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TESIS DOCTORAL

Análisis socioeconómico, carbono y diversidad arbórea en tres ecosistemas ganaderos de la Amazonía Ecuatoriana

DOCTORANDO

Don. SEGUNDO BOLIER TORRES NAVARRETE

DIRECTORES DE TESIS

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CÓRDOBA, 2023

TITULO: *Análisis socioeconómico, carbono y diversidad arbórea en tres ecosistemas ganaderos de la Amazonía Ecuatoriana*

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POSTGRADO EN RECURSOS NATURALES Y GESTIÓN SOSTENIBLE

Análisis socioeconómico, carbono y diversidad arbórea en tres ecosistemas ganaderos de la Amazonía Ecuatoriana

Tesis presentada por Don. SEGUNDO BOLIER TORRES NAVARRETE

para optar al grado de Doctor por la Universidad de Córdoba (España)

Vº Bº
Director

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Dr. Antón Rafael García Martínez

D. ANTÓN RAFAEL GARCÍA MARTÍNEZ, CATEDRÁTICO DE UNIVERSIDAD DEL DEPARTAMENTO DE PRODUCCIÓN ANIMAL DE LA UNIVERSIDAD DE CÓRDOBA.

INFORMA:

Que la Tesis Doctoral titulada ***"Análisis socioeconómico, carbono y diversidad arbórea en tres ecosistemas ganaderos de la Amazonía Ecuatoriana"***, que se recoge en la siguiente memoria y de la que es autor Don. SEGUNDO BOLIER TORRES NAVARRETE, ha sido realizada bajo mi dirección, cumpliendo las condiciones exigidas para que la misma pueda optar al Grado de Doctor con Mención Internacional por la Universidad de Córdoba.

Lo que suscribo como director de dicho trabajo y a los efectos oportunos, en Córdoba a 09 de enero de dos mil veintitrés.

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Fdo. Dr. Antón Rafael García Martínez

Quevedo, 31 de diciembre del 2022

Instituto de Estudios de Posgrado

Universidad de Córdoba, España

Estimados

Mediante el presente, tengo el agrado de informar que el señor Segundo Bolier Torres Navarrete con Cédula de Identidad No. 1711988855, candidato a Ph.D. en Recursos Naturales y Gestión Sostenible de la Universidad de Córdoba, ha realizado una estancia científica bajo mi supervisión en la Facultad de Ciencias Pecuarias y Biológicas de la Universidad Técnica Estatal de Quevedo desde el 01 de octubre al 31 de diciembre del 2022. Durante este periodo de esta estancia, el señor Torres ha realizado un análisis comparativo de las principales variables de capital (humano, social, natural, financiero y físico) y la evaluación del coste de oportunidad de las zonas de pastoreo en tres gradientes altitudinales de la Amazonía Ecuatoriana con el objeto de fomentar procesos de restauración diferenciados, basados en los costes de oportunidad de los hogares dedicados al pastoreo. Como fruto de este trabajo se ha submitido un paper titulado*: Livelihood capitals and opportunity cost for grazing areas restoration: A sustainable intensification strategy in Ecuadorian Amazon*. En la revista *Animals* (JCR-Q1), submitido el 30/12/2022.

Las principales actividades llevadas a cabo durante la estancia en la UTEQ se describen a continuación:

- Análisis de los capitales (humano, social, natural, financiero y físico) en los sistemas ganaderos con una base de datos de 167 hogares de la Amazonía Ecuatoriana
- Estimación del costo de oportunidad del área de pastoreo en las tres gradientes altitudinales en la Amazonía Ecuatoriana.
- Discusión de las estrategias de *land-sparing* y *land-sharing* para promover la restauración de paisajes y ganadería sostenible en la Amazonía Ecuatoriana.

Atentamente,

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TÍTULO DE LA TESIS:

Análisis socioeconómico, carbono y diversidad arbórea en tres ecosistemas ganaderos de la Amazonía Ecuatoriana

DOCTORANDO: Don. Segundo Bolier Torres Navarrete

INFORME RAZONADO DEL LOS DIRECTORES DE LA TESIS

(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

Durante el desarrollo de la Tesis el doctorando ha profundizado en el conocimiento sobre los medios de vida, costos de oportunidad del área de pastoreo y el contenido de carbono en pastizales con árboles en pequeños productores de leche y de doble propósito a lo largo de una gradiente altitudinal en la Reserva de Biosfera Sumaco en la Amazonía Ecuatoriana. Asimismo, se ha evaluado las buenas prácticas ganaderas más apropiadas en pequeños productores amazónicos en tres gradientes altitudinales. Se aplicaron metodologías cuantitativas y cualitativas relacionadas con la teoría de capitales y las buenas prácticas ganaderas orientadas a los logros de los objetivos de desarrollo sostenible (ODS). Posteriormente, se evaluaron a través de un análisis de actores claves 16 buenas prácticas apropiadas para cada uno de los tres pisos altitudinales.

La Tesis plantea un objetivo novedoso y estratégico, utilizando los resultados de un análisis comparativo de las principales variables de capital (humano, social, natural, financiero y físico) y la evaluación del coste de oportunidad de las zonas de pastoreo en las tres gradientes altitudinales para fomentar procesos de restauración diferenciados, basados en los costes de oportunidad de los hogares dedicados a zonas de pastoreo bajas y con un menor impacto en los medios de vida, facilitando el debate hacia la formulación de políticas sectoriales,

Finalmente, se proponen el enfoque de las dos estrategias para restauración de paisajes productivos (land-sparing) e intensificación sostenible (land-sharing), como alternativas ambientales, económicas y sociales que favorecen la restauración productiva, el mejoramiento de los ingresos en cada gradiente altitudinal del sistema a mediano y largo plazo.

El Doctorando presenta un manuscrito con los siguientes indicadores de calidad: 5 artículos JCR publicados, 2 artículo JCR en revisión, 2 publicaciones en congresos internacionales y 1 estancia de investigación en el extranjero.

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Artículos de investigación:

Torres, B., Herera-Feijoo, R., Torres, Y., & García, A. (2023). Evolución de las investigaciones en silvopasturas: un análisis bibliométrico a nivel global y Ecuador. Article under review in *Agronomy*, 30/12/2022. (JCR-Q1).

Torres, B., Andrade, V., Heredia-R, M., Toulkeridis, T., Estupiñán, K., Luna, M., Bravo, C., & García, A. (2022). Productive livestock characterization and recommendations for good practices focused on the achievement of the SDGs in the Ecuadorian Amazon. *Sustainability*, 14, 10738. https://doi.org/10.3390/su141710738

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Publicaciones en Congresos:

Torres B., Luna, M., Vargas. J.C., Torres, Y., & García A. (Julio 2017). Caracterización de fincas ganaderas de doble propósito en el cantón Arosemena Tola, Amazonía Ecuatoriana. Memorias del IV Congreso Internacional de Ciencia, Tecnología

Innovación y Emprendimiento CITE 2017. Bolívar, Ecuador. ISBN 978-9978-364-38-3. Pág. 1718-1719.

Bravo, C., **Torres, B.**, Alemán, R., Changoluisa, D., Marín, H., Reyes, H., Navarrete, H. 2017. Soil structure and carbon sequestration as ecosystem services under different land uses in the Ecuadorian amazon region, in Proceedings of the MOL2NET'17, Conference on Molecular, Biomedical & Computational Sciences and Engineering, 3rd ed., 15 January–15 December 2017, MDPI: Basel, Switzerland, doi:10.3390/mol2net-03-04859. https://sciforum.net/conference/mol2net-03/modec-03

Cursos:

Participación en el Curso Internacional: Metodología de la ciencia e investigación, Universidad Técnica Estatal de Quevedo (UTEQ) 2022 en Quevedo, Ecuador. 22-27 de agosto del 2022. (Duración 40 horas).

Participación en el Congreso Internacional, en la IUFRO 2017 en Freiburgo, Alemania. Septiembre del 2017. (Duración 40 horas).

Participación en el IV international congress of sciences, technology, innovation and entrepreneurship, Universidad Estatal de Bolivar. Guaranda. Del 05 al 07 de julio del 2017. Duración 40 horas.

Participación en el Primer Seminario de economía de recursos naturales y biocomercio: oportunidades y desafíos. Universidad Estatal Amazónica, Puyo, Ecuador. Del 26 al 28 de Junio del 2017. Duración 40 Horas.

Estancia de investigación:

Estancia de investigación en el Facultad de Ciencias Pecuarias y Biológicas, ***Universidad Técnica Estatal de Quevedo*** (UTEQ), durante el periodo comprendido entre octubre a Diciembre de 2022, con la finalidad de recibir formación y asesoría sobre la aplicación de la metodología de coste de oportunidad aplicados a silvopasturas para ganado bovino, para comparar los beneficios sacrificados por el uso de la tierra con los servicios ambientales que se podrían generar a través de la restauración de ecosistemas, en un estudio realizado a lo largo de la gradiente altitudinal en la Amazonía Ecuatoriana.

Agradecimientos

Esta meta no la hubiera podido lograr sin el apoyo del Prof. Dr. Antón García Martínez quien supervisó todo el trabajo como Director de esta Tesis, desde la Universidad de Córdoba. Así como también el apoyo recibido de distintas Instituciones y personas entre colegas, amigos y familiares, a quienes quiero dedicar este trabajo y agradecerles por el respaldo brindado. Sin embargo, necesitaría muchas páginas para mencionar a cada uno de ellos, por lo cual también quiero agradecer a todos quienes no mencione en los siguientes párrafos.

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- *A todos los productores de ganadería bovina de leche y doble propósito a lo largo de la gradiente altitudinal en la zona de la Reserva de Biosfera Sumaco, por su colaboración desinteresada y por sus labores en el mantenimiento de estos sistemas ganaderos que constituyen una estrategia de vida para gran parte de la población rural de la Amazonía Ecuatoriana.*
- *Y en especial quiero expresar mi profunda gratitud a mi compañera de vida Gabriela Elizabeth, a mis hijas Amelia y Omara y a mi suegra Fanny por ser mi constante apoyo. Agradezco también a mis padres Bolívar e Hilda y hermanos Alicia, Emma, Yenny, Alexandra, Bolívar y Alfredo, sobrinos y sobrinas que con cariño han sabido motivarme a dar lo mejor de mí. Un agradecimiento especial a mis amigos y colegas en Ecuador que a veces compartiendo una taza de café o un almuerzo han podido transmitirme algunas ideas interesantes para mejorar mi trabajo.*

Bolier Torres

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INTRODUCCIÓN

1. INTRODUCCIÓN

1.1. Justificación

A nivel global, casi la mitad de la tierra utilizable se encuentra actualmente en sistemas de ganadería o agricultura intensiva (Tilman et al., 2001) que producen aproximadamente la mitad de los alimentos del mundo, y ha sido reconocida como un instrumento importante para abordar la inseguridad alimentaria de los hogares rurales y la pobreza en las economías en desarrollo (Herrero et al., 2010). Sin embargo, estos sistemas ganaderos también se consideran la principal causa de la pérdida continua de ecosistemas tropicales (Seufert et al., 2012) debido al cambio de uso de la tierra para ampliar la frontera agrícola (Paul & Knoke, 2015; Tilman et al., 2002, 2011). Estos cambios en el uso de la tierra han sido responsables de alrededor del 9% de las emisiones mundiales de CO_2 durante la última década 2006-2015 (Le Quéré et al., 2018). Aunque la mayoría de estas estimaciones se han realizado utilizando grandes bases de datos con predicciones globales sujetas a un alto nivel de incertidumbre, la respuesta práctica a estos modelamientos debe ser tratada a nivel local, regional y global (Tilman et al., 2001). Por lo tanto, uno de los retos globales es analizar cómo lograr una producción agropecuaria de manera sostenible (Paul & Knoke, 2015; Tilman et al., 2002, 2011), especialmente para salvaguardar las zonas de mayor riesgo (Myers et al., 2000) a nivel local y facilitar la recomendación de políticas. En este sentido, la implementación de buenas prácticas ganaderas pudría contribuir con la provisión de productos agropecuarios más sostenibles y competitivos, y puede ser utilizada como una herramienta para el logro de algunos objetivos del desarrollo sostenible (ODS).

En la actualidad, los sistemas silvopastoriles (SSP) están siendo observados en múltiples iniciativas económicas y de conservación que tiene como fin aumentar el porcentaje de cobertura forestal globalmente (Chapman et al., 2020; Munsell et al., 2022; Smith et al., 2022). Este interés está asociado a la reducción de la emisión de gases de efecto invernadero (Cusack et al., 2021), ya que se estima que los SSP actualmente almacenan 6930 Tg C contribuyendo significativamente a mitigar los efectos del cambio climático en la biodiversidad (Chapman et al., 2020). Por otra parte, generan beneficios económicos a las poblaciones de los sectores rurales y urbanos que perciben ingresos relativamente bajos (da Silveira Pontes et al., 2021; Smith et al., 2022).

Por otro lado, en lo referente al cambio climático, a nivel mundial la temperatura media superficial se ha incrementado en promedio 0.66°C en los últimos 60 años (Valipour et al., 2021). Este aumento gradual ha generado que tanto las personas y animales (ganado) sean propensas al estrés por calor (McManus et al., 2022; Thornton et al., 2021), siendo esta exposición muy negativa para el sector de la producción ganadera (Choudhary & Sirohi, 2022). En este sentido, Zeppetello y colegas (2022) sugieren que los SSP ayudan a la regulación de la temperatura mediante un enfriamiento promedio entre −0,32 °C a −2,4 °C en zonas tropicales destinadas a estas actividades. Adicionalmente, también se ha evidenciado que el ganado criado bajo un SSP presenta mejores índices de calidad animal y peso corporal en comparación a los manejados bajo un sistema tradicional (Huertas et al., 2021). Esto se relaciona en que los SSP permiten que el ganado disponga de espacios bajo sombra que le sirven de refugio en días extremadamente calurosos, logrando que los animales tengan una baja exposición al estrés térmico e incremente su actividad de pastoreo y rumia (Huertas et al., 2021; McManus et al., 2022).

En América latina, la superficie de pastos se incremento un 246% desde 1850 a 2015 (Houghton & Nassikas, 2017). Sin embargo, (Winkler et al., 2021) sugieren que existe una expansión de 0,9 millones de km^2 desde 1960 hasta 2019. Se estima que estos cambios podrían haber generado una emisión promedio de 145 ± 16 Pg de carbono (C) (Houghton & Nassikas, 2017). No obstante, un fracción de estas emisiones es capturada de manera natural en un promedio anual de 3.2 ± 0.6 Pg de C, siendo nuevamente incorporado en la biomasa y suelo, logrando con ello reducir un 29% de las emisiones antropogénicas de C (Yue et al., 2020). El mitigar los impactos ambientales y socioeconómicos influenciados por la deforestación y el cambio climático es una de las necesidades de mayor urgencia actual (Doelman et al., 2020; Moffette et al., 2021; Nazareno & Laurance, 2020). En este contexto, integrar los beneficios de un sistema de captura de carbono basado en sistemas de silvopasturas es una alternativa para potenciar el almacenamiento de C en el suelo y biomasa (Bossio et al., 2020; Ferreiro-Domínguez et al., 2022). De acuerdo a Bussoni y colegas (2019), la implementación de esta actividad, puede darse de 4 formas: 1) plantación forestal y zonas de pastoreo de ganado; 2) SSP intensiva; 3) incorporar árboles dispersos en pastizales; 4) lograr pastizales en formaciones de árboles.

Dentro del contexto latinoamericano se encuentra Ecuador, uno de los países más biodiversos del planeta (Cazzolla Gatti et al., 2022; Raven et al., 2020), donde se encuentran dos *hotspots* de biodiversidad de mayor importancia en la conservación biológica en América del Sur: los Andes tropicales y el Corredor Tumbes-Chocó-Magdalena (Comer et al., 2022; Hu et al., 2021). Ecuador se encuentra constituido administrativamente por 4 regiones: Insular, Costa, Sierra y Amazonía. A su vez, la Región Amazónica Ecuatoriana (RAE) se encuentra conformada por seis provincias: Sucumbíos, Orellana, Napo, Pastaza, Morona Santiago y Zamora Chinchipe. La RAE se caracteriza por su gran riqueza biológica y endemismo, con un alto potencial para brindar servicios ecosistémicos a las poblaciones locales (Mejía et al., 2015; Raven et al., 2020).

Varios autores han reportado que la frontera agrícola en la RAE se está expandiendo a un ritmo sin precedentes (Kleemann et al., 2022; Torres et al., 2020), siendo la ganadería una de los principales conductores del cambio de uso de suelo y la deforestación (Torres et al., 2020). En esta región, se estima que para 2014 existían aproximadamente 1,2 millones de hectáreas con uso enfocado a pastos cultivados para la alimentación de ganado en la modalidad de ganadería extensiva (Lerner et al., 2015), contribuyendo a solventar la demanda nacional e internacional de proteína de origen animal y leche (Doelman et al., 2020).

A tenor de lo expuesto, en 2015, en gobierno ecuatoriano puso en marcha el proyecto de la Agenda de Transformación Productiva Amazónica – Reconversión Agro productiva Sostenible en la Amazonía Ecuatoriana (ATPA), con miras combatir la expansión acelerada de la frontera agrícola (MAGAP, 2015). El objetivo principal de la ATPA fuer convertir 300.000 hectáreas de pastizales en sistemas silvopastoriales, forestales, mixtos y agroforestales (MAGAP, 2015).

