopastoral practices via carbon sequestration in woody biomass in Colombian grassland. We derived tree cover maps from the MODIS Version 6 Vegetation Continuous Field MOD44B dataset for 2000-2017 and employed the Intergovernmental Panel on Climate Change Tier 1 default carbon storage estimates to calculate current and potential above- and below-ground biomass carbon stocks in existing grasslands. Total tree cover across all Colombian grasslands increased by about 20% from year 2000 (15%) to 2017 (18%). Concomitantly, the total (above- and belowground biomass carbon combined) biomass carbon (TBC) stocks increased by about 17% from 2000 (mean = 34 t C ha⁻¹; SD =18) to 2017 (mean = 39 t C ha⁻¹; SD =18). TBC stocks in Colombian grassland were 0.41 and 0.48 Petagrams (Pg) C in 2000 and 2017, respectively. Average 2017 carbon stock values ranged from 5 and 222 t C ha⁻¹; this suggests potential for increasing carbon stocks in areas of low tree cover. About 73% of the total grassland had TBC less than the <75th percentile. Increasing all carbon stocks to the current median and 75th percentile levels would increase total carbon stocks by about 0.06 Pg C (0.2 Pg CO₂e) and 0.15 Pg C (0.57 Pg CO₂e), respectively. This study provides valuable data on the climate change mitigation potential of silvopastoral systems as part of the Nationally Determined Contributions and Nationally Appropriate Mitigation Actions of Colombia and other Latin American countries. We highlighted on some of the potential impacts of increasing tree cover on grassland biomes. Limitations include a likely underestimation of tree cover, and an assumed direct linear relationship between tree cover and biomass were identified.

Keywords: Savanna ecosystem; land restoration; grazing management, silvopastoral systems (SPS); climate change; Latin America
About the authors

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**Robert Zomer** is a landscape ecologist with a broad interest in plant community, forest and agricultural ecology, and using geographic information systems, remote sensing, and environmental modeling for landscape-level spatial analysis. He has many years of experience working in the Himalayas, East Africa, South America and throughout Asia, including positions at the International Centre for Integrated Mountain Development in Nepal, the International Water Management Institute in Sri Lanka, and the International Centre for Research in Agroforestry in Kenya. His current interests focus on the application of advanced spatial tools at global to local levels, ecosystem management, and the impacts of climate change on terrestrial ecosystems and biodiversity conservation.

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### Acronyms

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<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information Systems</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>GLC</td>
<td>Global Land Cover</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>NAMA</td>
<td>Nationally Appropriate Mitigation Action</td>
</tr>
<tr>
<td>NDC</td>
<td>Nationally Determined Contribution</td>
</tr>
<tr>
<td>SPS</td>
<td>Silvopastoral systems</td>
</tr>
</tbody>
</table>
Introduction

Meeting the < 2 °C target set by the Paris Climate Agreement is predicated on significant greenhouse gas (GHG) emissions reductions in the agriculture and land use sector (Smith, 2016; Wollenberg et al., 2016). This sector is a major contributor to climate change, yet may also be part of the solution. Land use interventions offer potential for meeting 30% of the Paris Agreement’s ambition (Griscom et al., 2017; Witkowski and Medina, 2016). Most agriculture and land use mitigation interventions target reducing emissions from livestock systems, rice systems, deforestation, and nitrogen fertilizer. Another potentially significant intervention option is often overlooked: mitigation through agroforestry.

Agroforestry is the intentional use of trees on farms, ranches, and other managed landscapes. Agroforestry helps mitigate climate change by increasing carbon stocks in two important ways. First, trees accumulate carbon in woody biomass and soils (Yamamoto et al., 2007; Rueda et al. 2011). Secondly, agroforestry extends and increases land productivity as compared to conventional systems, thus reducing the incentive to establish new grasslands, and, consequently, reducing deforestation and landscape degradation rates. Though the magnitude of carbon accumulation possible through agroforestry is sometimes relatively small to other mitigation options, the vast area where it is technically feasible makes it particularly attractive as compared with alternative options.

