



Planting trees in livestock landscapes to protect soil and water also delivers carbon sequestration

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Abstract Ecuador has committed to climate change mitigation by reducing greenhouse gas emissions from anthropogenic activities, including livestock production. This sector can also contribute to mitigation by increasing carbon sequestration and storage capacity through increasing tree coverage. Although feasible, tree cover expansion would require agricultural land, creating a conflict with food production, thus appropriate areas need to be selected, and the impacts on livestock production quantified. Following water protection legislation and soil protection guidelines, we use a combination of measurements on 100 farms with land cover datasets to identify suitable

areas for increasing tree coverage in livestock landscapes. Land cover classification was performed in 2 km areas around 100 livestock farms in the coastal and Amazon regions in Ecuador. Riparian zones were identified following legislation and steepland pastures identified from a slope map. Pasture in riparian areas or steeplands (slope > 15%) were considered suitable for increasing tree coverage by restoration or silvopastoral systems (SPS). The impact of forest/silvopastoral on biomass production was quantified. Overall, 855 km of rivers were studied, between 1–18% of riparian areas were classified as pastures, whilst from the 85992 ha included in the land cover classification, 41668 ha were identified as steepland, 1–28% of steepland was covered by pastures. We estimate that steepland pasture conversion into forest could offset 1.8–10% of Ecuador's annual GHG emissions from the agricultural sector, but its impacts could represent a decrease > 50% of pasture biomass production at landscape level. Transformation of riparian and steepland pastures into SPS, could deliver important carbon sequestration, with a reduction in pasture biomass production of less than 20%.

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Introduction

The global population is expected to increase to ~11 billion by 2100 and with this, there will be an increase in demand for food (Valin et al. 2014). In addition, with economic shifts and without policies to the contrary, there is projected to be an increase in the demand for livestock derived products (Bodirsky et al. 2015). While increasing livestock production is technically feasible, by increasing the land area dedicated to pasture or forage production (Wirsén et al. 2010), any area-based productivity increase is constrained by other demands from society as climate change mitigation, which are as important as guaranteeing food production for human consumption. Reclaiming forest or wetland areas for agriculture purposes could result in a loss of carbon stocks (Tang et al. 2020), to the detriment of humankind which needs to guarantee a safe operating space for a sustainable planet Rockström (2009).

It has been estimated that globally, livestock contributes 3.1Gt CO₂ equivalent (CO₂ eq) emissions to the atmosphere (Caro et al. 2014), and is responsible for ~23% of the planetary temperature increase (Reisinger and Clark 2017). Despite its impacts on climate change, emissions reduction has so far been difficult to achieve, because it involves technological changes in the production systems, commercialization and consumer behaviour (Rivera-Ferre et al. 2016). The livestock sector can contribute to climate change mitigation, not only by reducing its direct emissions (Herrero et al. 2015), but also by avoiding carbon losses from current carbon stocks, and through increasing the carbon sequestration capacity of land used for rearing livestock (Iñamagua et al. 2022).

To limit global temperature increases to less than 1.5–2 °C above pre-industrial levels, negative emissions will almost certainly be required (Gasser et al. 2015), which could be partially delivered by halting deforestation and degradation (Houghton and Nassikas 2018), or forest restoration. Considering the dual requirement of reducing emissions and guaranteeing food provision, some studies (Lamb et al. 2016) have suggested frameworks such as land sparing, through increasing the productivity of existing agricultural land, so that other areas are taken out of production for conservation. Conversely, other studies have suggested land sharing as a strategy to deliver food and maintain the provision of other ecosystem services by

less intensive use of the land (Williams et al. 2018). Parallel to restoration, research on increasing the sustainability of production systems highlights the need for a climate friendly approach, capable of delivering food, while mitigating and adapting to climate change (Food and Agriculture Organization of the United Nations 2014). Increasing the density of trees in agricultural landscapes has been shown to deliver to both of these requirements.

Forest areas present an opportunity for an future increase in carbon storage (Daigneault et al. 2022). Nevertheless, strategies focused on land use conversion from pasture to forest can create conflicts, especially for developing regions, where smallholders own 28% of agricultural land. These conditions pose a challenge to transforming agricultural land into conservation areas, facing even legal challenges if governments want to encourage farmers to adopt a transition scheme. Policies aiming to maintain and increase carbon stocks on farmlands have been implemented worldwide, with mixed effects (Nakakaawa et al. 2010), and in some developing countries, current legislation encourages an increase in tree coverage in agricultural landscapes, albeit the primary objective of the policies has not been focused on increasing carbon sequestration, but rather on other objectives, such as water protection for buffer strips / riparian protection belts.

In this study we propose the use of existing guidelines for soil and water protection to increase carbon sequestration in agricultural/livestock landscapes. The overall aim of the paper is to assess the potential impact, in terms of carbon stocks, of tree cover increase in livestock landscapes of Ecuador, resulting from the full adoption of existing national legislation for river and water protection bodies (Ministerio del Ambiente and Ministerio de Agricultura, Ganadería, Acuacultura y Pesca 2012) and guidelines for avoiding soil erosion in steep areas (Shaxson 1999). In this study we: (1) identify suitable areas for increase in tree coverage in livestock landscapes based on water and soil protection principles, (2) quantify the potential changes in carbon stocks due to application of water and soil protection principles, (3) quantify the impacts of increasing tree coverage on pasture biomass production, and (4) assess the contribution of increasing tree coverage in livestock landscapes to offsetting emissions from agriculture in Ecuador.

Methods

The study was carried out on 100 farms, participating in the Climate Smart livestock project implemented by FAO-Ecuador. The overall methodology was divided in five stages outlined in in Fig. 1

On farm measurements

Farms were distributed in the amazon and coastal regions of Ecuador and reported livestock as one of the main activities (Fig. 2a). In each farm, two 1 ha plots were installed in areas identified by farm owners/administrators as areas representative of the farm pasture areas. Inside the 1 ha plots, a 0.1 ha circular plot was installed, its location inside the bigger plot was randomly selected and aimed to capture characteristics of trees on pastures (Fig. 2c). Height and diameter at breast height were recorded for all trees with a diameter at breast height ≥ 10 cm and height ≥ 2 m. Additionally two crown diameter

measurements were taken for every recorder tree (Fig. 4).