Sin embargo, hasta la fecha no se ha logrado cumplir con estos objetivos. No obstante, en estos mismos temas, actualmente existe un creciente interés a nivel global por implementar programas que incentiven la reforestación en zonas tropicales como la RAE (Hua et al., 2022; Koch & Kaplan, 2022; Londe et al., 2022), como una iniciativa global para mitigar los impactos inducidos por las actividades humanas y contribuir con el aumento de los beneficios generados por los servicios ecosistémicos al bienestar humano (Fedele et al., 2021; Koch & Kaplan, 2022).

Este creciente interés se refleja en las acciones que se están llevando a cabo a través de diversas iniciativas globales relacionadas con la reforestación como el Desafío de Bonn (Verdone & Seidl, 2017) y el Decenio de las Naciones Unidas para la Restauración (ONU, 2021), que pretenden reforestar 350 millones de hectáreas para 2030 (Romijn et al., 2019; Stanturf, 2021). En este contexto, muchos organismos se esfuerzan en buscar diversas formas de financiamiento para poner en marcha estas prácticas (Bosshard et al., 2021; Löfqvist & Ghazoul, 2019; Nazareno & Laurance, 2020), que también se ven conectados con el incremento de mercados de carbonos e incentivos económicos enfocados en la reforestación (Fleischman et al., 2021; Philipson et al., 2020; Yanai et al., 2020). Sin embargo, lograr concretar estos esfuerzos en la práctica y a nivel local no es una tarea fácil, para lo cual es necesario realizar una serie de estudios multidisciplinarios, que involucren los componentes socioeconómicos, medios de vida, tratamientos silviculturales y sobre todo analizando la percepción tanto de los productores como de los actores claves encargados de la asistencia técnica y tomadores de decisiones a nivel nacional y local. En Ecuador, este tipo de análisis, se constituyen en un reto para que la investigación científica genere orientaciones políticas que faciliten la implementación de estos objetivos en la RAE.

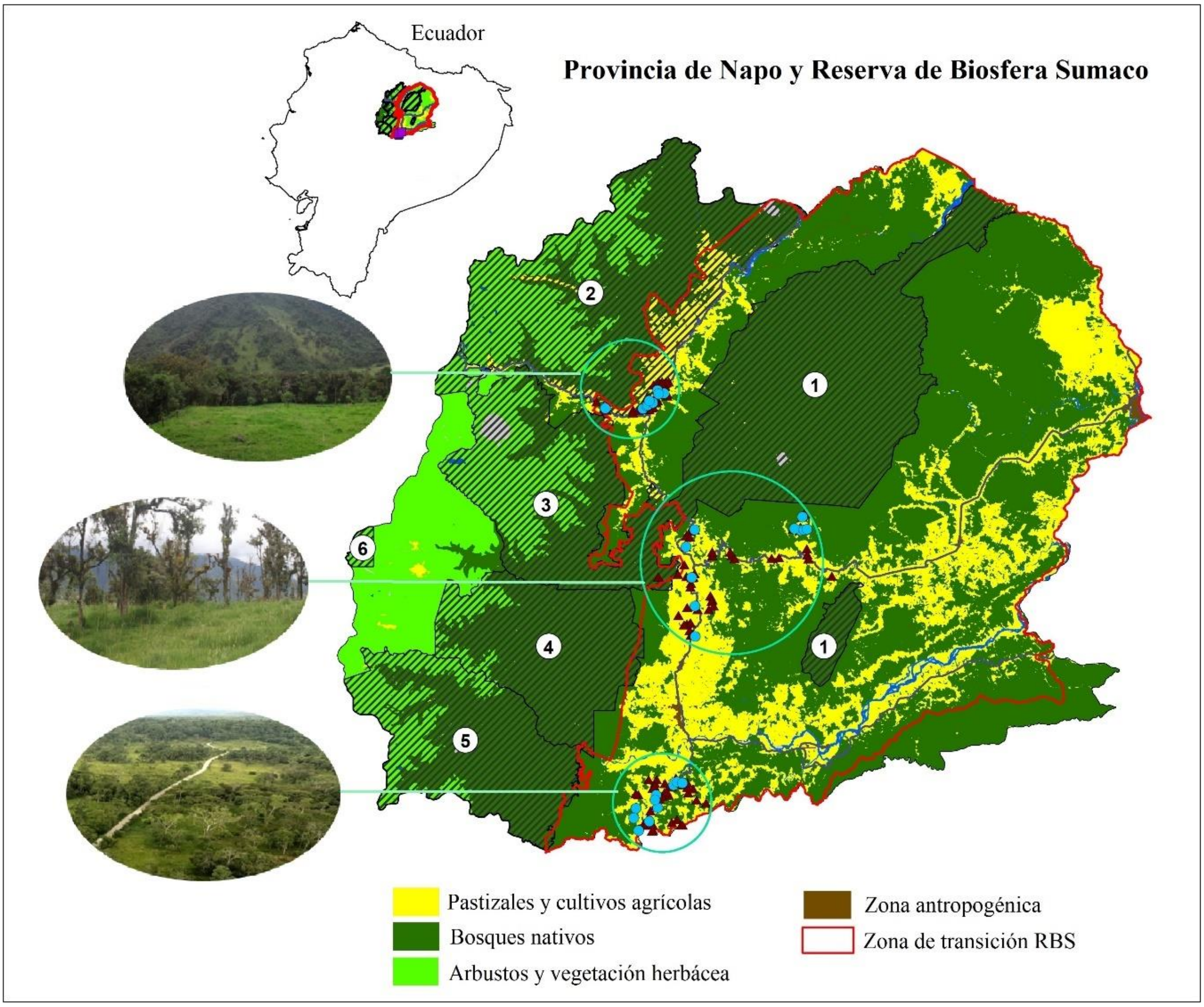

Figure 1. Mapa de la zona de estudio mostrando el paisaje a lo largo de la gradiente altitudinal y las áreas protegidas circundantes: 1) Parque Nacional Sumaco Napo Galeras; 2) Parque Nacional Cayambe Coca; 3) Reserva Ecológica Antisana; 4) Reserva Biológica Colonso Chalupas; 5) Parque Nacional Llanganates y 6) Parque Nacional Cotopaxi. Los puntos celestes muestran las parcelas temporales para evaluar las reservas de carbono y la diversidad arbórea, Los triángulos rojos representan los hogares de la muestra estudiada. Fuente: Autor, 2023.

Con estas perspectivas, en la provincia Amazónica de Napo se ejecutó la presente investigación, a lo largo de una gradiente andino-amazónica desde los 400 a los 2000 msnm., en una zona de importancia global, en las zonas de amortiguamiento y transición de la Reserva de Biosfera Sumaco (RBS) (**Error! Reference source not found.**), que tiene una extensión aproximada de un millón de hectáreas (Torres et al., 2018) y, que forma parte del *hotspot* biodiversidad (Trew & Maclean, 2021).

La RBS aún mantiene importantes extensiones de bosques nativo, pero también existen áreas significativas de pastizales en sistemas agropecuarios (Torres et al., 2022; Torres et al., 2018), en manos de pequeños productores rurales.

En la RBS, la estrategia de vida basada en ganadería es la fuente de subsistencia de mayor rentabilidad económica en comparación a otras estrategias de uso del suelo basadas en actividades agrícolas y forestales (Torres et al., 2022; Torres et al., 2018). En esta zona, se estima que el 56,1% de las actividades productivas realizadas por colonos locales se basan en métodos de subsistencia enfocados en la ganadería (Torres et al., 2021a).

A tenor de lo expuesto se planteó un objetivo general y varios específicos o parciales que se detallan a continuación.

1.2. Objetivo General

El objetivo general de la presente investigación fue analizar los aspectos socioeconómicos, stock de carbono y diversidad arbórea en sistemas ganaderos a lo largo de una gradiente altitudinal en la Amazonía Ecuatoriana.

1.3. Objetivos Específicos

Para la consecución de este objetivo general se plantearon los siguientes objetivos específicos o parciales que se corresponden con las diferentes publicaciones:

0. Como objetivo previo se realizó una revisión bibliográfica del concepto de agrosistema, su evolución y detectar el foco de investigación
1. Caracterizar los sistemas productivos ganaderos en pequeños finqueros a lo largo de una gradiente altitudinal en la Amazonía Ecuatoriana
2. Análisis socioeconómico de los sistemas ganaderos
3. Cuantificar la biomasa aérea y el carbono almacenado en sistemas ganaderos a lo largo de la gradiente altitudinal
4. Analizar la diversidad de árboles dispersos en los sistemas de pastizales a

lo largo de la gradiente altitudinal

5. Analizar y proponer buenas prácticas ganaderas considerando la gradiente altitudinal y los aspectos culturales para una reconversión productiva socialmente aceptable.

Todos los objetivos propuestos contribuirán al desarrollo de un análisis prospectivo de los sistemas ganaderos, orientados al logro de los objetivos del desarrollo sostenible (ODS) así como también a promover la restauración del paisaje e incremento del almacenamiento de carbono, considerando la gradiente altitudinal en la Amazonía Ecuatoriana, con esto resultado, se busca favorecer el diseño estratégico de políticas públicas, transferencia de tecnología y recomendaciones para su ejecución.

Por otra parte referir que el manuscrito desarrolla y profundiza en los objetivos recogidos en su día en el Plan de Investigación aprobado por la Comisión del Programa de Doctorado en Recursos Naturales y Gestión Sostenible de la Universidad de Córdoba.

REVISIÓN BIBLIOGRÁFICA

2. REVISION BIBLIOGRÁFICA

2.1. Introducción

La revisión bibliográfica se ha elaborado a partir del siguiente artículo, así como también del material presentado en diferentes congresos. Dada su relevancia y de acuerdo con la normativa del Instituto de Postgrado de la Universidad de Córdoba que regula la redacción y estructura de una tesis con mención internacional se ha procedido a exponer este capítulo tanto en inglés como en español.

Under review:

Torres, B., Herrera-Feijoo, R., Torres, Y., & García, A. (2023). Global evolution of research on silvopastoral systems through bibliometric analysis: insights from Ecuador. *Agronomy, 2023.*

Los análisis bibliometricos (AB) constituyen una herramienta robusta que contribuyen en este caso a la realización de una evaluación sistemática de los cambios del concepto del agrosistema silvopastoril. Además, son utilizados para identificar líderes de investigación, así como también los canales y redes de colaboración más relevantes, e incluso para la evaluación de la calidad en instituciones y de los propios evaluadores (Bastanchury-López & De-Pablos-Heredero, 2022; FAO., 2007; Mancilla-Leytón et al., 2022; Rangel et al., 2020; Torres et al., 2021a; Villarroel-Molina et al., 2019). Este tipo de estudio ha ganado amplia cobertura en los últimos años (Donthu et al., 2021; Ellegaard & Wallin, 2015).

Investigadores científicos utilizan los BA para analizar tendencias históricas y actuales de artículos, revistas, patrones de colaboración y componentes de investigación, a efectos de explorar la estructura intelectual de un dominio específico en la literatura científica existente (Donthu et al., 2021). La bibliometría logra identificar literatura importante, proporcionar palabras claves, instituciones, vínculos entre países y características de distribución en forma de mapa de conocimiento (Ellegaard & Wallin, 2015).

En general, cuantas más referencias incorpora un método bibliométrico, más capaces somos de comprender el campo de investigación (C. Chen, 2017). de esta forma, varios estudios han utilizado la bibliometría para el análisis de diversas disciplinas académicas, como el uso de la tierra y cobertura de la tierra en bosques tropicales (Velastegui-Montoya et al., 2022), forest carbon sequestration (Huang et al., 2020), Ecosystem Services Provided by Pastoral Husbandry (Mancilla-Leytón et al., 2022), entre otras.

El objetivo de la presente revisión realizada fue exploratorio, respecto a la evolución de las investigaciones enfocadas a los agrosistemas silvopastoriles en el periodo 1983 to 2022, con especial énfasis en el caso Ecuatoriano. Por una parte, se analizó su evolución del concepto; tanto desde punto de vista cuantitativo como cualitativo, enfocándose en las modificaciones del enfoque a través del tiempo.

Asimismo, en el trabajo se clasificaron los países según su interés en estos sistemas. Asimismo, a través de este estudio bibliométrico se abordan cuestiones clave, tales como:

¿Que países lideran este tipo de investigación?

¿Qué revistas son estratégicas en este ámbito?

¿Cómo se conforman las redes de investigación?

De cara al futuro, se analizaron los retos y posibles líneas futuras de investigación vinculados socioeconómicamente a estos sistemas productivos.

Por otra parte, se visualizaron los lideres ecuatorianos en este campo de conocimiento. Para alcanzar este objetivo se utilizó una metodología mixta cuantitativa y cualitativa en dos etapas. Por un lado, se midió mediante análisis de regresión la evaluación de las diferencias entre periodos (ANOVA) y la evolución de las publicaciones.

Procedimientos en el análisis bibliométrico

Este análisis bibliométrico se desarrolló en base a la metodología PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Figura 2).

Esta metodología facilita un análisis rápido, eficiente y transparente de los documentos científicos recogidos para el estudio (Page et al., 2021). En este sentido, este estudio se dividió en cuatro fases que permitieron el análisis óptimo de la producción científica mundial y en Ecuador en relación a los sistemas silvopastoriles: (I) Selección de bases de datos y criterios de búsqueda, (II) Criterios de exclusión, (III) Selección de software y datos, (IV) Interpretación de datos.

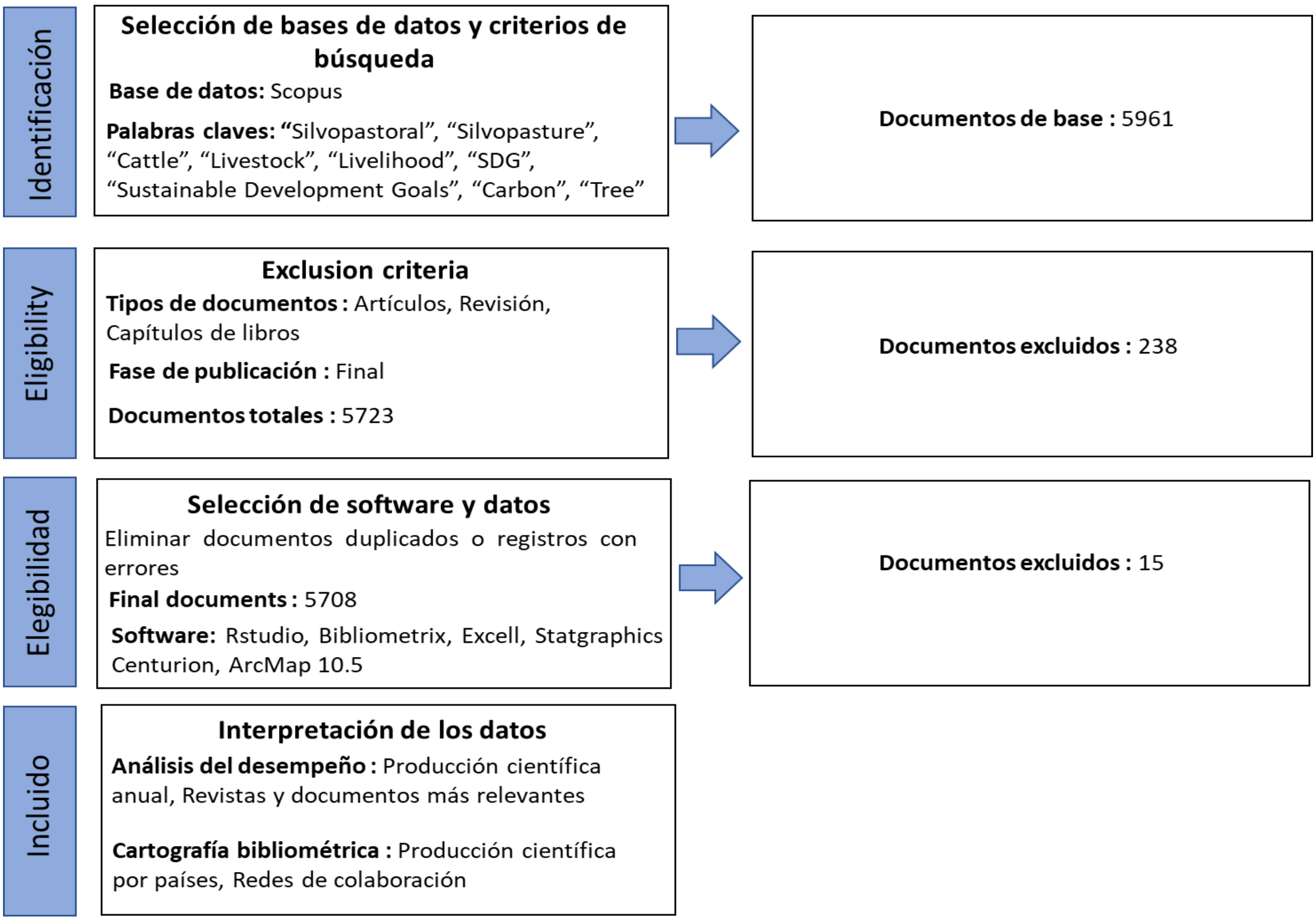

Figure 2. Diagrama basado en la declaración PRISMA que representa las cuatro fases de la metodología de investigación bibliométrica.