Nevertheless, agroforestry investments tend to lag behind those of other mitigation options. This is, in part, because there are very few estimates of the benefits of agroforestry for carbon emissions mitigation. Most global and regional calculations of carbon stocks ignore tree cover (Zomer et al., 2016). Zomer et al. (2014, 2016) used remote sensing based data for accounting for the carbon stock of trees in cropping systems worldwide. This work demonstrated that
current carbon stock calculations in agroforestry are vastly underestimated, and that corrections to include carbon stocks in woody biomass are warranted. However, Zomer et al. (2016) only considers agroforestry systems with crop production. There are many agroforestry systems outside of arable cropland, including silovapastural systems (SPS). Quantification of the potential carbon sequestration in these systems is crucial for enabling financing, policy, and programmatic actions. Where targets have been set, the estimates have subsequently informed the direction of national policy (e.g., the Indian Agroforestry Policy) and international commitments (e.g., Viet Nam’s Nationally Determined Contributions to the Paris Climate Agreement). This suggests that quantification of potential carbon targets and benefits is a crucial step in creating an enabling environment for investment in emissions reductions through agroforestry.

SPS are agroforestry arrangements that combine grassland fodder plants, such as grasses and legumes, with grazing animals and complementary-use trees (Calle et al., 2013). Like other agroforestry systems, SPS are an important climate intervention in terms of increasing carbon accumulation in trees and soils, as well as reduced deforestation and land degradation (i.e., climate change mitigation and adaptation). In addition, it has been shown that the use of forage trees that cattle can browse, improve animal productivity due to its high nutritional quality. Some of these tree forages (e.g., *Leucaena, Saman*) contain secondary metabolites (i.e. condensed tannins and saponins) with anti-methanogenic potential resulting in enteric methane emissions reductions (Valencia Salazar et al., 2018).

Livestock production for milk and meat is a key economic activity for the Latin American agricultural sector. It is also a major source of greenhouse gas (GHG), accounting for about 58 - 70% of the overall agricultural emissions in Latin America (Van Dijk et al., 2015). Grazing grassland occupies more than 550 million hectares of land in Latin America. It is characterized
by relatively high degrees of environmental degradation, and minimal rural employment (Durango et al., 2017). Nine Latin American countries have consequently identified SPS as a priority within their National Determined Contributions (NDCs) to the Paris Climate Agreement (Calle et al., 2013; Cardona et al., 2014) and Nationally Appropriate Mitigation Actions (NAMAs).

Colombia in particular has faced climactic challenges in the livestock sector (Tapasco et al., 2019). The El Niño-Southern Oscillation (ENSO) phenomenon in the last decade have caused US$1.8 billion in losses (FEDEGAN, 2018). Colombia has developed initiatives to address mitigation and adaptation to climate change (Tapasco et al., 2019). The Colombian government and National Livestock Federation (FEDEGAN) have a strategy to reduce GHG emissions from the agricultural sector by 13.46 Mt CO₂e yr⁻¹ by 2030, and have specifically named conversion of current grasslands to SPS among priority mitigation activities (FEDEGAN, 2018). Importantly, Tapasco et al. (2019) also identified SPS as the most promising policy option for achieving this goal, and Lerner et al (2017) notes that the country is in an ideal position to create integrated plans for sustainable cattle intensification, including SPS, conservation, and restoration initiatives.

Zomer et al. (2014, 2016) reported an average biomass carbon stock of approximately 53 tC 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., (2018) found that SPS that use controlled grazing practices and appropriate pasture species can increase average aboveground carbon sequestration by 2.29 - 6.54 t C ha⁻¹ yr⁻¹. López-Santiago et al. (2018) reported that Leucaena leucocephala (shrub legume) and Panicum maximum grass based SPS contain higher aboveground (41.8 ± 3.30 Mg DM ha⁻¹) and belowground (16.4 ± 1.95 Mg DM ha⁻¹) compared with deciduous tropical forest and grass monoculture systems in
Mexico. This led to a rapid expansion of SPS in Mexico. However, the mitigation potential of converting conventional grasslands to SPS has not been yet been estimated. To address this gap, we adapt Zomer et al.’s (2016) approach used for croplands to estimate current biomass carbon stocks, as well as potential carbon stocks under large-scale conversion of existing grasslands to SPS.

**Methods**

**Conceptual approach**

This analysis is complementary to Zomer et al. (2016). The methodology has been adapted to spatially quantify carbon sequestration from tree cover in grasslands and estimate potential carbon stocks under widespread implementation of SPS. The methodological steps are as follows:

1. Define the extent of grasslands in the target area.
2. Derive the current level of tree cover.
3. Estimate the carbon stocks in above and belowground biomass based on tree cover data.
4. Estimate the potential increase in tree cover to the 25\(^{th}\) percentile, median, and 75\(^{th}\) percentile of 2017 biomass carbon stocks.
5. Quantify the difference between current and potential tree cover and carbon sequestration (‘silvopastoral gap’).