Land cover map on livestock landscapes

Specific details on the procedure used for land cover mapping is described in detail in Iñamagua-Uyaguari (2021). In summary, a 2 km polygon buffer area was generated around one of the farm square plots (Fig. 2b) and a grid of 50×50 m was created. Considering vegetation and pasture composition might vary between and within regions, farms were grouped considering their proximity (SI Table 1). At each farm group, at least 20 squares were used for training the following land cover categories into forest (square predominantly covered by trees), pasture/crops (square covered entirely by pasture/crops), silvopastoral systems (square covered by pasture and trees, regardless of tree density) and 10 squares were used for validation. Land cover classification was performed in the 2 km buffer areas and performed

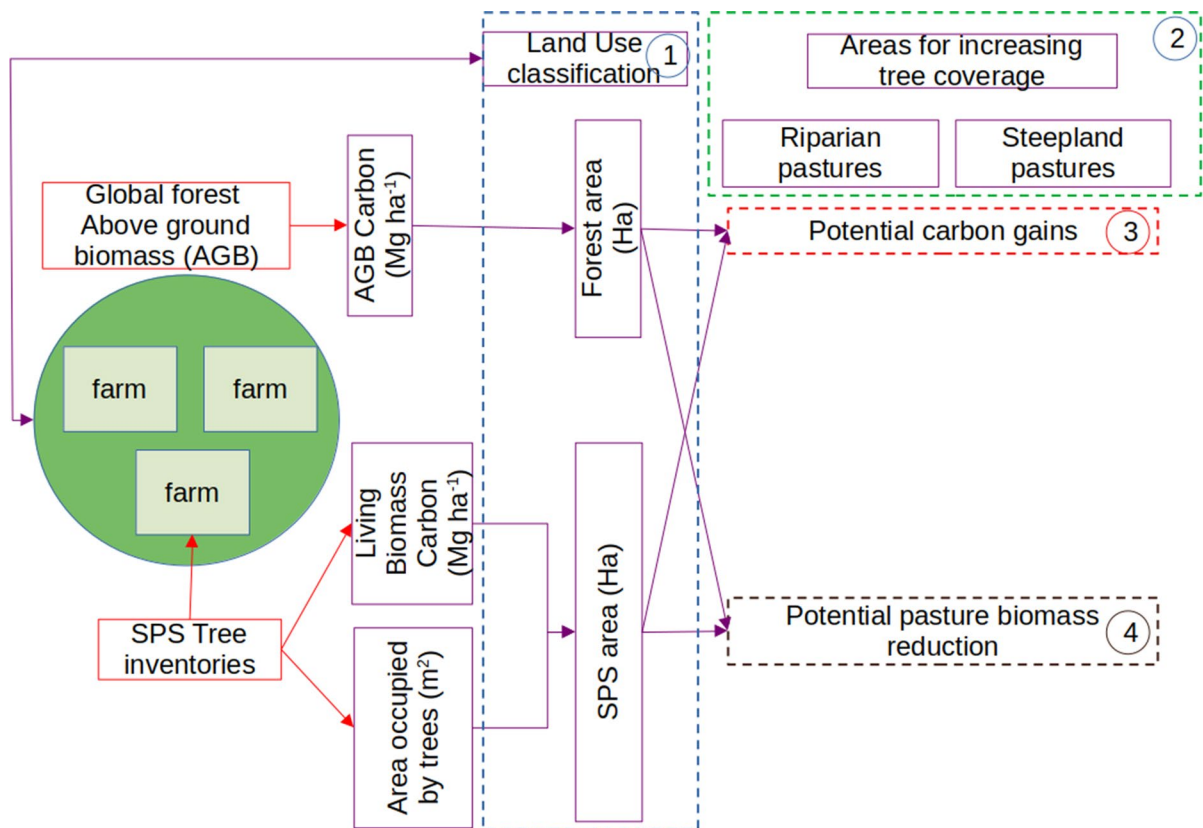


Fig. 1 Overall methodology

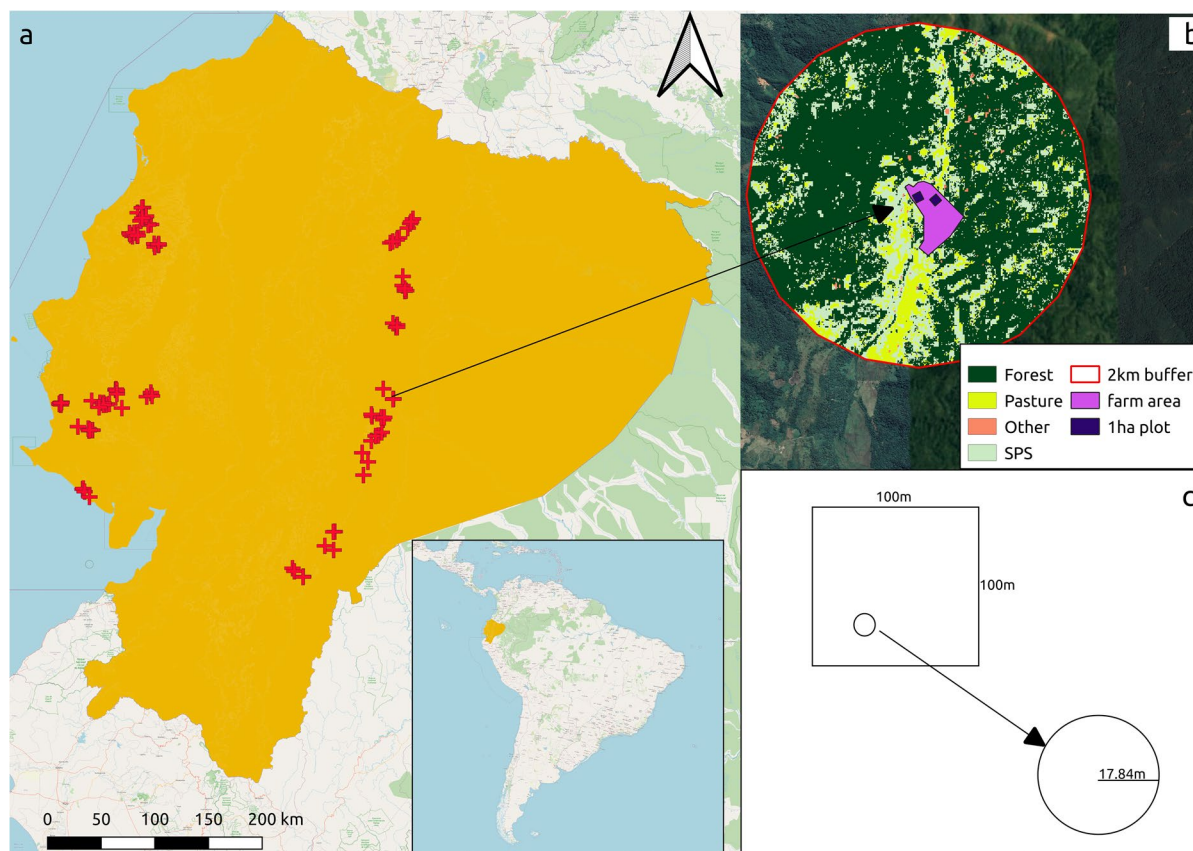


Fig. 2 Study site distribution across **a** coastal and amazon region; **b** land cover classes at landscape level (2 km buffer areas) and **c** plot characteristics for tree field measurements

at farm group (Table 1), using a random forest algorithm from the RandomForest package in R (Liaw et al. 2018). Sentinel 2A imagery European Space Agency (2020) 2019–2020 with cloud cover <20% were used for the classification algorithm. Classification performance was evaluated using the Out of bag error (OOB), and the relative accuracy for the validation plots at farm group.