I) Database Selection and Search Criteria

Un AB satisfactorio se basará en la recopilación de información científica procedente de datos de investigación académica exhaustivos y fiables. (Saltelli et al., 2008). En el mundo académico, WOS y Scopus son las bases de datos científicas más utilizadas y accesibles en las últimas décadas (Pranckutė, 2021). Scopus se inició en 2004 a través de la organización editorial Elsevier Science y actualmente está reconocida como una de las bases de datos científicas más relevantes (Zhu & Liu, 2020). Dicho reconocimiento se atribuye al hecho de que se proporciona una amplia cobertura de temas en diversas disciplinas con información científica para su posterior procesamiento mediante múltiples programas informáticos biométricos (Baas et al., 2020; Singh et al., 2021). Aunque WOS ofrece servicios similares, su cobertura de las disciplinas educativas es menor en comparación con Scopus (Thelwall, 2018). Además, Scopus proporciona información correspondiente a la afiliación de los autores, las revistas, las palabras clave y los índices de calidad de la producción científica, como el Scimago Journal Rank (SJR) (Baas et al., 2020; Pranckutė, 2021). Por ello, en este estudio se ha utilizado Scopus para generar una base de datos que incorporará el mayor número posible de documentos para comprender la evolución histórica de la investigación científica centrada en el análisis de los sistemas silvopastorales.

La búsqueda y recopilación de documentos Scopus se realizó en diciembre de 2022, utilizando información de títulos, resúmenes y palabras clave. Para realizar este proceso, se utilizó la siguiente sintaxis con la configuración de búsqueda avanzada de la base de datos científica Scopus: TITLE-ABS-KEY (silvopastoral OR silvopasture) AND (cattle OR livestock OR live-lihood OR SDG OR "sustainable development goals" OR carbon OR tree). La búsqueda arrojó 5961 documentos.

II) Criterios de exclusión

Inicialmente, se realizó una selección por tipo de documento. Reteniendo únicamente documentos científicos clasificados como artículos, capítulos de libros y revisiones. Las categorías seleccionadas se encontraban entre las más utilizadas en el ámbito científico, ya que proporcionaban una mayor profundidad sobre el tema analizado, eran también más extensas y han sido sometidas a un riguroso proceso de revisión ciega por pares, lo que proporciona una mayor fiabilidad en la información representada en este tipo de documentos (Donthu et al., 2021; Ellegaard & Wallin, 2015). Además, sólo se tuvieron en cuenta para el análisis los documentos que ya habían completado el proceso de revisión inter pares y se habían publicado antes de diciembre de 2022. En otras palabras, los documentos que se encontraban en estado de publicación final. Con estos criterios, se excluyeron 238 documentos, lo que dio como resultado 5723 documentos.

III) Selección de software y datos

En esta revisión bibliográfica se utilizaron 4 tipos de software para el análisis de la información científica recopilada:

RStudio: Es un software de acceso abierto que permite el análisis y procesamiento de big data. Se utilizó la versión 3.5 de R para procesar la información mediante el uso del paquete Bibliometrix.

Bibliometrix: Para el procesamiento y obtención de los índices bibliométricos se utilizó el paquete Bibliometrix, una nueva herramienta desarrollada para el entorno R (Aria & Cuccurullo, 2017). Este paquete ofrece diferentes funcionalidades para el uso de diversos conjuntos bibliográficos obtenidos de bases de datos científicas, permitiendo el desarrollo de múltiples análisis bibliométricos considerando la información presentada en una amplia variedad de artículos científicos.

Microsoft Excel: Es un software que permite el análisis e interpretación de documentos científicos a través de la producción científica anual, número de citas, revistas y documentos más citados, entre otros

Statgraphics Centurion: Este software facilita el análisis e interpretación de datos a través de diferentes métricas estadísticas. Se utilizó para analizar la producción científica anual y sus tendencias futuras en este estudio.

ArcMap: Es un software utilizado en el diseño e interpretación de información geográfica. Para este estudio se utilizó la versión 10.5, que permite representar en mapas la contribución por países y las redes de colaboración global consolidadas.

Una vez recogidos los datos de la base Scopus, se exportaron en formato CSV y BibTex. El formato BibTex incluía información bibliográfica, citas, resúmenes, palabras clave y referencias. Por su parte, el formato CSV se utilizó con una hoja de Microsoft Excel. Durante la revisión, se depuraron los datos eliminando los archivos duplicados y los registros incompletos o erróneos. Bajo estas consideraciones, se eliminaron 15 documentos, obteniéndose 5708 documentos.

Finalmente, para realizar el análisis para Ecuador, se clasificaron los documentos por país. La base de datos para Ecuador consideró 17 artículos científicos.

IV) Interpretación de los datos

Para llevar a cabo este análisis, se utilizó el formato de archivo BibText mediante el paquete Bibliometrix en Rstudio (Aria & Cuccurullo, 2017), periodo III, de 2004 a 2013 y Periodo IV, de 2014 a 2022). Se utilizó la prueba de rangos múltiples de Duncan para mostrar diferencias significativas entre los grupos ($p<0,001$). Posteriormente, se relacionaron el número de publicaciones encontradas (variable dependiente) y los años de estudio (variable dependiente) mediante regresión múltiple por mínimos cuadrados ordinarios (MCO). La normalidad de la distribución se verificó mediante las pruebas de Kolmogorov-Smirnov, Cramer-Von Mises y Anderson-Darling. Además, se realizó la prueba de Bartlett para verificar la igualdad de la varianza de los datos (homocedasticidad). El coeficiente de determinación (R^2) y el error cuadrático medio (ECM) se utilizaron para seleccionar el mejor modelo.

Además, se examinaron las revistas científicas con mayor número de artículos publicados en relación con los sistemas silvopastorales. Para enriquecer el análisis, se consideraron el nombre de la revista, el país de origen, la editorial, el SJR 2021 y el cuartil. De forma continua, se identificaron los artículos científicos más relevantes de las últimas décadas en el tema analizado. Así, se elaboró un ranking que incluía el nombre de los autores, el título del artículo, el nombre de la revista y el número de citas obtenidas

Cartografía bibliométrica

La producción científica se obtuvo a nivel de cada país; este análisis de bibliometría utiliza el país de afiliación de cada autor. Los datos obtenidos en este análisis se procesaron utilizando ArcMap 10.5 para el diseño de la cartografía. Por último, para el análisis global, se examinó la colaboración entre distintos autores de diferentes países para obtener la frecuencia de las colaboraciones científicas. Esta información se representa mediante un mapa de red de frecuencias en la interfaz gráfica de usuario de Bibliometrix.

Producción científica anual por periodos

La producción científica enfocada en sistemas silvopastoriles a nivel global comprende 5708 documentos durante los últimos 39 años (1983–2022) (Figura 3). Para fines de una mejor interpretación de los resultados, la producción científica se dividió en cuatro períodos de 10 años: Período I (1983-1993), Período II (1994-2003), Período III (2004-2013) y Período IV (2014-2022). Esta división por décadas facilita la comprensión del desarrollo y evolución del campo de estudio. En la tabla 1, se muestran los estadísticos descriptivos para cada uno de los periodos.

Table 1. Descriptive statistics for publications and cites numbers per period (Mean ± DS1 (CV, %2)).

Period	**Nº of publications**	**Nº of cites**
I (1983-1993)	4.3+3.4 (79)^{a}	103.7+72.0 (69)^{a}
II (1994-2003)	25.1+15.0 (60)^{a}	718.2+543.6 (76)^{a}
III (2004-2013)	139.6+61.4 (44)^{b}	4,503.5+1,496.1(33)^{b}
IV (2014-2022)	446.4+168.9(38)^{c}	4,751.2+1,965.1 (41)^{b}
Total	146.4+193.6 (132)	2,461.9+2,452.7 (99)

[1] Standard deviation, [2] Coefficient of variation; [a, b] Means with different letters show significant differences between groups within the same column.

El número de publicaciones fue creciente en el tiempo, aunque el periodo I y II mostraron un comportamiento similar, frente al periodo III y IV, con tres grupos de homogeneidad diferenciados ($p<0,001$). Por otra parte, a medida que aumenta el número de publicaciones se va reduciendo la dispersión de la variable hasta alcanzar en el periodo IV un 38% el coeficiente de variación. El número de citas se distribuye en dos grupos de homogeneidad; el periodo I y

II, frente al periodo III y IV (p<0,001). En la Figura 1 se muestra el comportamiento conjunto de ambas curvas por periodos.

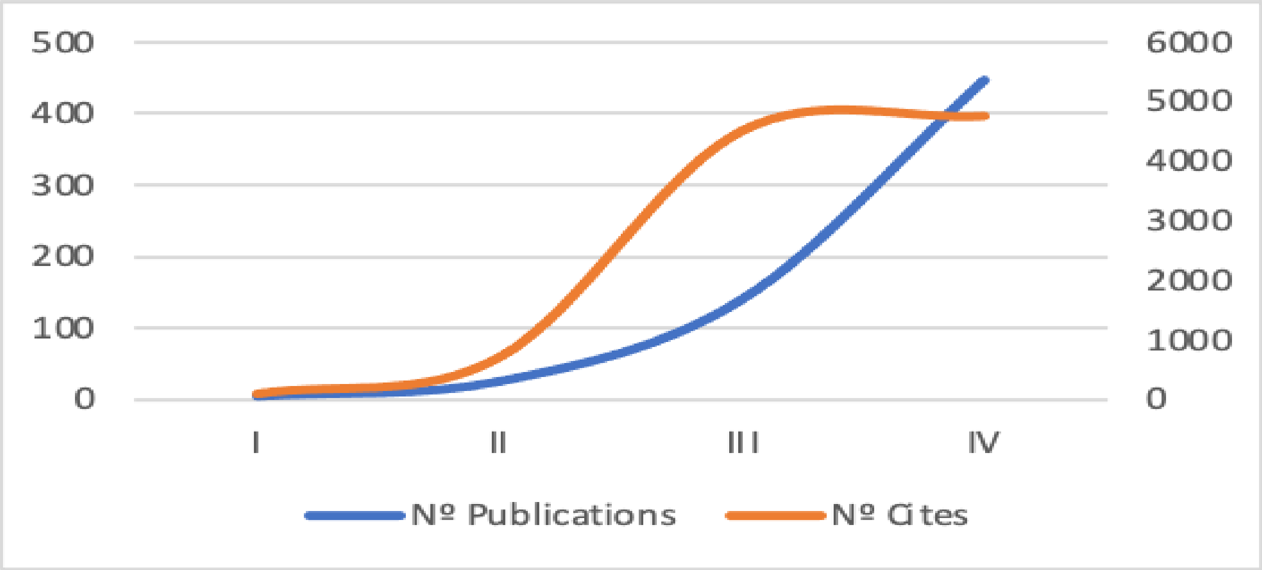

Figure 3. Evolución del número de publicaciones y citas por periodo.

En la Figura 4 se muestra la salida del modelo de regresión ajustado. Se compararon 14 modelos alternativos y en más de 10 se obtienen coeficientes de determinación superiores al 70% y en los modelos: Curva S, Multiplicativo, Logarítmico-Y Raíz Cuadrada-X, Exponencial, Log-Y Cuadrado-X, Raíz Cuadrada-X Cuadrado-X, Raíz Cuadrada Doble, Raíz Cuadrada-Y Log-X y Raíz Cuadrada-Y Inversa de X el R2 fue superior al 90%. La ecuación del better Model adjusted for the period 1983-2022 was Curve S: $Y = \exp(a + b/X)$, con un R^2 del 96,06%. Donde Y: Numero de publicaciones; X: Year (from 1983 to 2022); Parameter a: 342.662 and Parameter b: 678911.

Puesto que el valor-P< 0.05, existe una relación estadísticamente significativa entre el número de publicaciones y el año con un nivel de confianza del 95,0%. El estadístico R-Cuadrada indica que el modelo ajustado explica 96,057% de la variabilidad del número de documentos. El coeficiente de correlación es igual a -0,9801, indicando una relación relativamente fuerte entre las variables. El error estándar del estimado indica que la desviación estándar de los residuos es 0,397781. El error absoluto medio (MAE) de 0,281166 es el valor promedio de los residuos. El estadístico de Durbin-Watson (DW) examina los residuos para determinar si hay alguna correlación significativa basada en el orden en el que se presentan en el archivo de datos.

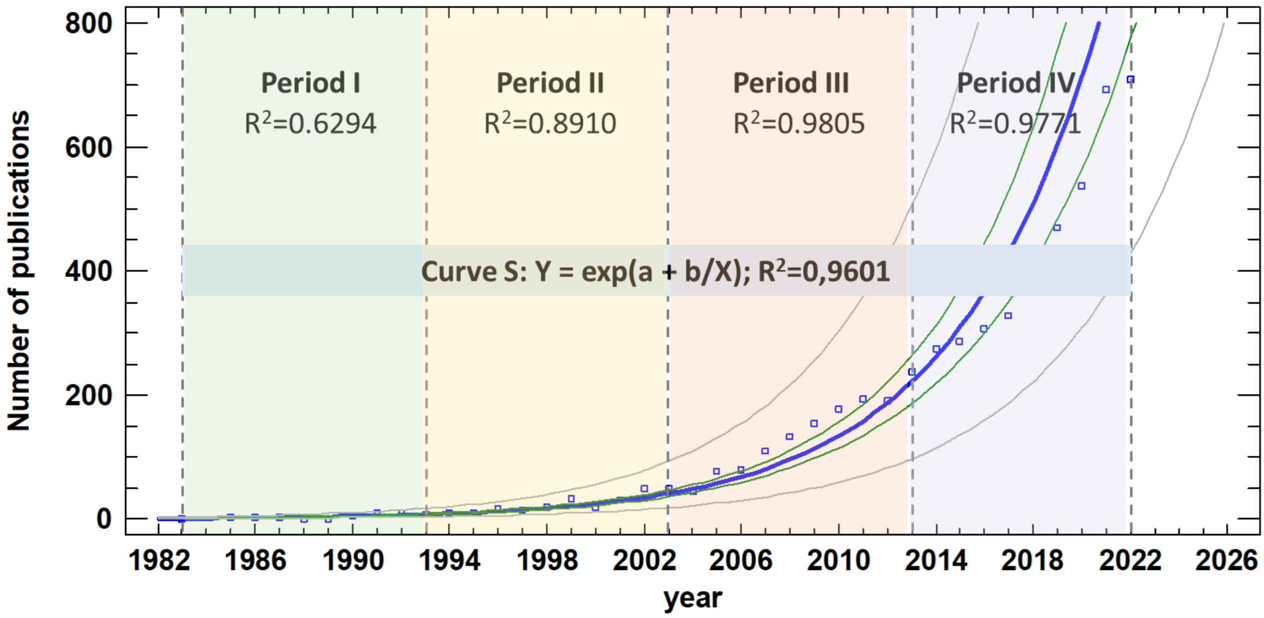

Figure 4. Evolution of the number of publications in agrosilvopastoril system per year (1983-2022). The model fit and the adjusted coefficient of determination used in each stage is shown.

Periodo I (1983-1993) – Caracterización de las silvopasturas

En este periodo se registraron 43 publicaciones científicas en sistemas silvopastoriles equivalente al 0,8% del total de artículos analizados. Dentro de esta década, se observó que 1991 y 1992 fueron los años con mayor producción con 9 artículos científicos respectivamente. Los temas de estudio se centraron en la contribución de los sistemas silvopastoriles en zonas áridas y semiáridas (Ormazábal, 1991), así también como la evaluación de factores físicos del suelo que afectan el crecimiento de árboles en pastos (Wairiu et al., 1993). La importancia de los usos múltiples del suelo por medio de la aplicación de iniciativas basadas en sistemas silvopastoriles (Peñaloza et al., 1985). Asimismo, también se registraron estudios centrados en la viabilidad económica y ecológica en plantaciones de pino en la Sierra Central del Ecuador (Garrison & Pita, 1992). Por otra parte, se evidenció un estudio de revisión enfocado en analizar las experiencias obtenidas con la implementación de sistemas silvopastoriles en Nueva Zelanda (Knowles, 1991).

Periodo II (1994-2003) – buenas prácticas

En este periodo se incrementaron las publicaciones en silvopasturas, con un total de 251 artículos, lo que representa el 4,4% de producción total del periodo analizado. Comenzaron las investigaciones a cuantificar el almacenamiento de carbono y analizar el ciclo del nitrógeno

(Kaur et al., 2002). Así como la relación entre el microclima y dinámica de nutrientes (Menezes et al., 2002), resaltándose la importancia de los sistemas silvopastoriles para el biomejoramiento de los suelos(Cardinael et al., 2017). Fueron frecuentes los estudios de los beneficios económicos que conlleva la implementación de los sistemas silvopastoriles (Grado et al., 2001; Husak & Grado, 2002), y la adopción de prácticas silvopastoriles (Rapey et al., 2001). Por otra parte, algo novedoso en este periodo fue la incorporación de conocimientos ancestral enfocados en el uso de árboles forrajeros en sistemas silvopastoriles (Morrison et al., 1996).

Periodo III (2004-2013) – servicios ecosistémicos

En este tercer periodo se evidenciaron 1.396 artículos que representan el 24,5% del total de documentos analizados, y la producción anual promedio supera los 45 artículos, con un máximo de 237 artículos reportados para 2013. Durante esta década, probablemente impulsados por la Declaración del Milenio a través de los objetivos del desarrollo del milenio (ODM) (ONU, 2000) y la evaluación de ecosistemas del milenio (Millennium ecosystem assessment, 2005) se destacan investigaciones centradas en la valoración ambiental y los pagos por servicios ambientales asociados a los sistemas silvopastoriles (Garbach et al., 2012; Pagiola et al., 2007, 2008, 2010; Shrestha & Alavalapati, 2004). Se potenciaron los estudios sobre el almacenamiento de carbono proporcionado por los sistemas silvopastoriles (Haile et al., 2008, 2010; Howlett et al., 2011; Tonucci et al., 2011). También a nivel de suelo, se aborda la reducción de la pérdida de nutrientes (Michel et al., 2007; Nair et al., 2007), el mejoramiento de la calidad ambiental de tierras agrícolas (Reis et al., 2010) y la influencia de los árboles como reservas de nutrientes (Nair et al., 2007). La mayoría de estas investigaciones proponen acciones para la mitigación de los efectos del cambio climático (Montagnini et al., 2013) y la recuperación de procesos ecológicos (Giraldo et al., 2011).