**Study area**

Given that both the Colombian government and independent researchers have identified SPS as a priority for achieving Colombia’s agricultural emission reduction goals (Tapasco et al., 2019), we focus on Colombia as a case study. As of 2015, Colombia had more than 12 million ha of grassland (13% of the national land mass) 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 Oreintales 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. Land cover and ecofloristic zones of Colombia, 2015](Source: European Space Agency, 2017a).

**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 (ESA, 2017a). 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 (ESA 2017). Percent tree cover was derived from the MODIS Version 6 Vegetation Continuous Field MOD44B dataset (Dimiceli et al., 2015). 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) (Dimiceli et al., 2015). A detailed description of the methodology used for this analysis is found in Zomer et al. (2014, 2016).

We used the default IPCC Tier 1 total carbon stock values for each ecofloristic zone as the minimum potential carbon stock values for 0% tree cover (Ruesch and Gibbs, 2008) (Table 1). The methodology used to determine these numbers is detailed in Zomer et al. (2016). 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. (2016). The biomass carbon value of the equivalent (or most similar) Global Land Cover (GLC) 2000 Mixed Forest class (Ruesch and Gibbs, 2008) was used as a surrogate above-ground biomass carbon value for each ecofloristic zone to simulate full tree cover (100%). Below-ground carbon sequestration potential was calculated using above-ground sequestration potential values and the root : shoot ratio for each of the ecofloristic zones as per IPCC Tier 1 values (Table 1) (Ruesch and Gibbs, 2008). Below- and above- ground 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, such that, for each ecofloristic zone:

- where tree cover= 0%, biomass carbon = Tier 1 value
- there are incremental linear increases as tree cover increases
- where tree cover = 100%, biomass carbon = maximum value for Mixed Forest

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 identify 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 those with medium potential, areas between the median and 75th percentile values as areas with low potential to increase carbon stocks and those with greater than 75th percentile values as areas which do not necessarily require any attention in the increase of carbon stocks. This approach is particularly useful for spatially targeting SPS-based mitigation actions (Heiskanen et al., 2017).

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

<table>
<thead>
<tr>
<th>Ecofloristic Zone</th>
<th>Area</th>
<th>Above ground carbon stock</th>
<th>Root to shoot ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ha</td>
<td>t C ha$^{-1}$</td>
<td>Minimum</td>
</tr>
<tr>
<td>Tropical Dry Forest</td>
<td>67,758</td>
<td>0.6</td>
<td>4</td>
</tr>
<tr>
<td>Tropical Moist deciduous Forest</td>
<td>9,487,070</td>
<td>77</td>
<td>8</td>
</tr>
<tr>
<td>Tropical Mountain System</td>
<td>1,076,967</td>
<td>8.8</td>
<td>6</td>
</tr>
<tr>
<td>Tropical Rainforest</td>
<td>1,469,597</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Tropical Shrubland</td>
<td>206,495</td>
<td>1.7</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>12,307,887</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

(Source: Ruesch and Gibbs, 2008)
Results

Estimates of tree-canopy cover on grassland in 2000, 2008 and 2017

Grassland tree cover per hectare ranged from 0% to 84% and 88% in 2000 and 2017 respectively across Colombian grasslands (Figure 2). For presentation purposes, we classify these results into 10%, 11-20% and 21-30%, and >30% tree cover as per Zomer et al. (2014) (Table 2). Total tree cover across all grasslands increased by about 20% from 2000 to 2017. 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% also increased across time, from 10% in 2000 to 12% in 2008 and 13% in 2017 (Table 2).