Identification of suitable areas for increasing tree coverage in riparian and steep slope areas in livestock landscapes

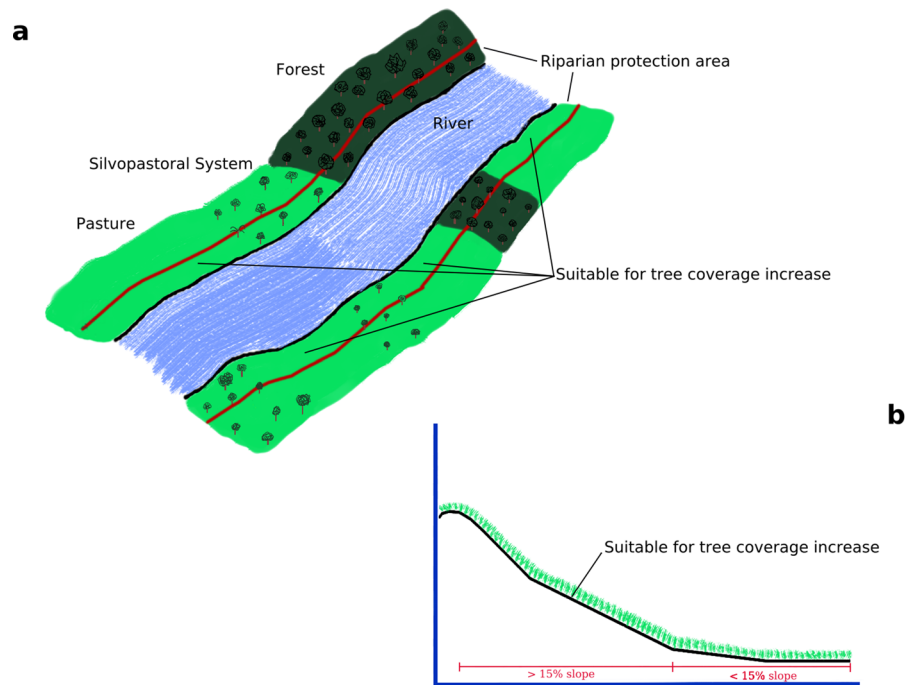
According to Ecuadorian legislation, buffer riparian areas should be covered by forest or natural vegetation. To identify current land cover in buffer riparian areas, the location of rivers in the studied landscapes were retrieved from the Ecuadorian National Agricultural Agency as a shapefile and later spatially

corrected by an operator in QGIS, using Google Earth 15 cm resolution, or Bing imagery basemaps, when a Google Earth image was not available. If small rivers or streams were visible from the satellite imagery and were not included in the rivers shapefile, these were drawn as a line and later exported as shapefile in QGIS software. Riverbed width (rbw) was measured by an operator at 1 km river/stream sections.

Following the Ecuadorian legislation for the protection of rivers and water bodies, riparian zones were identified by creating a buffer area around rivers and streams, with a minimum of 5 m for $rbw = 3$ m, 10 m for $rbw = 3.1–10$ m, 15 m for $rbw = 10.1–30$ m, 30 m for $riverbed > 30$ m (Ministerio del Ambiente and Ministerio de Agricultura, Ganadería, Acuacultura y Pesca 2012). Finally, the area of land cover categories within the riparian zones were calculated at farm group level (Fig. 3a). Pasture areas within the

Table 1 Land use classification at landscape level and in riparian zones (in parenthesis)

Farm group	Forest (%)	Pasture (%)	Sps (%)	Other (%)	Total (ha)
A1	32(60)	13(05)	38(22)	15(13)	2525(48)
A2	17(69)	31(09)	50(22)	–	5021(53)
A3	31(72)	22(03)	43(24)	–	4676(64)
A4	27(36)	21(10)	37(16)	14(37)	3708(87)
A5	40(45)	21(11)	33(15)	05(29)	4189(68)
A6	25(71)	25(15)	28(14)	–	3279(79)
A7	55(24)	13(12)	30(39)	03(25)	4264(100)
A8	26(21)	26(09)	39(60)	09(10)	4779(154)
A9	43(25)	20(10)	32(21)	05(43)	4989(70)
A10	50(36)	14(09)	30(25)	06(29)	3803(118)
C1	25(35)	28(15)	47(50)	–	11,873(177)
C2	10(09)	15(21)	19(02)	55(67)	3734(29)
C3	48(67)	11(01)	42(32)	–	3892(96)
C4	23(40)	27(09)	40(43)	09(08)	7296(75)
C5	14(44)	28(20)	48(28)	10(08)	6482(82)
C6	33(33)	19(18)	38(25)	10(23)	4029(74)
C7	58(38)	10(20)	30(31)	02(11)	2883(16)
C8	69(20)	08(15)	21(61)	03(04)	4569(77)

Fig. 3 Suitable areas for tree coverage increase **a** riparian zones and **b** steep-land pastures

riparian zones were considered as suitable for tree cover increase.

Guidelines for soil protection consider terrain slope, and often recommend that in areas where

slope > 12%, land cover should be mainly forest or pastures, avoiding tillage Shaxson (1999), although it has been reported that soil loss in pasture areas in

steeplands are influenced by the grazing pressure and slope (Mwendera et al. 1997).

For land cover identification regarding terrain slope, firstly we constructed a 30 m slope map expressed in percentage, from a 30 m resolution digital surface model from the Advance Spaceborne Thermal Emission and Reflection Radiometer – ASTER (NASA/METI/AIST/Japan Space Systems and U.S./Japan ASTER Science Team 2019). Slope was classified into flat (0–2% slope), gently undulating (2–5%), undulating (5–8%), rolling (8–15%), moderately steep (15–30%) and steep (> 30%) and finally this information was combined with the land cover map. Pastures on terrains with slope $\geq 15\%$ (steepland pastures) were considered as suitable for tree coverage increase (Fig. 3b). Results were tabulated at farm group and region level. Farm groups in the amazon region are labelled with letter A and farm groups in the coastal region with letter C.