Periodo IV (2014-2022) – restauración de paisajes

Finalmente, el último periodo es del de mayor relevancia en relación con el aumento de la producción científica centrada en sistemas silvopastoriles. En este periodo se publicaron 4255 documentos científicos que representa el 74,5% del total de artículos considerados en este análisis. Esta década, se observó un crecimiento anual siendo el pico de publicaciones el año 2022 con 708 artículos, esto sugiere que los sistemas silvopastoriles es una temática de gran interés a nivel global. Se abordaron temas como: la conversión de pastos extensivos a silvopastoreo con árboles maderables como medida para mejorar la salud de los suelos (Poudel et al., 2022) y la restauración tierras degradadas (Kumar et al., 2022). Otro estudios, se centraron en la combinación de sistemas silvopastoriles y bosques remanentes bajo estrategias de ganadería (Aryal et al., 2022), beneficios de enfriamiento térmico en los sistemas silvopastoriles tropicales (Zeppetello et al., 2022) y como estos pueden potenciar la de mitigación de los efectos del cambio climático relacionado a las emisiones de gases de efecto invernadero generadas en actividades ganaderas (Brook et al., 2022).

El enfoque en las investigaciones también se relación con el lanzamiento de los objetivos de desarrollo del milenio (ODS) por parte de las Naciones Unidas (UN, 2015). Finalmente, durante este periodo se pudo evidenciar la inclusión drones y sensores remotos para la caracterización de árboles leñosos que se encuentran de forma dispersa dentro de sistemas silvopastoriles (Iñamagua-Uyaguari et al., 2022).

Países con mayor número de publicaciones

Partiendo del análisis de la afiliación de los autores suscritos en los artículos a nivel de países, se consideraron las contribuciones totales por naciones en relación a la temática de estudio (Centobelli et al., 2022; McAllister et al., 2022). Para ello, se elaboró un mapa usando el software ArcMap 10.5 para visualizar geográficamente las aportaciones detectadas en 138 países (Figura 5). En este sentido, la Figura 3 se presenta el mapa de la contribución científica mundial en los últimos 39 años reportada en temas relacionados a sistemas silvopastoriles. La gama de colores utilizados en el mapa permite diferenciar el número de documentos científicos para cada país, mientras que los países en blanco denotaron la ausencia de poblaciones reportadas.

Entre los 10 países principales, destacan cinco países americanos (Estados unidos, Brasil, México, Colombia, Argentina), dos de Asia (China, India), tres países europeos (España, Alemania, Reino unido). El país con mayor número de publicaciones fue Estados unidos con 1090 documentos, mientras tanto Brasil y España ocupan el segundo y tercer lugar con 954 y 601 documentos, respectivamente. Finalmente, se pudo evidenciar que gran parte de las investigaciones reportadas han sido llevadas a cabo en países desarrollados y países que han presentado incrementos significativos en actividades enfocadas en la agricultura y ganadería (Aryal et al., 2022; Jaureguiberry et al., 2022; Winkler et al., 2021; Zeppetello et al., 2022).

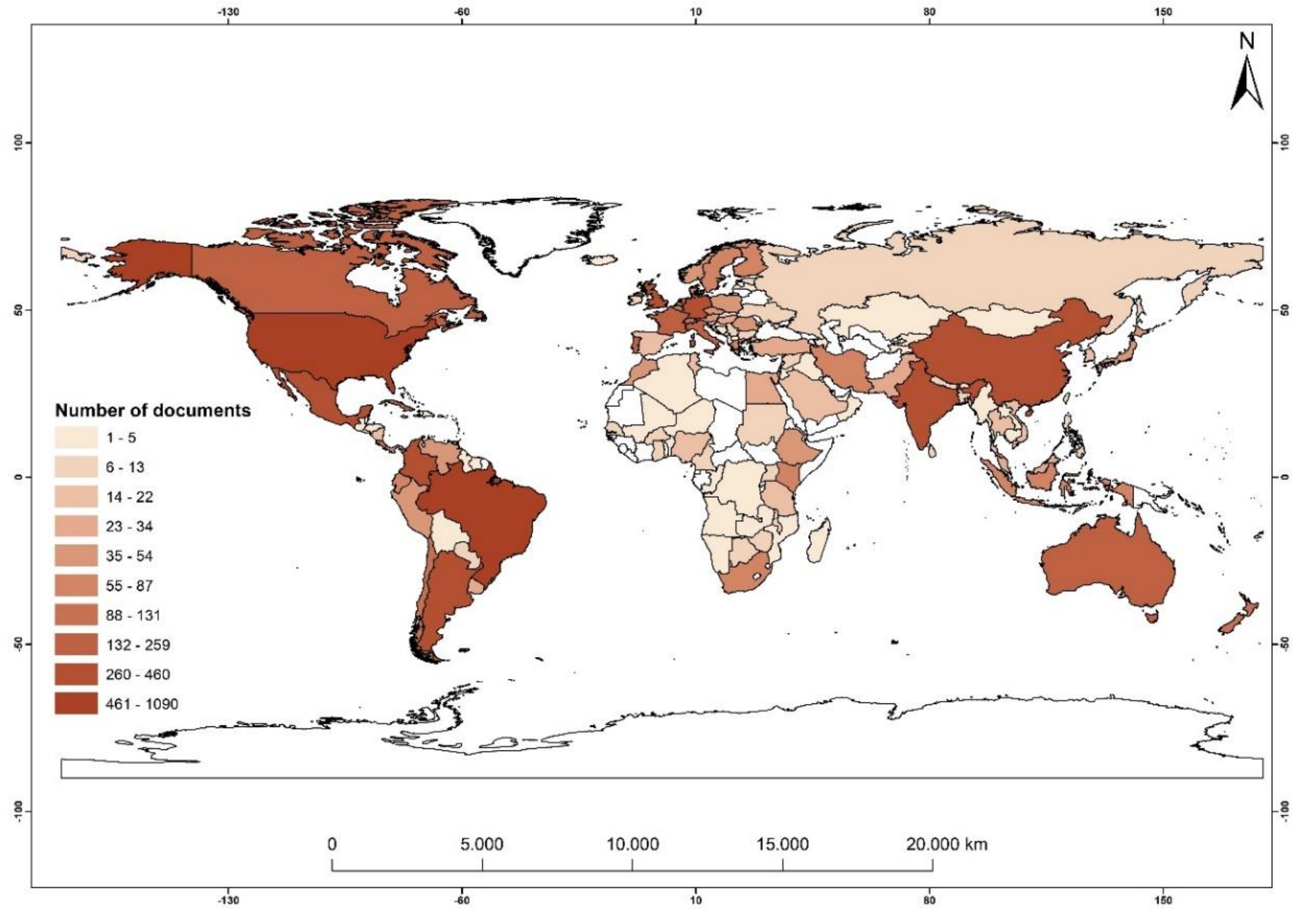

Figure 5. Número de publicaciones sobre sistemas silvopastoriles por país.

Respecto al continente americano: En Estados Unidos se orientaron a los beneficios de la conservación de pastos abiertos a silvopastoreo para mejorar la salud del suelo (Poudel et al., 2022). Del mismo modo, investigaciones que reportan que los sistemas silvopastoriles podrían beneficiar a un enfriamiento de −0,32 °C a −2,4 °C por cada 10 toneladas métricas de carbono leñoso por hectárea (Zeppetello et al., 2022). Por otra parte, también se encontraron estudios centrados en analizar los sistemas silvopastoriles como una alternativa para la mejora del bienestar animal y el desempeño productivo (Lemes et al., 2021). Se constató la innovación con el uso de imágenes satelitales de alta resolución espacial para estimar índices foliares y biomasa área en pastos espacial (J. Wang et al., 2019), y se realizó la comparación entre sistemas silvopastoriles entre países (Cubbage et al., 2012). En lo que concierne a lo económico, se observó estudios enfocados en analizar la rentabilidad de los sistemas silvopastoriles (Husak & Grado, 2002). *Pino loblolly, Ceanothus integerrimus, Acacia koa* (Akau et al., 2022; Huntsinger, 1996; Nyakatawa et al., 2012).

El segundo líder fue Brasil, con publicaciones enfocadas en relacionar a los sistemas silvopastoriles con el bienestar animal mediante la estimación de índices de confort térmico

(Deniz et al., 2019; Pezzopane et al., 2019), la influencia de los sistemas de pastoreo, agricultura y cultivo-ganadería en las reservas de C (Carvalho et al., 2010), y la integración de leguminosas en sistemas silvopastoriles para impulsar las reservas de C y N en el suelo (Lira Junior et al., 2020). Así como, los cambios en el carbono orgánico del suelo durante 22 años de pasturas, mediante sistemas integrados de cultivos y ganadería (Cá et al., 2022). Por otro lado, también se constató que una de las especies de mayor consideración para estrategias silvopastoriles y mitigación del cambio climático en Brasil fue el Eucalipto (Bosi et al., 2020; de Macêdo Carvalho et al., 2022; de Oliveira et al., 2022; Horst et al., 2022).

Desde Europa, España lidera la producción científica, contribuyendo con publicaciones centradas en la promoción de políticas silvopastoriles en áreas mediterráneas europeas (Rodriguez-Rigueiro et al., 2021). Por otra parte, también se evaluó el potencial de los árboles y el clima para regular el balance de carbono del suelo (Ferreiro-Domínguez et al., 2022). El manejo adecuado de plantaciones de madera de alta calidad en sistemas silvopastoriles (López-Díaz et al., 2020), y el establecimiento de sistemas silvopastoriles en terrenos agrícolas abandonados en el Noroeste de España (Pasalodos-Tato et al., 2009). En relación a lo económico, se observó un estudio centrado en analizar la rentabilidad ambiental y económica del pastoreo de ganado en fincas bajo un sistema silvopastoril (Campos et al., 2018). Finalmente, las especies más relevantes fueron: *Quercus ilex*, *Quercus rubra*, *Pinus radiata*, *Fraxinus excelsior*, *Prunus avium*, *Pinus pinea*, *Eucalyptus nitens*, *Betula pubescens* (Campos et al., 2018; Fernández-Núñez et al., 2014; Ferreiro-Domínguez, Rigueiro-Rodríguez, et al., 2016; Mancilla-Leyton et al., 2013; Mosquera-Losada et al., 2015, 2016; Rivest et al., 2011).

Revistas con mayor número de documentos

En la Tabla 2 se muestran los índices de desempeño y calidad de las diez revistas líderes con mayor numero documentos que colaboran para generar conocimiento relacionado a los sistemas silvopastoriles. Estas revistas contienen 1275 de las 5708 publicaciones analizadas, lo que representa el 22,3% de la producción científica. La tabla en cuestión muestra los indicadores de desempeño de revistas como SJR y su cuartil para 2021.

Agroforestry Systems es la revista líder en contribuciones científicas, con 533 artículos que representan el 9,3% del total de documentos publicados. Esta revista presenta un índice SJR de 0,59 y se encuentra en Q1 según la última evaluación del 2021. El documento más relevante de la revista fue publicado por Cubbage et al. (Cubbage et al., 2012) y ha sido citado 78 ocasiones en la literatura científica. Este documento se centró en realizar una comparación de los sistemas silvopastoriles en ocho regiones del mundo, considerando sus métodos de investigación y experiencia en esas regiones.

El segundo lugar lo ocupa Forest Ecology And Management con 161 documentos y dispone de un índice SJR de 1,11 y actualmente se encuentra dentro del primer cuartil (Q1). Su artículo más citado (72 citas) fue publicado por Mohan et al. (1998), el cual se centra en evaluar el potencial de producción de biomasa de nueve taxones tropicales multipropósito de rápido crecimiento, cuatro de los cuales se cultivaron bajo dos sistemas de manejo de la tierra (bosques y silvopastoralismo).

Finalmente, la tercera revista de mayor producción científica fue Agriculture Ecosystems And Environment, la cual se caracteriza por haber publicado 99 articulos, posee un índice SJR de 1,66 y se encuentra dentro del primer cuartil (Q1). Uno de los aportes científicos de mayor relevancia dentro de esta revista analizó el papel de los incentivos positivos y el intercambio de información para estimular la adopción de prácticas de conservación silvopastoril (Garbach et al., 2012).

Table 2. Clasificación de revistas por número de publicaciones en sistemas silvopastoriles.

Revistas	País	Editorial	Número de documentos	SJR 2021	Quartile
Agroforestry Systems	Netherlands	Springer	533	0,59	Q1
Forest Ecology and Management	Netherlands	Elsevier	161	1,11	Q1
Agriculture Ecosystems and Environment	Netherlands	Elsevier	99	1,66	Q1
Sustainability	Switzerland	MDPI	92	0,66	Q1
Livestock Research for Rural Development	Colombia	Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria	84	0,25	Q3
Forests	Switzerland	MDPI	71	0,62	Q1
Plant And Soil	Netherlands	Springer	62	1,12	Q1
Science Of the Total Environment	Netherlands	Elsevier	61	1,81	Q1
Tropical And Subtropical Agroecosystems	Mexico	Universidad Autónoma de Yucatán	58	0,2	Q3
Land Use Policy	United Kingdom	Elsevier	54	1,64	Q1

Los 10 documentos citados con mayor frecuencia

Se identificaron las publicaciones más citadas para resaltar los temas de mayor interés. En este contexto, la producción científica enfocada en sistemas silvopastoriles a nivel global (5708 documentos) presenta 95,355 citas. La Tabla 3 presenta el top 10 de los documentos más citados con 1023 citas, lo que representa el 1.07% del total.

Dentro de este grupo, destacan publicaciones enfocados en países de América del Sur (Nicaragua, Colombia, Argentina, Chile, Brasil, Paraguay, Uruguay), América del Norte (Estados unidos, particularmente en Florida), Asia (India), Europa (Grecia) y Oceanía (Nueva Zelanda). Entre los documentos analizados, se pudo identificar que los documentos más antiguos fueron publicados por Kumar et al. Mohan et al. (1998) en 1998 y Wedderburn &

Carter (1999) en 1999. El documento publicado por Mohan et al. (1998) evaluó las tasas de acumulación de biomasa y nutrientes en árboles multipropósito en experimentos de lotes arbolados y silvopastoreo. Mientras que Wedderburn & Carter (1999) cuantifico la caída, características químicas y la tasa de descomposición de hojarasca de árboles funcionales para su uso en sistemas silvopastoriles.

Por otra parte, se pudo observar que el documento más reciente fue publicado en 2012. En esta investigación, Cubbage et al. (2012) se enfocaron en describir y comparar prácticas agrícolas reales y ensayos de investigación de sistemas silvopastoriles en ocho regiones dentro de siete países del mundo.

Shrestha et al. (2004) concentró 197 citas. Los autores evaluaron la sostenibilidad de decisiones de adopción de silvopastoreo por medio de la implementación de un enfoque de fortalezas, debilidades, oportunidades y amenazas (FODA) y un proceso de jerarquía analítica (AHP). Entre los principales hallazgos de esta investigación, se determinó que la custodia de la tierra, la diversificación de ingresos, los beneficios ambientales y los programas de apoyo del gobierno son las principales perspectivas para la adopción del silvopastoril (Shrestha et al., 2004).

El segundo lugar lo ocupan Pagiola et al. (2007), donde los investigadores describen los resultados alcanzados por el Proyecto Regional Integrado de Manejo de Ecosistemas Silvopastoriles (PRIMES, por sus siglas en español), el cual tiene como meta fomentar el pago por servicios ambientales a los agricultores por su contribución a la conservación de la biodiversidad y secuestro de carbono que brinda la implementación de las estrategias silvopastoriles. Este articulo sugiere que la implementación del PRIMES permitió la adopción de sistemas silvopastoriles que a su vez generaron los servicios ecosistémicos esperados. No obstante, los autores mencionan que existe mucha incertidumbre con respecto la sostenibilidad financiera que permita el pago por servicios ambientales (Pagiola et al., 2007).

Por último, en tercer documento más citado relacionado con sistemas silvopastoriles fue publicado por Haile et al. (Haile et al., 2008), el cual se enfocó en determinar los contenidos totales de carbono del suelo a seis profundidades del suelo (0–5, 5–15, 15–30, 30–50, 50–75 y 75–125 cm) en sistemas silvopastoriles, para evaluar el potencial de almacenamiento carbono. Entre los principales resultados, los autores llegaron a la conclusión que la integración de los árboles en pastos abiertos genera aun del carbono orgánico del suelo, particularmente a profundidades más bajas (Haile et al., 2008). La Tabla 3 muestra los 10 trabajos mas citados.

Table 3. Top 10 most cited papers with 1023 citations, representing 1.07% of the total..