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

<table>
<thead>
<tr>
<th>Tree Cover (%)</th>
<th>2000</th>
<th>2008</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ha (%)</td>
<td>ha (%)</td>
<td>ha (%)</td>
</tr>
<tr>
<td>&lt;=10</td>
<td>5,507,090</td>
<td>3,210,585</td>
<td>3,319,775</td>
</tr>
<tr>
<td>11-20</td>
<td>3,883,571</td>
<td>4,861,344</td>
<td>4,700,027</td>
</tr>
<tr>
<td>21-30</td>
<td>1,715,737</td>
<td>2,708,461</td>
<td>2,709,611</td>
</tr>
<tr>
<td>&gt;30</td>
<td>1,201,488</td>
<td>1,527,496</td>
<td>1,578,474</td>
</tr>
<tr>
<td>Total</td>
<td>12,307,887</td>
<td>12,307,887</td>
<td>12,307,887</td>
</tr>
</tbody>
</table>
Figure 2. Tree Cover Change from 2000 to 2017
Sánchez-Cuervo et al. (2012) found that woody vegetation showed increasing trend from 2001 to 2010 at the national scale in Colombia. This was mainly attributed to woody regrowth resulted from tree/shrub recovery following land abandonment resulting from armed conflicts, economic development, and increase in rainfall (Fagua et al., 2019; PNUD, 2011; Sánchez-Cuervo et al., 2012). Contrary to our findings, however, Sánchez-Cuervo et al. (2012) reported that woody cover decreased in the Grasslands biome. According to the Global Forest Watch estimate, Colombia has lost about 3.72 M ha of tree cover (Global Forest Watch, 2020).

**Biomass carbon stocks**

The TBC carbon stock increased by about 17% from 2000 (mean = 34 t C ha$^{-1}$; SD = 18) to 2017 (mean = 39 t C ha$^{-1}$; SD = 18). Land area with <10 t C ha$^{-1}$ decreased from 2000 to 2017, and land area with 26 – 100 C ha$^{-1}$ increased (Table 4). TBC stocks in Colombian grassland were 0.41 and 0.48 Petagrams (Pg) C in 2000 and 2017, respectively. Average 2017 carbon stock values ranged from 5 and 222 t C ha$^{-1}$. The highest average stock per hectare was recorded in the tropical rainforest ecofloristic zone, which accounts for 12% of total grassland.

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

<table>
<thead>
<tr>
<th>Biomass carbon</th>
<th>Average (SD) (t C ha$^{-1}$)</th>
<th>Total (Pg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above ground</td>
<td>27 (14)</td>
<td>31 (14)</td>
</tr>
<tr>
<td>Total biomass</td>
<td>34 (18)</td>
<td>39 (18)</td>
</tr>
</tbody>
</table>
Table 4. Land area carbon stocks in 2000, 2008, and 2017

<table>
<thead>
<tr>
<th>Total carbon stocks (t C/ha)</th>
<th>2000</th>
<th></th>
<th>2008</th>
<th></th>
<th>2017</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ha</td>
<td>%</td>
<td>ha</td>
<td>%</td>
<td>ha</td>
<td>%</td>
</tr>
<tr>
<td>&lt;=10</td>
<td>489,333</td>
<td>4</td>
<td>610,508</td>
<td>5</td>
<td>355,760</td>
<td>3</td>
</tr>
<tr>
<td>11-25</td>
<td>4,967,851</td>
<td>40</td>
<td>2,715,698</td>
<td>22</td>
<td>3,063,775</td>
<td>25</td>
</tr>
<tr>
<td>26-50</td>
<td>4,937,931</td>
<td>40</td>
<td>6,199,358</td>
<td>50</td>
<td>6,207,735</td>
<td>50</td>
</tr>
<tr>
<td>51-75</td>
<td>1,185,878</td>
<td>10</td>
<td>1,968,009</td>
<td>16</td>
<td>1,796,833</td>
<td>15</td>
</tr>
<tr>
<td>76-100</td>
<td>514,348</td>
<td>4</td>
<td>575,421</td>
<td>5</td>
<td>643,622</td>
<td>5</td>
</tr>
<tr>
<td>&gt;100</td>
<td>212,545</td>
<td>2</td>
<td>238,892</td>
<td>2</td>
<td>240,161</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>12,307,887</td>
<td>100</td>
<td>12,307,887</td>
<td>100</td>
<td>12,307,887</td>
<td>100</td>
</tr>
</tbody>
</table>
Figure 3. Biomass carbon stock change from 2000 to 2017 (t C ha⁻¹).
Carbon stock gaps by ecofloristic zone

The highest carbon stock per hectare and the largest standard deviation occur in tropical rainforest; the lowest carbon stock per hectare and the smallest deviation occur in shrubland 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 CO₂e). By the same token, about 46% of grasslands have carbon stocks lower than the median (Figure 4). Increasing these carbon stocks to the median and 75th percentile would increase total stocks in Colombian grassland by 0.06 Pg C (0.2 Pg CO₂e) and 0.15 Pg C (0.57 Pg CO₂e), respectively.