Carbon stock changes resulting from potential increase in tree cover in livestock landscapes

Suitable areas for increasing tree coverage can be transformed completely to conservation areas by (i) allowing or facilitating tree growth, or (ii) by the transformation of pasture areas into SPS, by planting trees or allowing trees to grow and cohabit with pasture species. Both scenarios could deliver an increase in the aboveground carbon due to woody vegetation. The carbon was assigned to the areas identified as potential for tree increase by extrapolation of the measured carbon content in silvopastoral systems and forest nearby the identified areas. To estimate carbon stock changes, we averaged biomass derived carbon values in forest (Santoro 2018), in riparian areas and in the analysed landscape at group level, then extrapolated to the areas suitable for increasing tree coverage. For the SPS scenario, carbon derived from woody biomass obtained at plot level was averaged at farm group level and extrapolated to the areas suitable for increasing tree coverage. Carbon at plot level was estimated using an allometric pantropical equation, proposed by Chave et al. (2014). Wood density was obtained from (Zanne et al. 2009). Belowground biomass was calculated using Cairns et al. (1997)'s

equation. Total biomass in SPS was expressed as carbon by multiplying it by 0.47 IPCC (2006).

Impacts of a potential increase in tree coverage on pasture biomass production

Transforming current riparian or steepland pastures into secondary forest or SPS could lead to a decrease in pasture biomass production, due to competition for space and resources such as light, water and nutrients. To account for the influence of increase in tree coverage on pasture biomass production, the decrease on pasture biomass was expressed as the area lost for pasture growth under current land cover, assuming current conditions represent 100% production. When suitable areas are transformed to forest conservation, it is assumed a 100% decrease on pasture production on given areas, thus biomass lost can be interpreted as the area under conservation and can be expressed as a percentage of the total pasture area at group level. SPS conditions are suitable for pasture growth, and its influence on biomass production is conditioned by tree density and tree characteristics. For SPS, the decrease in pasture biomass production was quantified as the area lost for pasture production due to tree occupancy, which was calculated as the area underneath tree canopy. For this, two tree crown diameter measurements were taken for every surveyed tree (Fig. 4a, b). A crown opacity of 60% and 30% was assumed for trees and palm trees, respectively. Opacity refers to the amount of shade a tree crown allows to pass to the understory layer, due to the leaves and branches density. Crown was assumed to be circular, thus the tree occupancy area was calculated with Eq. (1) as suggested by Somarriba (2002):

$$Aoc = (\pi r^2) * Opacity \quad (1)$$

Crown radius was estimated as the average crown diameter divided by two. Finally, area under tree occupancy values were summed and expressed as a proportion of plot area (Fig. 4c, d). Average values were estimated at farm group level and extrapolated to the areas suitable for increasing tree coverage. Pasture biomass decrease was expressed as the area lost for pasture production at farm group level.

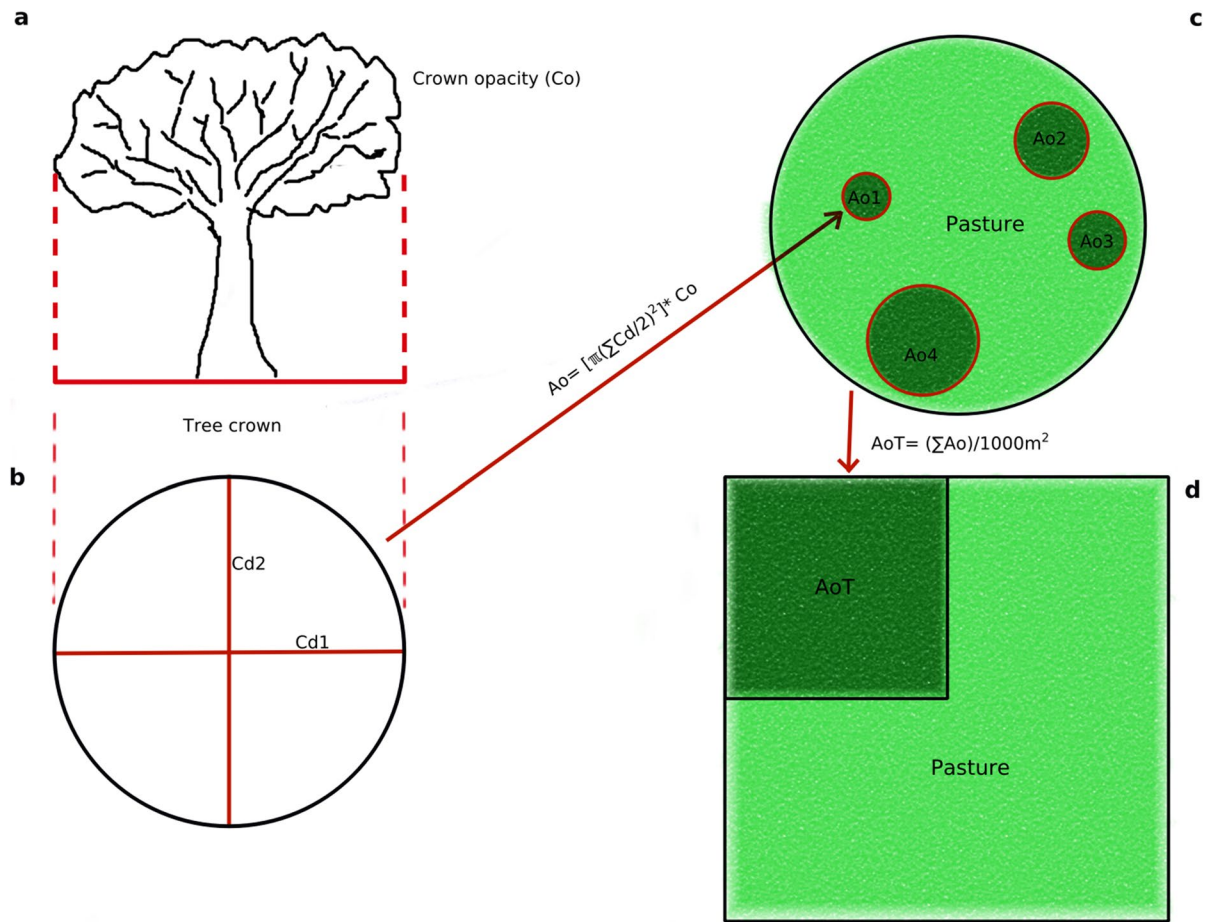


Fig. 4 Calculation of tree occupancy in pasture areas. **a, b** tree crown diameter measurements; **c** area under tree occupancy at plot level and **d** Estimate of tree occupancy in 1 ha pasture areas

Results

In total, 85,992 ha were included by land cover classification in the 2 km radius area to the studied farms (Fig. 5, SI Fig. 1a–p), with 41,233 ha in the Amazon region with forest and SPS covering 36% each, and pasture representing the third largest land cover (21%). The 44,759 ha in the coastal under study were covered mainly by SPS/agroforestry systems (39%), followed by forest (31%) and pasture/agriculture areas (20%) (Table 1).