Ranking	Autor	Article	Journal	Citations
1	Shrestha et al. (2004)	Exploring the potential for silvopasture adoption in south-central Florida: An application of SWOT-AHP method	Agricultural systems	197
2	Pagiola et al.(2007)	Paying for the environmental services of silvopastoral practices in Nicaragua	Ecological economics	171
3	Haile et al. (2008)	Carbon storage of different soil-size fractions in Florida silvopastoral systems	Journal of Environmental Quality	118
4	Pagiola et al.(2008)	Can the poor participate in payments for environmental services? Lessons from the Silvopastoral Project in Nicaragua	Environment and Development Economics	89
5	Cubbage et al. (2012)	Comparing silvopastoral systems and prospects in eight regions of the world	Agroforestry Systems	78
6	Giraldo et al. (2011)	The adoption of silvopastoral systems promotes the recovery of ecological processes regulated by dung beetles in the Colombian Andes	Insect Conservation and Diversity	77
7	Haile et al. (2010)	Contribution of trees to carbon storage in soils of silvopastoral systems in Florida, USA	Global Change Biology	77
8	Plieninger et al. (2011)	Land-use legacies in the forest structure of silvopastoral oak woodlands in the Eastern Mediterranean	Regional Environmental Change	76
9	Wedderburn et al. (1999)	Litter decomposition by four functional tree types for use in silvopastoral systems	Soil Biology and Biochemistry	72
10	Kumar et al. (1998)	Comparison of biomass production, tree allometry and nutrient use efficiency of multipurpose trees grown in woodlot and silvopastoral experiments in Kerala, India	Forest Ecology and Management	72

Redes de colaboración

La colaboración científica permite la transferencia conocimientos y potencia la innovación de tecnología por medio de la contribución documentos publicados por la contribución multidisciplinaria de autores originarios de diversos países a escala global. En sentido, se pudo identificar para el campo de investigación enfocado en sistemas silvopastoriles, 119 países han colaborado en el desarrollo de documentos científicos. De este total, al menos 77 países poseen 3 artículos en colaboración con autores de otros países. En la Figura 6, se muestran el mapeo de la red global de colaboraciones científicas entre países de diversas regiones del mundo.

En general, el país con mayor número de contribuciones entre naciones es Estado unidos con 80 colaboraciones, seguido de Alemania en segundo puesto con 64 aportaciones y en tercera posición Reino unido con 64.

En relación a Estados unidos, sus colaboraciones se han centrado en la evaluación de los sostenibilidad (Shrestha et al., 2004), el análisis del pago por servicios ambientales (Garbach et al., 2012; Pagiola et al., 2007, 2008, 2010; Shrestha & Alavalapati, 2004), el potencial de almacenamiento de carbono en el suelo (Haile et al., 2008, 2010; Howlett, Moreno, et al., 2011; Howlett, Mosquera-Losada, et al., 2011; Tonucci et al., 2011; Vallejo et al., 2012), la transferencia de nitrógeno (Sierra & Nygren, 2006) y la reducción de la perdida de nutrientes en fincas (Nair et al., 2007). Además, también estas colaboraciones se han enfocado en evaluar el microclima y la dinámica de nutrientes (Menezes et al., 2002), así como también las consideraciones ecológicas en el diseño y manejo sostenible de silvopastoreo (Jose et al., 2019). Alemania, ha cooperado en documentos centrados en evaluar determinar la reducción de la deforestación y el potencial de mitigación de los efectos de gases invernadero (Landholm et al., 2019), el efecto de la herbívora en árboles en un sistema de reforestación (Riedel et al., 2013), el cambio de uso y cobertura de tierra (Cárdenas et al., 2018), la dinamia de fosforo(Ferreiro-Domínguez et al., 2016), producción de carne y redes alimentarias (Pereira et al., 2021; Röhrig et al., 2021).

Finalmente, Reino unido ha aportado investigaciones enfocadas en determinar el crecimiento, la producción y el secuestro de carbono con especies maderables nativas (Andrade et al., 2008), la evaluación de la producción de leche en fincas ganaderas de doble propósito (Yamamoto et al., 2007), el análisis la renta ambiental del pastoreo de ganado (Campos et al., 2018), la determinación del potencial de secuestro de carbono de la biomasa arbórea y del suelo (Beckert et al., 2016), la cuantificación del cambio en el uso de la tierra y depósitos de carbono en el suelo (Fornara et al., 2018), la comprensión de prácticas sustentables (Tschopp et al., 2020).

Figure 6. Redes de colaboración en sistemas silvopastoriles.

2.2. Análisis de Ecuador

Producción científica y distribución por provincial

La producción científica enfocada en sistemas silvopastoriles en Ecuador comprende 17 artículos (Figura 7) publicados durante las últimas 3 décadas (1992–2022)). El primer artículo para Ecuador fue publicado en 1992 por Garrison & Pita (1992). En este documento, los autores evaluaron diez plantaciones de pino en las provincias de Tungurahua y Chimborazo por su potencial como sistemas silvopastoriles y, además, discuten las posibilidades de integrar a los agricultores locales en el manejo y uso apropiado de las mismas. Entre 1993 y 2014 no se reportaron publicaciones científicas para Ecuador en relación con la temática abordada. Mientras que el mayor número de contribuciones se obtuvo en 2021.

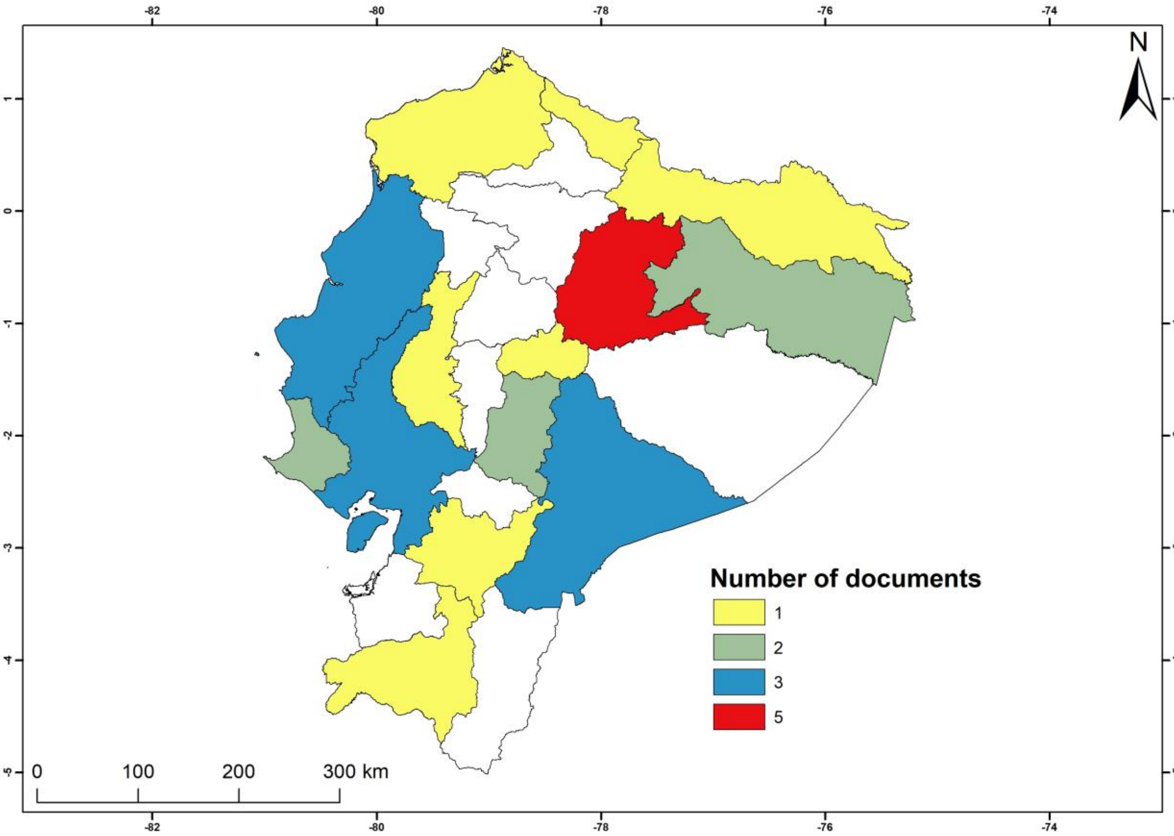

Figure 7. Mapeo del número de contribuciones científicas en silvopasturas por provincias en Ecuador.

Por otra parte, en relación con el año vigente (2022), se observó un total de 3 artículos. Entre estos artículos, el documento más reciente fue publicado por Torres et al. (2023), en este estudio, los investigadores evaluaron las reservas de carbono en los sistemas silvopastoriles de la Amazonía ecuatoriana. Entre los principales hallazgos reportados entre este estudio, se indican el alto potencial que poseen los sistemas de pastoreo tradicional con árboles dispersos para el secuestro de carbono en la Amazonía ecuatoriana.

Por este motivo, también se indica que los sistemas silvopastoriles permiten concretar estrategias enfocadas en la mitigación y adaptación del cambio climático en los países tropicales.

Finalmente, los autores, recomiendan que estos sistemas deben ser manejados aplicando las mejores prácticas de manejo ganadero (BMPs) para mitigar la expansión de la frontera agrícola en la amazonia ecuatoriana.

Además, estos los sistemas silvopastoriles podrían asociarse a iniciativas enfocadas en REDD+ de Ecuador, aportando de esta forma a las contribuciones determinadas a nivel nacional (NDCs), las cuales fueron planteadas como meta del Acuerdo de París para estabilizar la temperatura promedio global en menos de 2 °C.

Artículos más relevantes

En la Tabla 4 se muestran los 10 documentos más citados que han sido reportados para Ecuador con lo que concierne a sistemas silvopastoriles. Entre los documentos analizados, el estudio de Lerner et al. (2015) es el articulo más citado con 28 citas. En esta investigación, los autores se enfocaron en determinar ccuáles son los factores socioecológicos asociados con el surgimiento aparentemente espontáneo de paisajes silvopastoriles y posible las explicaciones de la variación en la densidad de árboles que se encuentran en los pastos. El segundo lugar, lo ocupan Raes et al. (2017), donde se investiga las preferencias de los agricultores para participar en contratos de pago para adoptar sistemas silvopastoriles en Ecuador. Finalmente, el tercer documento más citado fue publicado por McGroddy et al. (2015). En este estudio, los autores se plantearon como objetivo principal, cuantificar el carbono de biomasa almacenado en sistemas silvopastoriles espontáneos en la provincia de Morona Santiago perteneciente a la amazonia ecuatoriana.

Table 4. Documentos más citados sobre sistemas silvopastoriles en Ecuador.

Ranking	Autor	Artículo	Revista	Citaciones
1	Lerner et al.(2015)	The spontaneous emergence of silvo-pastoral landscapes in the Ecuadorian Amazon: patterns and processes	Regional Environmental Change	28
2	Raes et al. (2017)	Farmers' Preferences for PES Contracts to Adopt Silvopastoral Systems in Southern Ecuador, Revealed Through a Choice Experiment	Environmental management	19
3	McGroddy et al. (2015)	Carbon Stocks in Silvopastoral Systems: A Study from Four Communities in Southeastern Ecuador	Biotropica	19
4	Torres et al. (2018)	Determinants of agricultural diversification in a hotspot area: Evidence from colonist and indigenous communities in the Sumaco Biosphere Reserve, Ecuadorian Amazon	Sustainability	18
5	Hayes et al. (2015)	Can Conservation Contracts Co-exist with Change? Payment for Ecosystem Services in the Context of Adaptive Decision-Making and Sustainability	Environmental management	15

6	Cañadas-L et al. (2018)	Growth and yield models for teak planted as living fences in coastal Ecuador	Forests	14
7	González Marcillo et al. (2021)	Assessment of guinea grass panicum maximum under silvopastoral systems in combination with two management systems in Orellana province, Ecuador	Agriculture	5
8	Vargas-Tierras et al. (2018)	Characterization and role of Amazonian fruit crops in family farms in the provinces of Sucumbíos and Orellana (Ecuador)	Ciencia y Tecnología Agropecuaria	4
9	Diana Rade et al. (2017)	Silvopastoral System Economical and Financial Feasibility with Jatropha Curcas L. in Manabí, Ecuador	Revista MVZ Córdoba	4
10	Torres et al. (2021a)	Identification and assessment of livestock best management practices (BMPs) using the REED+ approach in the Ecuadorian amazon	Agronomy	3

2.3. Introduction

Bibliometric analysis (BA) is a robust tool that contributes to a systematic assessment of changes in the silvopastoral agrosystem concept. In addition, it is used to identify research leaders, as well as the most relevant collaboration channels and networks, and even for the evaluation of the quality of institutions and peer reviewers themselves. (Bastanchury-López & De-Pablos-Heredero, 2022; FAO., 2007; Mancilla-Leytón et al., 2022; Rangel et al., 2020; Torres et al., 2021a; Villarroel-Molina et al., 2019). This type of study has achieved wide coverage in recent years (Donthu et al., 2021; Ellegaard & Wallin, 2015). Scientific researchers use BA to analyze historical and current trends of articles, journals, collaboration patterns and research components to explore intellectual structure of a specific domain in the existing scientific literature. (Donthu et al., 2021). Bibliometrics can identify important literature, providing keywords, institutions, links between countries and distribution characteristics in the form of a knowledge maps (Ellegaard & Wallin, 2015). Generally, the more references a bibliometric method incorporates, the better we are able to understand the field of research. (C. Chen, 2017). Thus, many studies are using bibliometrics for the analysis of various academic disciplines, such as land use and land cover in tropical forests (Velastegui-Montoya et al., 2022), forest carbon sequestration (Huang et al., 2020), and ecosystem services provided by pastoral husbandry (Mancilla-Leytón et al., 2022), among others.

The objective was to perform an exploratory review of the evolution of research focused on silvopastoral agrosystems from 1983 to 2022, with special emphasis on Ecuador's case. We analyzed the evolution of the concept, from a quantitative and qualitative point of view, focusing on the approach modifications over time. Likewise, the work classified the countries depending on their interest in these systems. In addition, this bibliometric study addresses some key questions, such as: Which countries are leaders in this kind of research? Which journals play a strategic role in this field? How are research networks developed? Looking to the future, the challenges and possible future lines of research linked socioeconomically to these productive systems were analyzed. Furthermore, Ecuadorian leaders in this field of knowledge were visualized. To achieve this objective, a two-stage quantitative and qualitative mixed methodology was used. Differences between periods were evaluated (ANOVA) and the evolution of publications was measured by regression analysis.

Bibliometric analysis

This bibliometric analysis was developed based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology, facilitating a quick, efficient and transparent analysis of the scientific documents collected for the study (Page et al., 2021). In this sense, this study was divided into four phases allowing the optimal analysis of the global scientific production and in Ecuador in relation to silvopastoral systems (Figure 8): (I) Database selection and search criteria, (II) Exclusion criteria, (III) Software and data selection, (IV) Data interpretation.

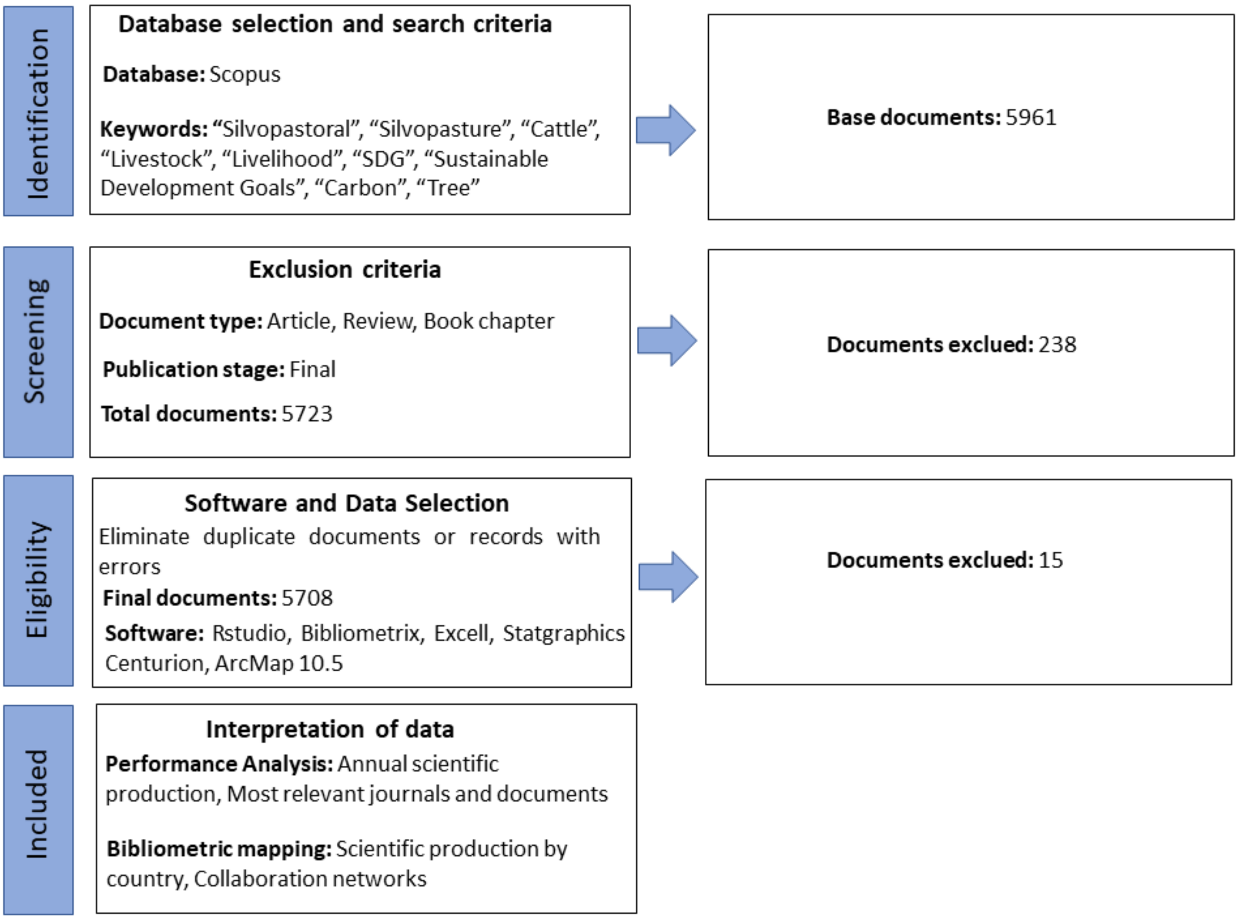

Figure 8. Diagram based on the PRISMA statement depicting the four phases of the bibliometric research methodology.