![Bar chart showing carbon stock gaps by ecofloristic zone](image)

Figure 4. 25th, median, and 75th percentile carbon stock ha⁻¹ 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 level of biomass carbon gaps. This helps identify priority areas for SPS interventions in Colombia.
Discussion

Zomer et al. (2016) reported that the contribution of trees on global arable land was over 4 times higher than when estimated with IPCC default values. Similarly, this study found that carbon stocks in grassland of Colombia has likely also been under-estimated. We found mean values of 34 tC ha$^{-1}$ in 2000, and 39 tC ha$^{-1}$ in 2017, which is more than four times larger than the IPCC Tier 1 global estimate of 8 tC ha$^{-1}$. On the other hand, the global study by Liu et al. (2015) reported that the TBC in grasslands and croplands did not show significant change during 1993-2010. Liu et al. (2015) used harmonized VOD data for 1993 onwards derived from a series of passive microwave satellite sensors to estimates above ground canopy in forest and non-forest land use types (Liu et al., 2011).
Zomer et al. (2014), reported an average biomass carbon stock of about 53 tC ha\(^{-1}\) in Colombian arable land in 2000. Our study showed that average Colombian grasslands contained 36% less carbon (34 tC ha\(^{-1}\)) in the same year. While reduced by comparison to arable land, this significant levels of carbon in silvopastoral systems suggests 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 under grazing and cultivated lands, respectively.

Colombian grassland soils contain approximately 0.48 Pg C. The potential carbon stock of SPS is notable for its ability to accumulate carbon on relatively short time frames. The carbon content of soils changes over decades. 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 meet the <2\(^\circ\) 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 (Zomer et al 2016). In turn, all of these mechanisms extend and improve productivity, both in terms of quality and quantity.

SPS grasslands go beyond carbon stock potential to offer myriad co-benefits. SPS have direct positive impacts on the livelihoods of producers and environmental quality (Montagnini et al., 2013b). Trees create micro-climates that help protect crops and livestock from sun, wind, and extreme temperatures (Dinesh et al., 2017; Eekhout and de Vente, 2018). SPS systems 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 (Cuartas et al. 2014). 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, SPS must be tested locally as one of a suite of potential climate-smart agricultural solutions with the aim of developing a project portfolio that minimizes tradeoffs and maximizes co-benefits.

SPS trees also have complementary uses that augment climate resiliency and diversify household income. Complementary uses may include, e.g. timber plantations, living fences, tree alleys, windbreaks, fuelwood, perennial crops, silviculture, and fodder banks (Chara et al., 2018; Montagnini et al., 2013). 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 (Lerner et al., 2017). 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, national regulatory targets, etc.

However, scaling up SPS will not be straightforward. Calle et al. (2009) demonstrated the importance of adequate technical assistance to farmer adoption of SPS in Colombia. In spite of the growing international demand for carbon-efficient and environmentally-friendly animal products (Lerner et al 2017), very few producers will plant trees in grasslands just for the sake of climate change mitigation (Mbow et al., 2014). 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 (Tapasco et al, 2019), has been shown to incentivize adoption (Murgueitio et al., 2011).

**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 (Havlík et al., 2014; Serna et al., 2017; Tapasco et al., 2019). It is important to considered trade-offs across expected ecosystem services from increasing tree cover in grassland biome. 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 (Abreu et al., 2017). Bond et al. (2019) and Parr et al. (2012) also reported that large-scale increase in tree cover in grasslands could impact African grassland biomes. Several similar comments (e.g., Friedlingstein et al., 2019; Skidmore et al., 2019) were given to the global tree restoration potential optimistic analysis by Bastin et al. (2019).
Limitations of the study

The data used in this study was generated on a global scale, and thus may have some limitations when down-scaled to a national analysis. Tree cover is measured via remote sensing and interpreted from MODIS VCF; as such, it is an estimate of percentage crown cover, not tree density nor tree biomass per se, and is likely to underestimate tree cover (Zomer et al., 2014). Remotely sensed data should be validated with ground-level measurements. We assumed a linear increase in biomass carbon stocks with increasing tree cover, which may not be accurate in all cases. We considered grasslands as proxy to silvopastural systems as were not able to find maps under silvopastural systems.
References


Witkowski, K., Medina, D., 2016. Agriculture in the new climate action plans of Latin America (Intended Nationally Determined Contributions).


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