Land cover in riparian and steep slope areas

In total 573 km of rivers were included in this study, 291 km located in the Amazon region, with an average river width of 26.8 m, maximum width of 87.6 m

and minimum of 6.55 m. In the coastal region, there was a total of 282 km of rivers, with an average width of 13.4 m, a maximum of 29 m and a minimum of 7.17 m. Once the national guidelines for water protection were applied, the area under protection accounted for 1466 ha. In the Amazon region, the predominant land cover in riparian areas was forest, ranging from 21 to 72%, pasture areas occupied only 3 to 15% of those protection areas. In the coastal region SPS and forest covered a similar area, ranging from 2–9 to 61–67% for SPS and forest, respectively. Pasture areas covered from 1–18% of the riparian protection areas (Table 1).

Land cover classification into terrain categories showed that, in the Amazon region, approximately 51% (21,135 ha) of the area under study was located in terrains with moderate or steep slope (SI Table S1),

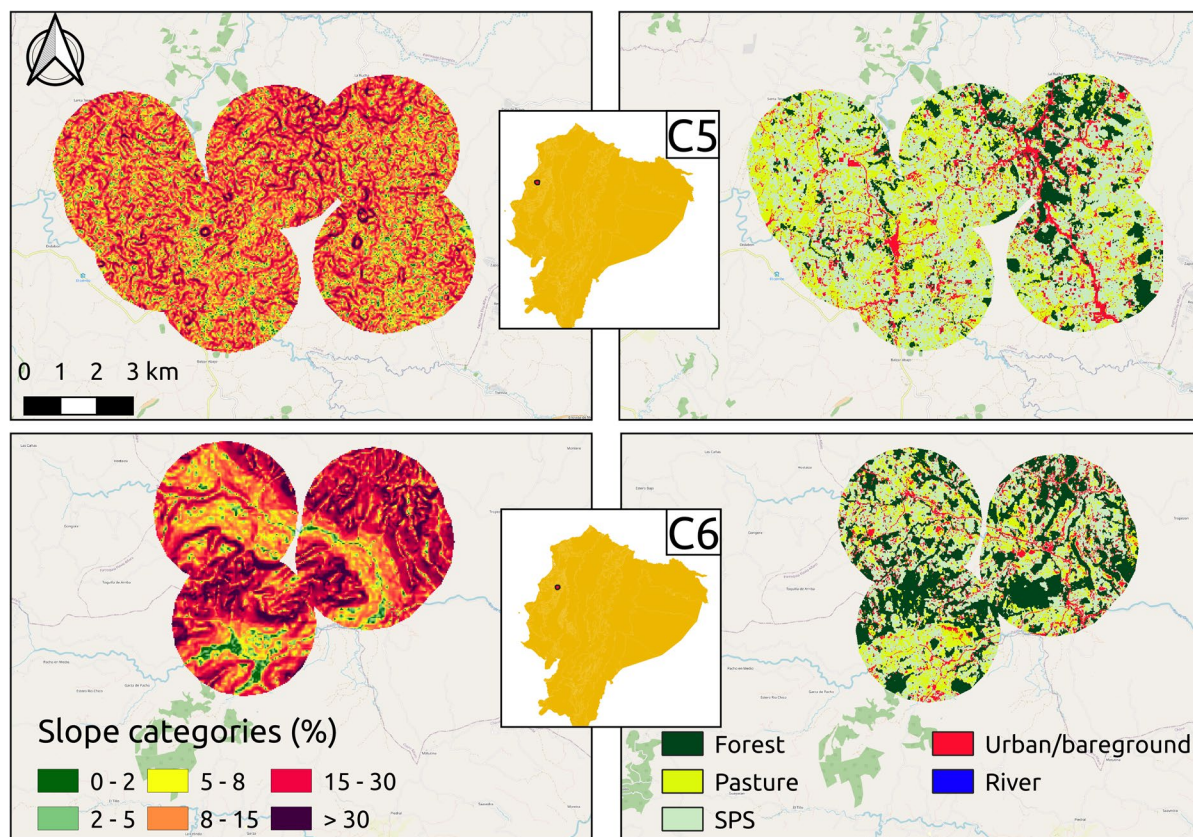


Fig. 5 Land cover and slope classification in livestock landscapes, C5 and C6 corresponds to the farm groups in the coastal region. Other farm groups maps are available as supplementary information

whilst in the coastal region, up to 45% (20,533 ha) could be classified as moderately or steep slope terrains. When land cover and terrain slope classification were considered together, a total of 8,011 ha covered by pastures were found, accounting for 3750 ha under slope $> 15\%$ in the Amazon region, 4261 ha the coastal region farm groups (Fig. 6). Following soil protection guidelines, the 8011 ha are suitable for reforestation or silvopastoral systems implementation.

Carbon stocks and potential increase under soil and water protection scenarios

Four scenarios for increasing trees in livestock landscapes were proposed. Scenarios 1 and 2 assumed that national guidelines for water protection would be followed, areas under pasture cover within the riparian buffer zones would be converted into forest (scenario 1) or silvopastoral systems (scenario 2).

Scenarios 3 and 4 assumed that pasture in areas with slope $\geq 15\%$ would be converted into forest (scenario 3) or silvopastoral systems (scenario 4). Overall, in the Amazon region, silvopastoral systems presented higher tree density than in the coastal region, which influenced the carbon content. Forest carbon values followed the same trend, with higher carbon content in the Amazon region (Table 2).

Converting riparian pastures into forest or SPS, could result in an increase of 7192 Mg C or 1692 Mg C respectively for the entire area under study, whilst the conversion of steep slope pastures could increase carbon stocks by 404,833 or 70,166 Mg C, if converted to forest or SPS, respectively (Fig. 7). If both riparian and steep pastures were considered for restoration purposes, carbon stocks could increase by 412 Gg C, or 71.85 Gg C if converted to SPS, although some pasture in riparian areas could be included on steep land pastures.