I) Database Selection and Search Criteria

A successful BA will be based on the collection of scientific information from comprehensive and reliable academic research data (Saltelli et al., 2008). In academia, WOS and Scopus are the most widely used and accessible scientific databases in recent decades (Pranckutė, 2021). Scopus was initiated in 2004 through the publishing organization Elsevier Science and is currently recognized as one of the most relevant scientific databases (Zhu & Liu, 2020). Such recognition is attributed to the fact that a broad coverage of topics in various disciplines is provided with scientific information to be further processed by multiple biometric software (Baas et al., 2020; Singh et al., 2021).

Although WOS offers similar services, its coverage of educational disciplines is less compared to Scopus (Thelwall, 2018). In addition, Scopus provides information corresponding to author affiliation, journals, keywords and quality indexes of scientific production, such as the Scimago Journal Rank (SJR) (Baas et al., 2020; Pranckutė, 2021). Therefore, in this study, Scopus was used to generate a database that will incorporate as many documents as possible to understand the historical evolution of scientific research focused on the analysis of silvopastoral systems.

The search and collection of Scopus documents was carried out in December 2022, using information from titles, abstracts and keywords. To perform this process, the following syntax was used with the advanced search settings of the Scopus scientific database: TITLE-ABS-KEY (silvopastoral OR silvopasture) AND (cattle OR livestock OR live-lihood OR SDG OR "sustainable development goals" OR carbon OR tree). The search returned 5961 documents.

II) Exclusion criteria

Initially, a selection was performed by type of document. Retaining only scientific documents classified as articles, book chapters and reviews. The selected categories were among the most widely used in the scientific field since they provided greater depth on the subject analysed, were also more extensive and have been subjected to a rigorous process of blind peer review, providing greater reliability in the information represented in this type of document (Donthu et al., 2021; Ellegaard & Wallin, 2015).

In addition, only documents that had already completed the peer review process and were published before December 2022 were considered for the analysis. In other words, documents that were in final publication status. Under these criteria, 238 documents were excluded, resulting in 5723 documents.

III) Software and Data Selection

In this bibliographic review, 4 types of software were used for the analysis of the scientific information collected:

RStudio: It is an open access software that allows the analysis and processing of big data. R version 3.5 was used to process the information through the use of the Bibliometrix package.

Bibliometrix: The Bibliometrix package, a new tool developed for the R environment was used to process and obtain the bibliometric indexes (Aria & Cuccurullo, 2017). This package offers different functionalities for the use of various bibliographic sets obtained from scientific databases, allowing the development of multiple bibliometric analyses considering the information presented in a wide variety of scientific articles.

Microsoft Excel: It is a software that allows the analysis and interpretation of scientific documents through the annual scientific production, number of citations, most cited journals and documents, among others

Statgraphics Centurion: This software facilitates the analysis and interpretation of data by means of different statistical metrics. It was used to analyze the annual scientific production and its future trends in this study.

ArcMap: It is a software used in the design and interpretation of geographic information. Version 10.5 was used for this study, enabling the representation in maps of the contribution by country and the consolidated global collaboration networks.

Once the data were collected from the Scopus database, they were exported in CSV and BibTex format. The BibTex format included bibliographic information, citations, abstracts, keywords and references. Meanwhile the CSV format was used using a Microsoft Excel sheet. During the review, the data were cleaned by eliminating duplicate files and incomplete or erroneous records. Under these considerations, 15 documents were eliminated, obtaining 5708 documents.

Finally, to carry out the analysis for Ecuador, the documents were classified by country. The database for Ecuador considered 17 scientific articles.

IV) Interpretation of Data

Performance analysis

To carry out this analysis, the BibText file format was used by means of the Bibliometrix package in Rstudio (Aria & Cuccurullo, 2017), initially the annual scientific production was obtained, which consisted of the number of scientific documents published and the number of citations per year. This information was exported in xls format and processed in Microsoft

Excel and subsequently entered in Statgraphics Centurion. Quantitative variables were compared using an analysis of variance (ANOVA) establishing the periods as fixed (Period I, from 1983 to 1993; Period II, from 1994-2003; Period III, from 2004 to 2013 and Period IV, from 2014 to 2022). Duncan multiple range test was used to show significant differences among groups ($p<0.001$). Subsequently, the number of publications found (dependent variable) and the years of study (dependent variable) were related using ordinary least squares (OLS) multiple regression. The normality of the distribution was verified using the Kolmogorov-Smirnov, Cramer-Von Mises and Anderson-Darling tests. In addition, Bartlett's test was performed to verify the equality of the variance of the data (homoscedasticity). The coefficient of determination (R^2) and the mean square error (MSE) were used to select the best model.

Furthermore, the scientific journals with the highest number of papers published in relation to silvopastoral systems were examined. To enrich the analysis, the name of the journal, country of origin, publisher, SJR 2021 and quartile were considered. Continuously, the most relevant scientific papers in the last decades in the analyzed subject were identified. Hence, a ranking was elaborated including the name of the authors, title of the article, name of the journal and the number of citations obtained.

Bibliometric Mapping

Scientific production was obtained at the country level; this Bibliometrix analysis uses the country of affiliation of each author. The data obtained in this analysis were processed using ArcMap 10.5 for the design of the cartography. Finally, for the global analysis, collaboration between different authors from different countries was examined to obtain the frequency of scientific collaborations. This information is represented by means of a frequency network map in the Bibliometrix graphical user interface.

Annual scientific production by period

The scientific production focused on silvopastoral systems at the global level comprises 5708 papers during the last 39 years (1983-2022) (Figure 9). For a better interpretation of the results, the scientific production was divided into four 10-year periods: Period I (1983-1993), Period II (1994-2003), Period III (2004-2013) and Period IV (2014-2022). This breakdown by decades facilitates the understanding of the development and evolution of the field of study.

Table 5. Descriptive statistics for publications and cites numbers per period (Mean ± DS1 (CV, %2)).

Period (y)	**Number of publications**	**Number of cites**
I (1983-1993)	4.3+3.4 (79)[a]	103.7+72.0 (69)[a]
II (1994-2003)	25.1+15.0 (60)[a]	718.2+543.6 (76)[a]
III (2004-2013)	139.6+61.4 (44)[b]	4,503.5+1,496.1(33)[b]
IV (2014-2022)	446.4+168.9(38)[c]	4,751.2+1,965.1 (41)[b]
Total	146.4+193.6 (132)	2,461.9+2,452.7 (99)

[1] Standard deviation, [2] Coefficient of variation; [a, b] Means with different letters show significant differences between groups within the same column.

The number of publications increased over time, although periods I and II showed similar behavior compared to periods III and IV, with three different homogeneity groups ($p<0.001$). On the other hand, as the number of publications increased, the dispersion of the variable decreased, reaching a 38% coefficient of variation in period IV. The number of citations is distributed in two homogeneous groups; periods I and II, compared to periods III and IV ($p<0.001$). Figure 9 shows the joint behavior of both curves by periods.

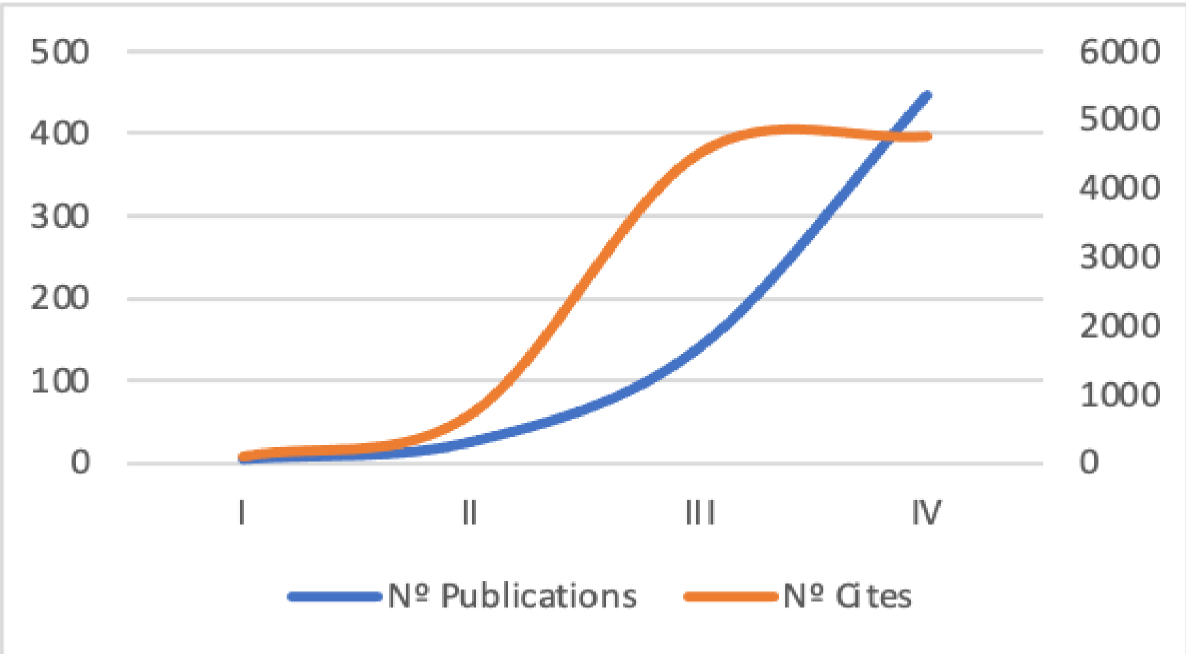

Figure 9. Evolution of number of publications and citations by period.

Figure 10 shows the results of the fitted regression model. Fourteen alternative models were compared and in more than 10 of them the coefficients of determination were higher than 70% and in the models: S-Curve, Multiplicative, Logarithmic-Y-Squared Root-X, Exponential, Log-Y-Squared-X, X-Squared-X-Squared Root, Double-Squared Root, Y-Squared Root Log-

X and Inverse Y-Squared Root of X the R2 was higher than 90%. The equation of the better Model adjusted for the period 1983-2022 was Curve S: Y = exp(a + b/X), with an R2 of 96.06%. Where Y: Number of publications; X: Year (from 1983 to 2022); Parameter a: 342.662 and Parameter b: 678911.

Since the p-value < 0.05, indicates a statistically significant relationship between the number of publications and the year with a confidence level of 95.0%. The R-Squared statistic indicates that the fitted model explains 96.057% of the variability of the number of documents. The correlation coefficient is -0.9801, indicating a relatively strong relationship between the variables. The standard error of the estimate indicates that the standard deviation of the residuals is 0.397781. The mean absolute error (MAE) of 0.281166 is the average value of the residuals.

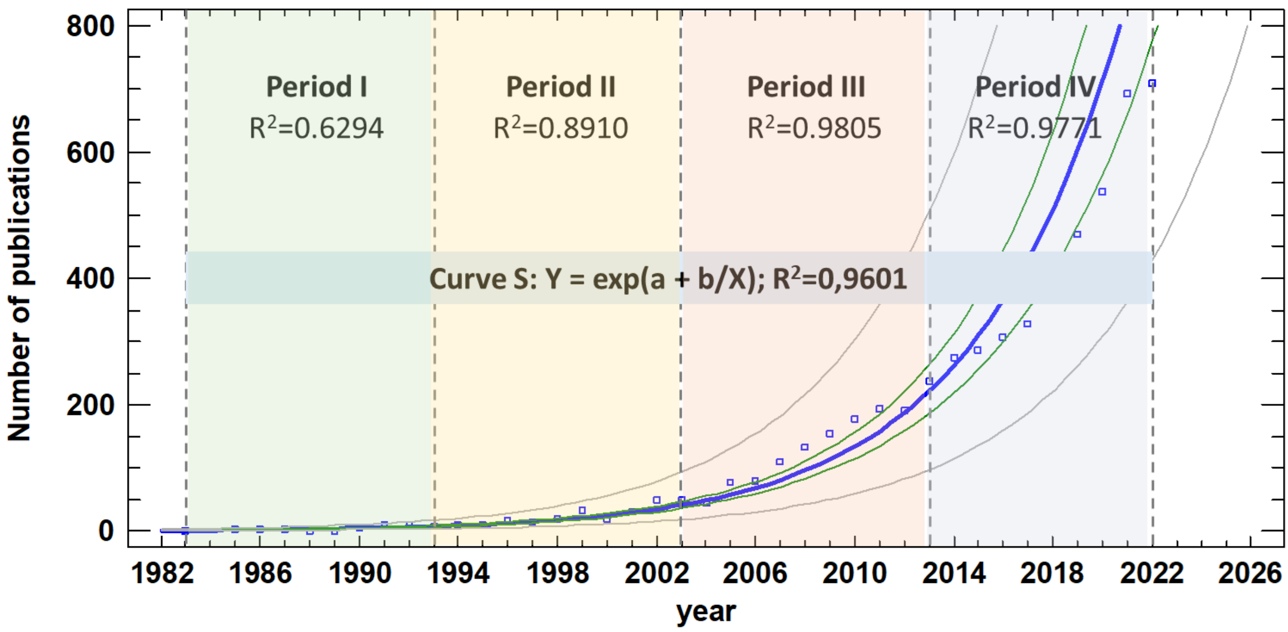

Figure 10. Evolution of the number of publications in agrosilvopastoril system per year (1983-2022). The model fit and the adjusted coefficient of determination used in each stage is shown.

<u>Period I (1983-1993) - silvopasture characterization</u>

During this period, 43 scientific publications on silvopastoral systems were recorded, equivalent to 0.8% of the total number of articles analyzed. Within this decade, 1991 and 1992 were the years with the highest production, with 9 scientific articles, respectively. The study subjects focused on the contribution of silvopastoral systems in arid and semi-arid zones (Ormazábal, 1991), as well as the evaluation of soil physical factors affecting tree growth in pastures (Wairiu et al., 1993). The importance of multiple land uses through the application of initiatives based on silvopastoral systems is stressed by (Peñaloza et al., 1985). Likewise, studies focused on the economic and ecological viability of pine plantations in the Central Highlands of Ecuador were also reported (Garrison & Pita, 1992). In addition, a review study focused on analyzing the experiences obtained with the implementation of silvopastoral systems in New Zealand (Knowles, 1991).

Period II (1994-2003) - best practices

During this period, publications on silvopastures increased, with a total of 251 articles, representing 4.4% of total production in the period analyzed. Research began to quantify carbon storage and analyze the nitrogen cycle (Kaur et al., 2002). As well as the relationship between microclimate and nutrient dynamics (Menezes et al., 2002), highlighting the importance of silvopastoral systems for soil bioimprovement (Cardinael et al., 2017).

There were frequent studies of the economic benefits of implementing silvopastoral systems (Grado et al., 2001; Husak & Grado, 2002), and the adoption of silvopastoral practices (Rapey et al., 2001). Moreover, a novelty in this period was the incorporation of ancestral knowledge focused on the use of fodder trees in silvopastoral systems (Morrison et al., 1996).

Period III (2004-2013) - ecosystem services

In this third period, 1,396 articles were evidenced, representing 24.5% of the total number of documents analyzed, and the average annual production exceeds 45 articles, with a maximum of 237 articles reported for 2013. During this decade, probably driven by the Millennium Declaration through the Millennium Development Goals (MDGs) (ONU, 2000) and the Millennium Ecosystem Assessment (Millennium ecosystem assessment, 2005) research focused on environmental valuation and payments for environmental services associated with silvopastoral systems (Garbach et al., 2012; Pagiola et al., 2007, 2008, 2010; Shrestha & Alavalapati, 2004). Studies on carbon storage provided by silvopastoral systems were enhanced (Haile et al., 2008, 2010; Howlett, Moreno, et al., 2011; Tonucci et al., 2011).

Also at the soil level, the reduction of nutrient loss (Michel et al., 2007; Nair, Nair, et al., 2007), the improvement of the environmental quality of agricultural lands (Reis et al., 2010) and the influence of trees as nutrient reserves (Nair, Haile, et al., 2007) are addressed. Most of these studies propose actions to mitigate the effects of climate change (Montagnini et al., 2013) and the recovery of ecological processes (Giraldo et al., 2011).

Period IV (2014-2022) - landscape restoration

Finally, the last period is the most relevant in relation to the increase in scientific production focused on silvopastoral systems. In this period, 4255 scientific papers were published, representing 74.5% of the total number of articles considered in this analysis. During this decade, an annual growth was observed, with a peak of publications in the year 2022 with 708 articles, suggesting that silvopastoral systems are a topic of great interest at a global level. The conversion of extensive pastures to silvopasture with timber trees as a measure to improve soil health (Poudel et al., 2022) and the restoration of degraded lands (Kumar et al., 2022). were addressed. Other studies focused on the combination of silvopastoral systems and remaining forests under livestock strategies (Aryal et al., 2022), the benefits of thermal cooling in tropical silvopastoral systems (Zeppetello et al., 2022) and how these can enhance the mitigation of climate change effects related to greenhouse gas emissions generated by cattle ranching activities (Brook et al., 2022). The focus on research was also related to the launching of the Millennium Development Goals (MDGs) by the United Nations (UN, 2015). Finally, during this period, the inclusion of drones and remote sensors for the characterization of woody trees that are dispersed within silvopastoral systems was evidenced (Iñamagua-Uyaguari et al., 2022).