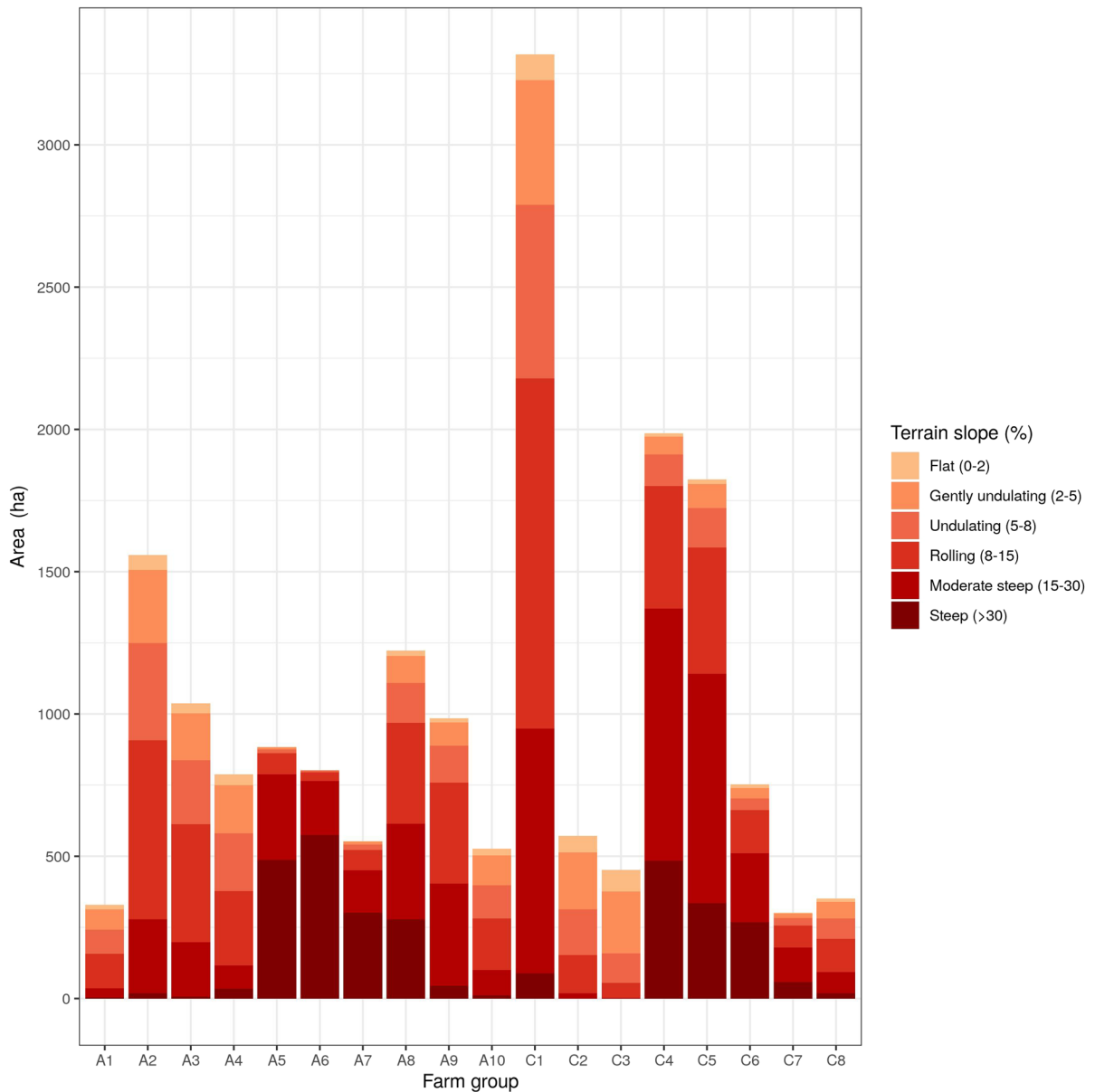


Fig. 6 Pasture distribution regarding slope categories

Increase in tree coverage impacts on landscape pasture biomass production

Decrease in pasture biomass production as a result of land cover conversion from pasture depends on the land cover substitution, either from riparian or steep pastures into forest or SPS. Declines in pasture biomass when replacing riparian pastures with forest ranged from 0.16 to 2.17% of expected biomass

production in the Amazon region. In the coastal region, the decrease ranged from 0.24 to 3.22%. Replacement to SPS of the same areas ranged from 0.03 to 0.56% and 0.01 to 0.43% for the Amazon and coastal region farm groups, respectively (Fig. 8b). When pasture in stepland ($\geq 15\%$ slope) areas were considered for conversion into forest, the decrease in pasture biomass production ranged from 11 to 95%, whilst in the coastal region decline ranged from 0.4 to

Table 2 Carbon content in forest and silvopastoral systems

Farm group	SPS	N Trees	Carbon trees (Ton C ha ⁻¹)	Forest	
				Riparian areas (Ton C ha ⁻¹)	Landscape area (Ton C ha ⁻¹)
A1		112	26.51	57.35	70.50
A2		136	14.51	91.33	79.92
A3		84	23.47	94.52	84.24
A4		117	18.01	53.42	56.10
A5		51	6.40	80.99	94.82
A6		64	4.28	82.95	83.87
A7		111	12.34	60.27	91.92
A8		52	9.88	42.72	40.09
A9		49	5.00	49.25	62.13
A10		116	23.96	62.08	80.34
C1		29	7.18	21.71	21.56
C2		26	5.74	9.85	9.43
C3		38	5.61	3.22	4.02
C4		49	5.69	22.58	27.41
C5		41	11.15	25.24	17.44
C6		42	6.42	32.20	52.45
C7		94	6.01	27.37	58.61
C8		59	9.38	30.96	41.09

69% at farm group level. In the scenario of steepland pastures conversion into SPS, the expected decline in biomass ranged from 2.46 to 16.33% and 0.02 to 16.31% for the Amazon and coastal region, respectively. (Fig. 8a).

Discussion

It has been reported that as human population increases, forest areas tend to decrease (Morales-Hidalgo et al. 2015), and contrary to what has been promoted by the Ecuadorian national guidelines for water bodies and river protection (Ministerio del Ambiente and Ministerio de Agricultura, Ganadería, Acuacultura y Pesca, 2012), land cover in riparian areas is only partially occupied by forests, in some cases almost 50% of the supposed protected area being under agriculture/livestock occupancy (Table 1). In this study, we have identified pastures on steep slope terrains as potential areas for restoration or SPS implementation, delivering both reduction in soil degradation processes, as on sites under similar conditions (Descroix et al. 2001; Fu et al. 2000; Hartanto et al. 2003), and increasing carbon stocks

(Paulick et al. 2017). Nevertheless, estimated tree carbon content on steep areas might be lower than expected, due to a lower nutrient content on the upper part of the slopes (Werner and Homeier 2015).

The total carbon storage increase that could be achieved by converting riparian pastures and steeply sloping pasture areas to forest or SPS is 412 and 72 Gg C (equal to 1512.04 and 263.68 Gg CO₂eq), respectively, although carbon values in forest averaged less than those reported for (Silver et al. 2000) for tropical forest aged between 20 and 50 years. Changes in carbon stocks could be equivalent to 1.8–10% of Ecuador's annual agricultural GHG emissions for 2012 which were 14,648 Gg CO₂eq (Ministerio del Ambiente del Ecuador 2017), so if applied at national level, could be an important contribution to Ecuador's nationally determined contribution (NDC) under the United National Framework Convention on Climate Change.

Several initiatives have been launched worldwide to mitigate climate change effects, with some of them focused on forest restoration for increasing negative emissions. In terms of climate change, the effects of increasing tree coverage are almost entirely positive, since this leads to an increase in the carbon stocks

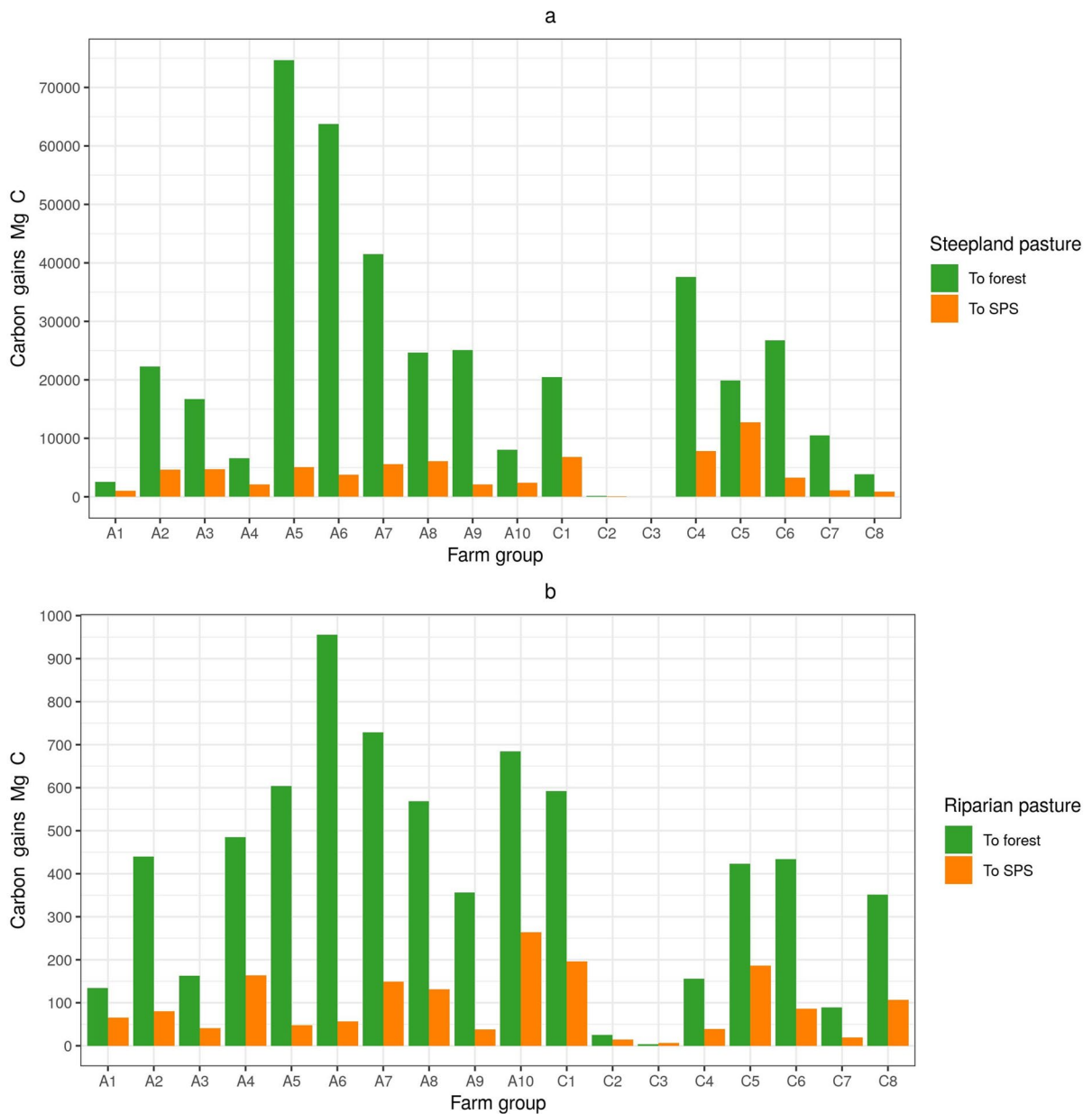


Fig. 7 Carbon gains from pasture conversion into forest/SPS from **a** Steepland pasture and **b** riparian pastures

and sequestration capacity (Bastin et al. 2019), with the additional benefit of delivering other ecosystem services (Matos et al. 2020). Nevertheless, the application of restoration activities in agricultural landscapes can be a challenge. For example, in landscapes dominated by human activities, like cropping and livestock production, replacing food production areas could deliver mixed results, such as increasing

carbon stocks but a reduction in production areas could reduce food production of the region (Smith et al. 2020) or simply displace production elsewhere.

We were not able to include soil carbon in this study, but Aryal et al. (2022), showed that pastures with dispersed trees have higher carbon stocks than open pastures in livestock-dominated landscapes in Mexico, and Beckert et al. (2016) also found that