Country classification by publications

On the basis of the analysis regarding the affiliation of the authors subscribed to the articles at the country level, the total contributions by nation were considered in relation to the subject of study (Centobelli et al., 2022; McAllister et al., 2022). For this purpose, a map was produced using ArcMap 10.5 software to geographically visualize the contributions detected in 138 countries (Figure 11). In this sense, Figure 8 shows the map of the world scientific contribution in the last 39 years reported on topics related to silvopastoral systems. The range of colors used in the map allows differentiating the number of scientific papers for each country, while countries in white denote the absence of reported populations. Among the top 10 countries, there are five American countries (United States, Brazil, Mexico, Colombia, Argentina), two Asian countries (China, India), three European countries (Spain, Germany, United Kingdom). The country with the highest number of publications was the United States with 1090 documents, while Brazil and Spain were in second and third place with 954 and 601 documents, respectively. Finally, it became evident that most of the research reported has been carried out in developed countries and countries that have presented significant increases in activities focused on silvopastures (Aryal et al., 2022; Jaureguiberry et al., 2022; Winkler et al., 2021; Zeppetello et al., 2022).

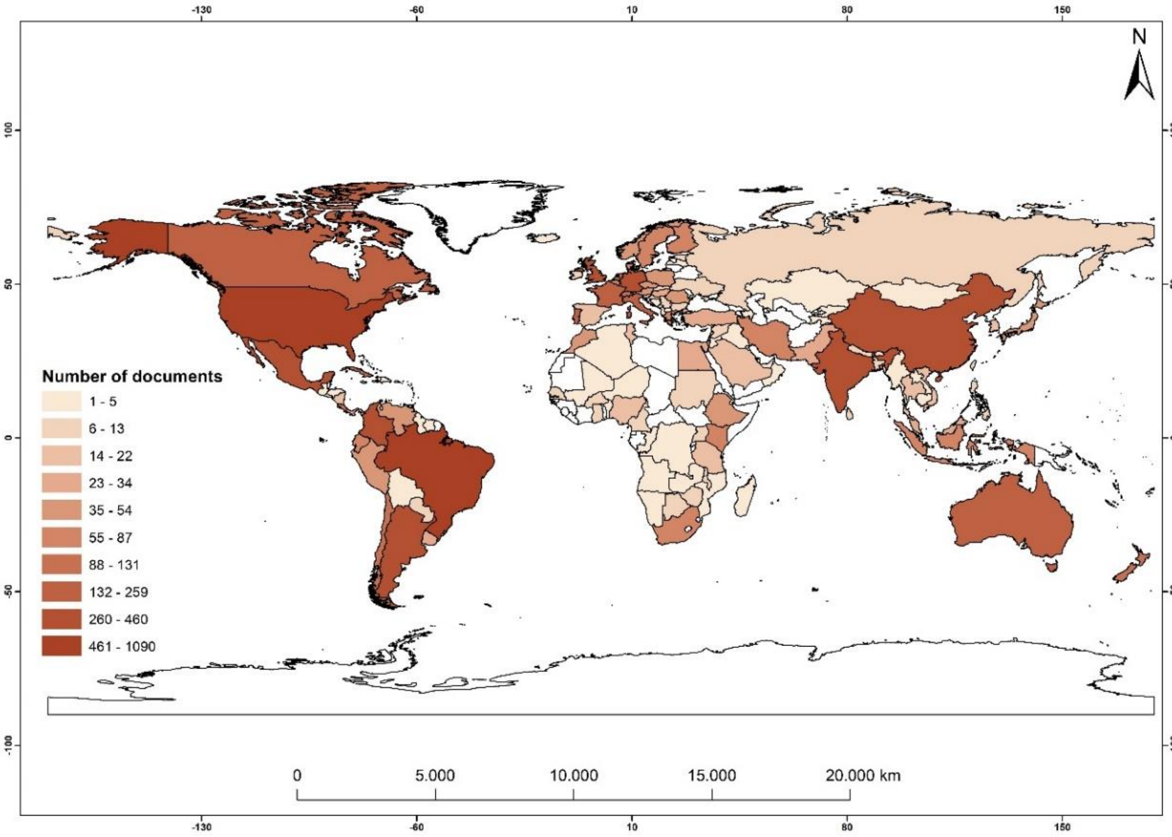

Figure 11. Number of publications on silvopastoral systems by country.

Regarding the American continent: In the United States, the benefits of open grassland conservation to silvopastoralism for improving soil health were oriented (Poudel et al., 2022). Similarly, research reported that silvopastoral systems could benefit from a cooling of -0.32 °C to -2.4 °C for every 10 metric tons of woody carbon per hectare (Zeppetello et al., 2022). Besides, studies were also found focused on analyzing silvopastoral systems as an alternative for the improvement of animal welfare and productive performance (Lemes et al., 2021). Innovation was found with the use of high spatial resolution satellite images to estimate leaf indices and area biomass in spatial pastures (J. Wang et al., 2019), and a comparison was made between silvopastoral systems between countries (Cubbage et al., 2012). Regarding economics, studies focused on analyzing the profitability of silvopastoral systems were observed (Husak & Grado, 2002). *Loblolly pine*, *Ceanothus integerrimus*, *Acacia ko*a (Akau et al., 2022; Huntsinger, 1996; Nyakatawa et al., 2012).

The second leader was Brazil, with publications focused on relating silvopastoral systems to animal welfare by estimating thermal comfort indices (Deniz et al., 2019; Pezzopane et al., 2019), the influence of grazing, agriculture and crop-livestock systems on C stocks (Carvalho et al., 2010), and the integration of legumes in silvopastoral systems to boost soil C and N stocks (Lira Junior et al., 2020). As well as, changes in soil organic carbon during 22 years of grazing, through integrated crop-livestock systems (Cá et al., 2022). On the other hand, it was also found that one of the species of greatest consideration for silvopastoral strategies and climate change mitigation in Brazil was the Eucalyptus (Bosi et al., 2020; de Macêdo Carvalho et al., 2022; de Oliveira et al., 2022; Horst et al., 2022).

From Europe, Spain leads the scientific production, contributing with publications focused on the promotion of silvopastoral policies in European Mediterranean areas (Rodriguez-Rigueiro et al., 2021). The potential of trees and climate to regulate soil carbon balance has also been evaluated (Ferreiro-Domínguez et al., 2022). The proper management of high quality wood plantations in silvopastoral systems (López-Díaz et al., 2020), and the establishment of silvopastoral systems in abandoned agricultural lands in Northwest Spain (Pasalodos-Tato et al., 2009) are also among the themes of interest. In relation to economics, a study focused on analyzing the environmental and economic profitability of livestock grazing on farms under a silvopastoral system was observed (Campos et al., 2018). Finally, the most relevant species were: *Quercus ilex*, *Quercus rubra*, *Pinus radiata*, *Fraxinus excelsior*, *Prunus avium*, *Pinus pinea*, *Eucalyptus nitens*, *Betula pubescens* (Campos et al., 2018; Fernández-Núñez et al., 2014; Ferreiro-Domínguez, Rigueiro-Rodríguez, et al., 2016; Mancilla-Leyton et al., 2013; Mosquera-Losada et al., 2015, 2016; Rivest et al., 2011).

Journals with the largest number of documents

Table 6 shows the performance and quality indexes of the ten leading journals with the highest number of papers that collaborate to generate knowledge related to silvopastoral systems. These journals contain 1275 of the 5708 publications analyzed, which represents 22.3% of the scientific production. The table shows the performance indicators of journals such as SJR and their quartile for 2021.

Agroforestry Systems is the leading journal in scientific contributions, with 533 articles representing 9.3% of the total number of published papers. This journal has an SJR index of 0.59 and is in Q1 according to the latest evaluation for 2021. The most relevant paper of the journal was published by Cubbage et al. (Cubbage et al., 2012) and has been cited 78 times in the scientific literature. This paper focused on a comparison of silvopastoral systems in eight regions of the world, considering their research methods and experience in those regions. The second place is occupied by Forest Ecology and Management with 161 papers and with a SJR index of 1.11 and it is currently in the first quartile (Q1). Its most cited paper (72 citations) was published by Mohan Kumar et al. (1998), which focuses on evaluating the biomass production potential of nine fast-growing multipurpose tropical taxa, four of which were grown under two land management systems (forest and silvopasture). Finally, the third journal with the highest scientific production was Agriculture Ecosystems and Environment, which is characterized by having published 99 articles, it has an SJR index of 1.66 and is in the first quartile (Q1). One of the most relevant scientific contributions in this journal analyzed the role of positive incentives and information exchange to stimulate the adoption of silvopastoral conservation practices (Garbach et al., 2012).

Table 6. Ranking of journals by number of publications in silvopastoral systems.

Journal	Country	Editorial	Number of documents	SJR 2021	Quartile
Agroforestry Systems	Netherlands	Springer	533	0,59	Q1
Forest Ecology and Management	Netherlands	Elsevier	161	1,11	Q1
Agriculture Ecosystems and Environment	Netherlands	Elsevier	99	1,66	Q1
Sustainability	Switzerland	MDPI	92	0,66	Q1
Livestock Research for Rural Development	Colombia	Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria	84	0,25	Q3
Forests	Switzerland	MDPI	71	0,62	Q1
Plant and Soil	Netherlands	Springer	62	1,12	Q1
Science Of The Total Environment	Netherlands	Elsevier	61	1,81	Q1
Tropical and Subtropical Agroecosystems	Mexico	Universidad Autónoma de Yucatán	58	0,2	Q3
Land Use Policy	United Kingdom	Elsevier	54	1,64	Q1

The 10 most frequently cited documents

The most cited publications were identified to highlight the topics of greatest interest. In this context, the scientific production focused on silvopastoral systems at the global level (5708 documents) presents 95,355 citations. Table 7 presents the top 10 most cited papers with 1023 citations, representing 1.07% of the total.

Within this group, publications focused on South American countries (Nicaragua, Colombia, Argentina, Chile, Brazil, Paraguay, Uruguay), North America (United States, particularly Florida), Asia (India), Europe (Greece) and Oceania (New Zealand). Among the documents analyzed, the oldest documents were published by Mohan Kumar et al. (1998) in 1998 and Wedderburn & Carter (1999) in 1999. On the one hand, the paper published by Kumar et al. (Mohan Kumar et al., 1998) evaluated biomass and nutrient accumulation rates in multipurpose trees in woodlot and silvopasture experiments. While Wedderburn & Carter (1999) quantified the fall, chemical characteristics and litter decomposition rate of functional trees for use in silvopastoral systems. On the other hand, it was noted that the most recent paper was published in 2012. In this research, Cubbage et al.(2012) focused on describing and comparing actual agricultural practices and research trials of silvopastoral systems in eight regions within seven countries of the world..

Shrestha et al. (2004) concentrated 197 citations. The authors evaluated the sustainability of silvopastoral adoption decisions by implementing a strengths, weaknesses, opportunities, and threats (SWOT) approach and an ana-lytical hierarchy process (AHP). Among the main findings of this research, land stewardship, income diversification, environmental benefits and government support programs were found to be the main prospects for silvopastoral adoption (Shrestha et al., 2004). The second place is occupied by Pagiola et al. (2007), where the researchers describe the results achieved by the Regional Integrated Project for the Management of Silvopastoral Eco-systems (PRIMES), which aims to fund payment for environmental services to farmers for their contribution to biodiversity conservation and carbon sequestration provided by the implementation of silvopastoral strategies.

Table 7. Top 10 most cited papers with 1023 citations, representing 1.07% of the total.

Ranking	Autor	Article	Journal	Citations
1	Shrestha et al.(2004)	Exploring the potential for silvopasture adoption in south-central Florida: An application of SWOT-AHP method	Agricultural systems	197
2	Pagiola et al.(2007)	Paying for the environmental services of silvopastoral practices in Nicaragua	Ecological economics	171
3	Haile et al. (2008)	Carbon storage of different soil-size fractions in Florida silvopastoral systems	Journal of Environmental Quality	118
4	Pagiola et al. (2008)	Can the poor participate in payments for environmental services? Lessons from the Silvopastoral Project in Nicaragua	Environment and Development Economics	89
5	Cubbage et al. (2012)	Comparing silvopastoral systems and prospects in eight regions of the world	Agroforestry Systems	78
6	Giraldo et al. (2011)	The adoption of silvopastoral systems promotes the recovery of ecological processes regulated by dung beetles in the Colombian Andes	Insect Conservation and Diversity	77
7	Haile et al. (2010)	Contribution of trees to carbon storage in soils of silvopastoral systems in Florida, USA	Global Change Biology	77
8	Plieninger et al. (2011)	Land-use legacies in the forest structure of silvopastoral oak woodlands in the Eastern Mediterranean	Regional Environmental Change	76
9	Wedderburn et al. (1999)	Litter decomposition by four functional tree types for use in silvopastoral systems	Soil Biology and Biochemistry	72
10	Kumar et al. (1998)	Comparison of biomass production, tree allometry and nutrient use efficiency of multipurpose trees grown in woodlot and silvopastoral experiments in Kerala, India	Forest Ecology and Management	72

This article suggests that the implementation of PRIMES allowed the adoption of silvopastoral systems that in turn generated the expected ecosystem services. However, the authors mention that there is much uncertainty regarding the financial sustainability of payment for environmental services (Garbach et al., 2012). Finally, the third most cited paper silvopastoral systems was published by Haile et al. (2010), which focused on determining the total soil carbon contents at six soil depths (0-5, 5-15, 15-30, 30-50, 50-75 and 75-125 cm) in silvopastoral systems, to evaluate the carbon stored potential. Among the main results, the authors concluded that the integration of trees in open pastures generates even more soil organic carbon, particularly at shallower depthss (Haile et al., 2008).

Collaboration networks

Scientific collaboration allows the transfer of knowledge and enhances technology innovation through the contribution of papers published by the multidisciplinary contribution of authors from different countries on a global scale. In the field of research focused on silvopastoral systems, 119 countries have collaborated in the development of scientific papers. Of this total, at least 77 countries have 3 articles in collaboration with authors from other countries. Figure 12 shows the mapping of the global network of scientific collaborations between countries in different regions of the world.

In general, the country with the highest number of contributions among nations is the United States with 80 collaborations, followed by Germany in second place with 64 contributions and the United Kingdom in third place with 64. In relation to the United States, its collaborations have focused on the evaluation of sustainability (Shrestha et al., 2004), the analysis of payment for environmental services (Garbach et al., 2012; Pagiola et al., 2007, 2008, 2010; Shrestha & Alavalapati, 2004), soil carbon storage potential (Haile et al., 2008, 2010; Howlett, Moreno, et al., 2011; Howlett, Mosquera-Losada, et al., 2011; Tonucci et al., 2011; Vallejo et al., 2012), nitrogen transfer (J. Sierra & Nygren, 2006) and the reduction of nutrient loss on farms (Nair et al., 2007). In addition, these collaborations have also focused on evaluating micro-climate and nutrient dynamics (Menezes et al., 2002), as well as ecological considerations in the design and sustainable management of silvopasture (Jose et al., 2019). Germany has cooperated in papers focused on assessing deforestation reduction and mitigation potential of greenhouse gas effects (Landholm et al., 2019), the effect of herbivory on trees in a reforestation system (Riedel et al., 2013), land use and land cover change (Cárdenas et al., 2018), phosphorus dynamics (Ferreiro-Domínguez, Nair, et al., 2016), meat production and food webs (Pereira et al., 2021; Röhrig et al., 2021). Finally, the United Kingdom has contributed research focused on determining growth, production and carbon sequestration with native timber species (Andrade et al., 2008), the evaluation of milk production in dual purpose cattle farms (Yamamoto et al., 2007), the analysis of the environmental rent of cattle grazing

(Campos et al., 2018), the determination of the carbon sequestration potential of tree biomass and soil (Beckert et al., 2016), the quantification of land use change and soil carbon deposition (Fornara et al., 2018), and the understanding of sustainable practices (Tschopp et al., 2020).