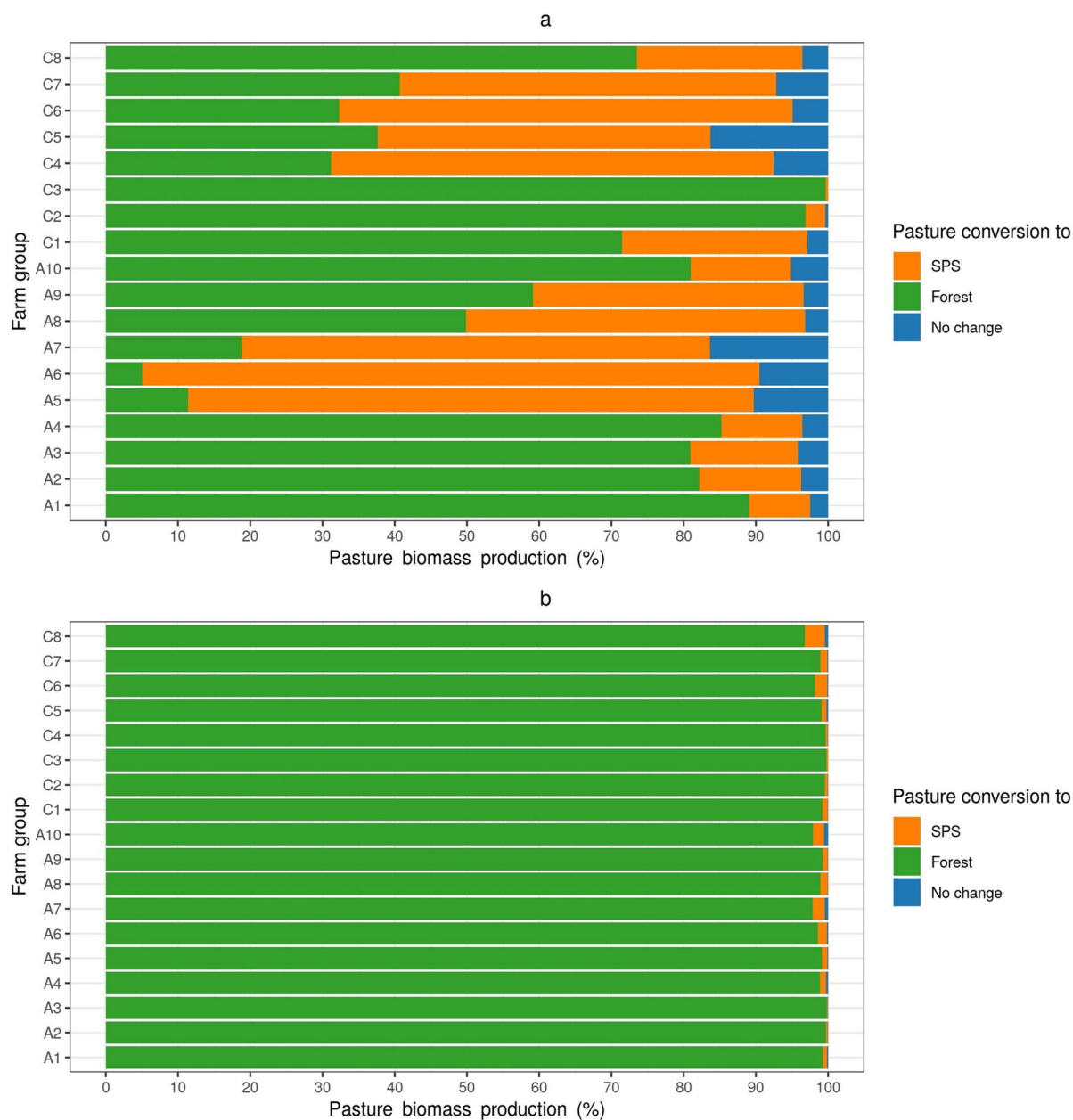


Fig. 8 Potential decline in pasture biomass level due to tree coverage increases in **a** steepland pastures or **b** riparian pastures into forest/SPS

woodlands and silvopastoral systems in Scotland also had higher soil carbon stocks than pastures. Given these findings, and given that silvopasture has been implemented to reduce soil degradation by reducing erosion, it is likely that if soil carbon were included, the beneficial effect of trees in livestock landscapes

on carbon stocks would have been even more pronounced.

Since we use a deterministic approach to calculate carbon stock impacts, the results are simply the product of the area that can be used for trees / SPS and the estimated carbon stocks of these areas extrapolated for nearby areas, there are no stochastic elements in

our analysis, and we cannot ascribe an uncertainty to these estimates. However, since our ultimate goal (objective 4) was to assess the contribution of increasing tree coverage in livestock landscapes to offsetting emissions from agriculture in Ecuador, these estimates are considered accurate enough for estimating the approximate magnitude of the potential. Future studies could employ more sophisticated approaches, for instance ecosystem biogeochemical models along with the opportunity maps we produced, to further refine the carbon benefits of increasing tree coverage in livestock landscapes in Ecuador.

Regardless of potential increase in carbon stocks (Fischer and Vasseur 2002), one of the main constraints to farmers' adoption to silvopastoral systems is the perception of its negative impacts on pasture production. Tree-pasture interactions are complex and its magnitude is influenced by management, ecological and climatic factors. The most recognized interaction between trees and pasture is the shade projected by the trees, which has been extensively studied in experimental and field conditions. For example, Lin et al., (2001) reported that for some grass and legume species, shaded conditions increased pasture quality, and even at 50% shade, species like *Arachis Pinto* maintain productivity levels similar to full sun conditions, whilst in *Brachiaria humidicola*, productivity was 17% smaller than under full sun (Soares de Andrade et al. 2004). Another way trees interact with pastures, is through modifying micro-climatic conditions, either air temperature, wind velocity or soil moisture (Pezzopane et al. 2015), indirectly influencing on the livestock productivity (Lemes et al. 2021). Other interactions on silvopastoral systems are related to soil fertility due to litter deposition from trees (Martínez-Atencia et al. 2020), which can have an effect on the nutrient availability on the pasture areas (Sharrow et al. 1999). In this study, the effects of tree coverage and pasture productivity, have been considered solely from an area based approach, meaning that areas occupied by trees are considered losses on pasture production and considering a tree-grass relationship as neutral. Although this approach neglects the potential positive effects of trees on pasture areas, it could reflect the direct impact of tree incorporation on pasture areas under tree densities reported for the studied areas, thus we provide comprehensible estimates for pasture biomass losses for restoration and SPS scenarios at landscape level.

Regardless of the selected scenario (restoration or silvopastoral), steepland pastures present a larger impact in terms of potential carbon accumulation or pasture productivity decline, which are conditioned by the share of steepland pastures in each site. On average, potential carbon gains on the Amazon region are larger than in the Coastal region. It could be explained by the forest characteristics (more density, larger trees) (Llerena Silvia et al. 2019) and the characteristics of trees on pastures, which follow similar trends to the forest areas. To encourage restoration or silvopastoral systems, implementation of a flexible payment for ecosystem services (PES), could be a successful strategy (Raes et al. 2017). Ecuador has experience in implementing PES schemes; under the "Socio Bosque" program, government paid farmers to protect forest areas inside the farms, resulting in carbon stock increases (Eguiguren et al. 2019). Therefore, it may work in a similar way, to encourage abandonment of pasture areas on steep slopes or riparian pastures for reforestation practices or to passive natural regeneration, which is an inexpensive strategy to increase carbon sequestration on pasture areas. Although its success is contingent on seed availability and pasture conditions, in some cases, site conditions after several years of abandonment do not allow natural regeneration (Palomeque et al. 2017). Is worth considering that forest regeneration can also be enabled by seed dispersal organisms (Bello et al. 2015), thus there is a need to address also fauna conservation, for the key role they play in seed dispersal and other ecosystem services (Krause and Nielsen 2019).

Conclusions

At landscape level, the conversion of riparian pastures into forest could result in an increase of carbon stocks with a minimum impact on the pasture biomass production, although it might not be the same for farm owners on riparian areas. This could be a significant contribution to Ecuador's climate change mitigation efforts, as the increase in carbon stocks represents 1.8%- 10% of Ecuador's annual GHG emissions from agriculture. Pasture in steep terrains occupy larger areas in both amazon and coastal region, making it difficult to follow a restoration approach because it could potentially compromise more than 50% the pasture biomass production, in some cases, affecting the

economy and food security of smallholders. Instead, adopting silvopastoral practices could increase carbon stocks while reducing pasture biomass by less than 20% of potential pasture production. Considering the long periods of time it takes to create and implement environmental policies, especially in developing countries, enforcing already implemented policies, as discussed in this manuscript, could deliver multiple benefits contributing to accomplish national mitigation goals.

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Code availability Available upon request from authors.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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