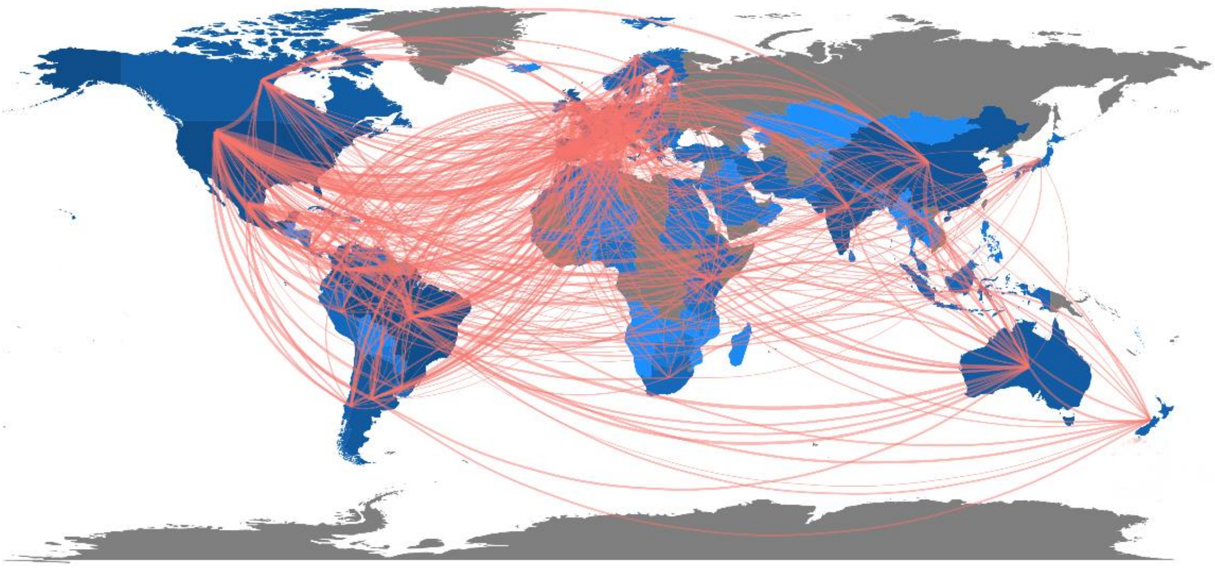

Figure 12. Collaborative networks in silvopastoral systems.

2.4. Ecuador Analysis

Scientific production and distribution by province

The scientific production focused on silvopastoral systems in Ecuador comprises 17 articles (Figure 113) published during the last 3 decades (1992-2022). The first article for Ecuador was published in 1992 by Garrison et al. (Garrison & Pita, 1992). In this paper, the authors evaluated ten pine plantations in the provinces of Tungurahua and Chimborazo for their potential as silvopastoral systems and, in addition, discuss the possibilities of integrating local farmers in their management and appropriate use. Between 1993 and 2014, no scientific publications were reported for Ecuador in relation to the topic addressed. While the highest number of contributions was obtained in 2021. On the other hand, in relation to the current year (2022), a total of 3 articles were observed. Among these articles, the most recent paper was published by Torres et al. (Torres et al., 2023), in this study, the researchers evaluated carbon stocks in silvopastoral systems in the Ecuadorian Amazon. Among the main findings reported in this study, the high potential of traditional grazing systems with dispersed trees for carbon sequestration in the Ecuadorian Amazon is indicated. For this reason, it is also indicated that silvopastoral systems allow the implementation of strategies focused on mitigating and adapting to climate change in tropical countries. Finally, the authors recommend that these systems should be managed by applying the best livestock management practices (BMPs) to mitigate the expansion of the agricultural frontier in the Ecuadorian Amazon. In addition, these silvopastoral systems could be associated with REDD+ focused initiatives in Ecuador, thus contributing to the Nationally Determined Contributions (NDCs), which were set as a goal of the Paris Agreement to stabilize the global average temperature at less than 2 °C.

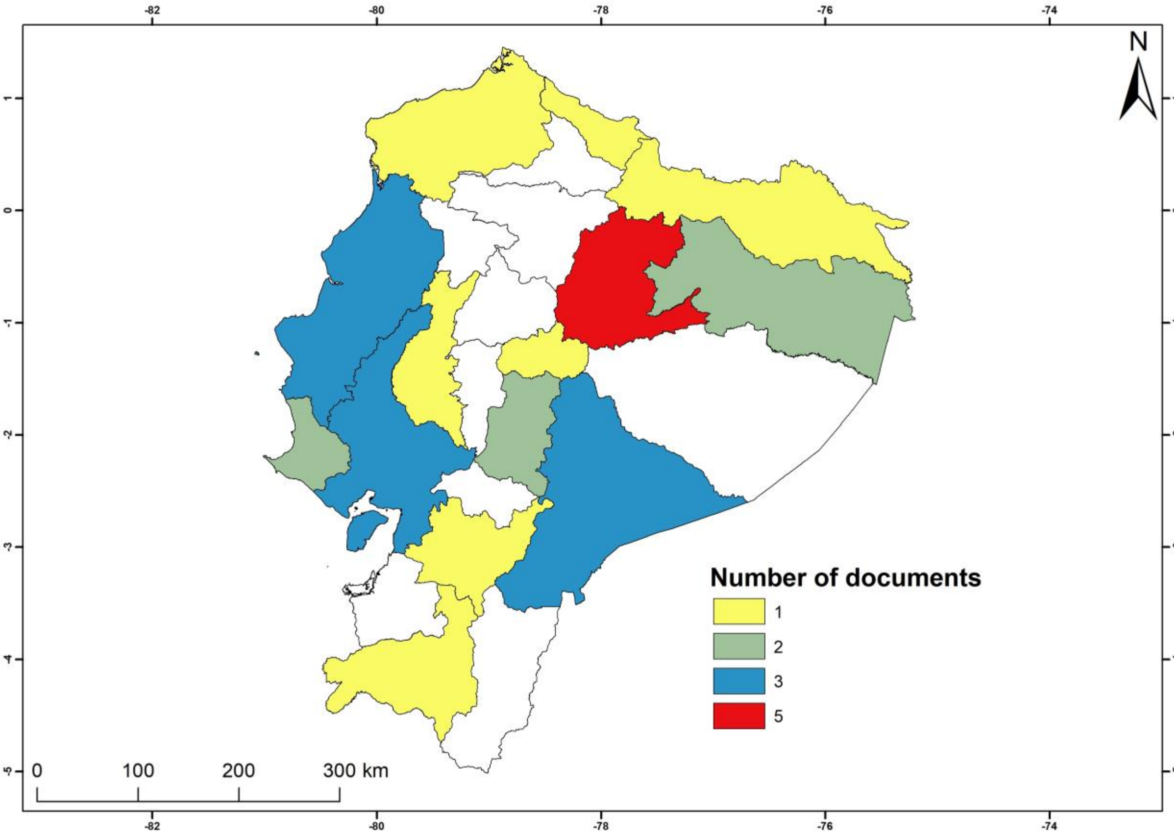

Figure 13. Mapping the number of scientific contributions by province for Ecuador.

Most relevant documents

Table 8 shows the 10 most cited papers that have been reported for Ecuador concerning silvopastoral systems. Among the analyzed papers, the study by Lerner et al. (Lerner et al., 2015) is the most cited paper with 28 citations. In this research, the authors focused on determining the socio-ecological factors associated with the apparently spontaneous emergence of silvopastoral landscapes and possible explanations for the variation in tree density found in pastures. The second place is occupied by Raes et al. (Raes et al., 2017), which investigates farmers' preferences to participate in payment contracts to adopt silvo-pastoral systems in

Ecuador. Finally, the third most cited paper was published by McGroddy et al. (McGroddy et al., 2015), in this study, the authors' main objective was to quantify the biomass carbon stored in spontaneous silvopastoral systems in the province of Morona Santiago in the Ecuadorian Amazon.

Table 8. Most cited documents on silvopastoral systems in Ecuador.

Ranking	Autor	Article	Journal	Citations
1	Lerner et al.(2015)	The spontaneous emergence of silvo-pastoral landscapes in the Ecuadorian Amazon: patterns and processes	Regional Environmental Change	28
2	Raes et al. (2017)	Farmers' Preferences for PES Contracts to Adopt Silvopastoral Systems in Southern Ecuador, Revealed Through a Choice Experiment	Environmental management	19
3	McGroddy et al. (2015)	Carbon Stocks in Silvopastoral Systems: A Study from Four Communities in Southeastern Ecuador	Biotropica	19
4	Torres et al. (2018)	Determinants of agricultural diversification in a hotspot area: Evidence from colonist and indigenous communities in the Sumaco Biosphere Reserve, Ecuadorian Amazon	Sustainability	18
5	Hayes et al. (2015)	Can Conservation Contracts Co-exist with Change? Payment for Ecosystem Services in the Context of Adaptive Decision-Making and Sustainability	Environmental management	15
6	Cañadas-L et al. (2018)	Growth and yield models for teak planted as living fences in coastal Ecuador	Forests	14
7	González Marcillo et al. (2021)	Assessment of guinea grass panicum maximum under silvopastoral systems in combination with two management systems in Orellana province, Ecuador	Agriculture	5
8	Vargas-Tierras et al. (2018)	Characterization and role of Amazonian fruit crops in family farms in the provinces of Sucumbíos and Orellana (Ecuador)	Ciencia y Tecnología Agropecuaria	4
9	Diana Rade et al. (2017)	Silvopastoral System Economical and Financial Feasibility with Jatropha Curcas L. in Manabí, Ecuador	Revista MVZ Córdoba	4
10	Torres et al. (2021a)	Identification and assessment of livestock best management practices (BMPs) using the REED+ approach in the Ecuadorian amazon	Agronomy	3

MATERIAL Y METODOS

3. MATERIAL Y METODOS

3.1. Descripción de la zona estudio

3.1.1. Ubicación geográfica del área de estudio

Esta investigación se llevó a cabo en un *hotspot* de biodiversidad y endemismo del mundo denominado (Uplands Western Amazonia *hotspot*) (Mittermeier et al., 1998; Myers, 1988; Myers et al., 2000) considerado como una importante área donde se encuentra la Reserva de la Biosfera Sumaco (RBS), creada en el año 2000 por el programa Hombre y Biosfera (MAB) de la UNESCO, ubicada en la provincia de Napo. Se trabajó con hogares ganaderos ubicados desde los 400 metros sobre el nivel del mar en la zona baja hasta los 2000 metros sobre el nivel del mar en la zona alta (Figura 14).

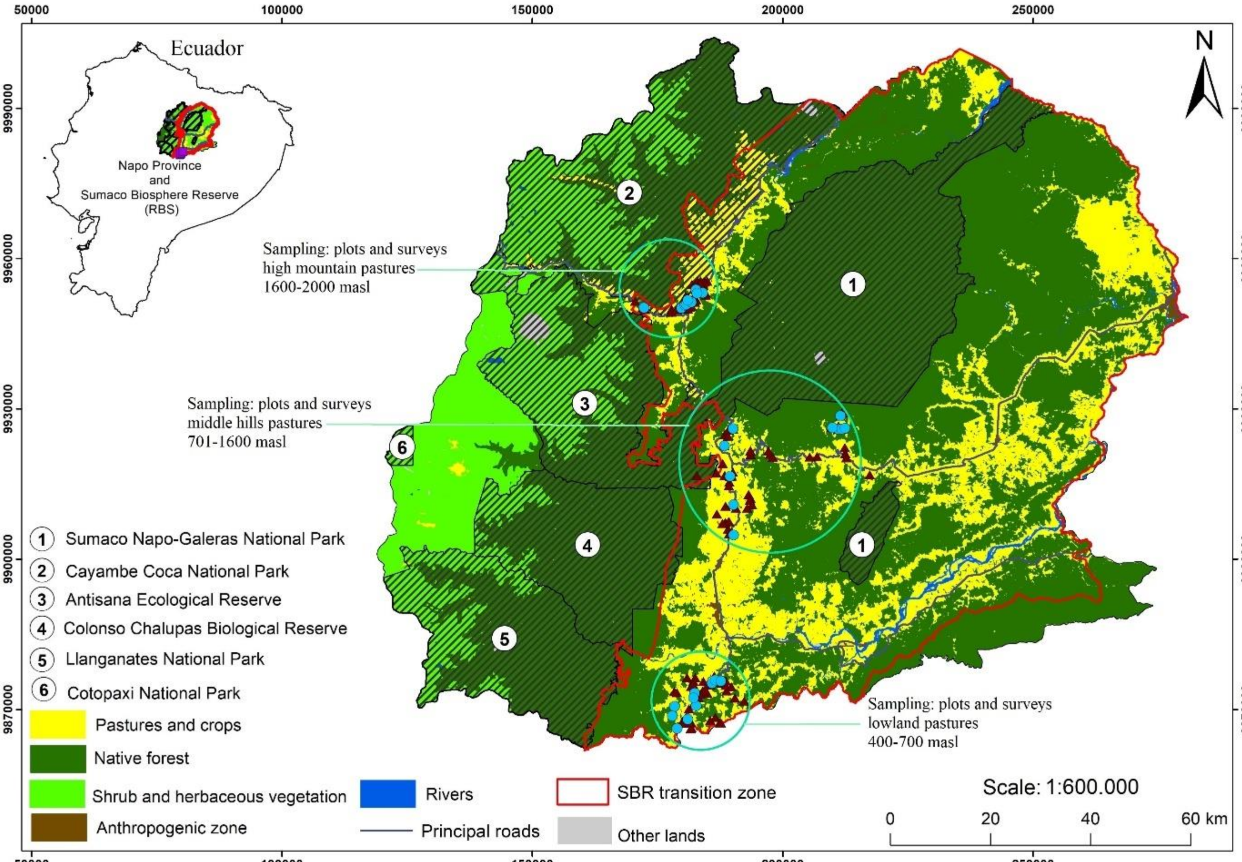

Figure 14. Ecuador and the study area, the Sumaco Biosphere Reserve. The sky-blue dots show the households studied for papers 1, 2 and 5. The red triangles represent the plots sites studied in paper 3 and 4. Source: Author, 2022.

Los ecosistemas predominantes fueron los siguientes: bosque siempreverde de pie de monte (BsPn03) en la zona baja y bosque siempreverde montano bajo (BsBn01) y bosque montano siempre verde (BsMn01), ubicados en las zonas baja, media y alta en la parte norte de la Cordillera Oriental de los Andes (Borges et al., 2016). La región en estudio presenta un clima tropical con altas temperaturas y se divide en tres zonas: una zona baja con un rango de temperatura entre 22 y 24 °C, una precipitación anual de 3.950 mm y una humedad relativa del 84% al 87%; una zona media, con una precipitación anual de 4.500 mm, una temperatura media de 24 °C y una humedad relativa inferior al 80%; y una zona alta con una precipitación anual superior a 2.000 mm, un rango de temperatura entre 14 y 19 °C y una humedad relativa del 88%.

3.1.2. Bioclimatic characteristics

The predominant bioclimatic conditions vary along the elevational gradients, with a mean annual temperature of 35.67 °C and annual rainfall of 5,209 mm in Lowlands zone, 33.65 °C and 4,728 mm in Middle hills; 26.70 °C and 2,205 mm in High mountains zone respectively (Figure 15).

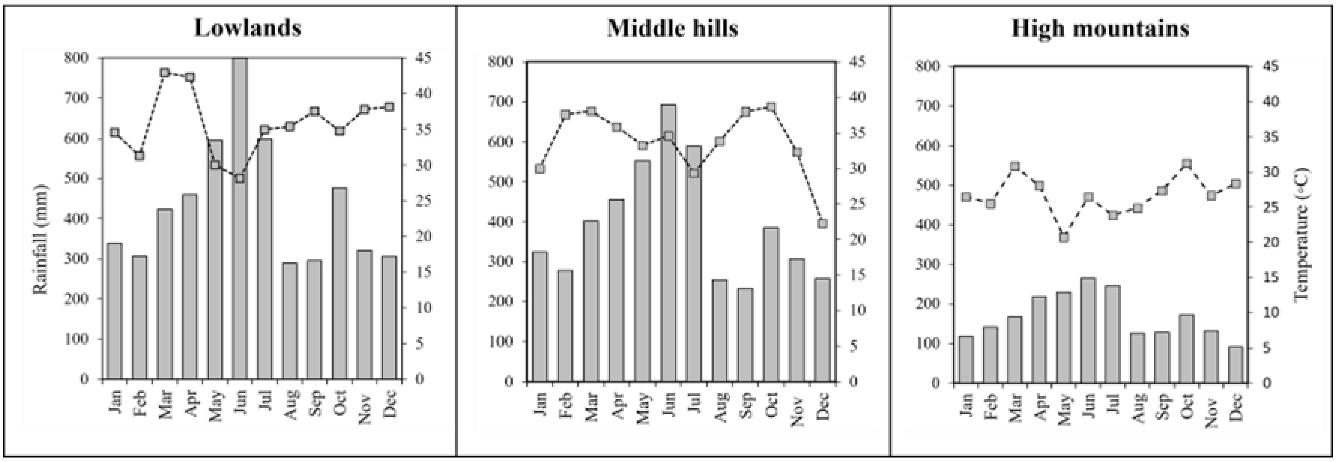

Figure 15. Monthly mean rainfall and temperature values (2012-2021) along altitudinal gradient (lowlands, middle hills, and high mountains). Source: authors' own elaboration based on the information available in Huntington et al. (2017).

3.1.3. Sistemas de pastizales en la gradiente altitudinal estudiada

Livestock activity along the elevational gradient began with different settlement histories. The high zone between 1601 and 2000 masl was settled first, followed by the low zone between 400 and 700 masl (45 years ago), and, lastly, the middle zone between 701 and 1600 masl. Our reasons for selecting these three zones were based on ecology, local knowledge, and settlement history. In addition, the elevational gradient (zone) was considered as a fixed factor, as we were interested in the potential differences between the zones (Table 9).

Table 9. Characteristics of the three elevational gradients of the studied scattered tree on cattle farmland in the SBR, Ecuadorian Amazon.

Variables	Lowlands	Middle hills	High mountains	Sample mean
Elevation range (masl)	400-700	701-1600	1601-2000	800
Average elevation (masl)	543.1	1114.1	1778.0	1145
Year of settlement	1975	1984	1952	1970
Cattle system	meat and dairy	meat and dairy	dairy	meat and dairy
Mean annual rainfall	5209	4728	2025	3987
Mean temperature (^{o}C)	35	33	26	32

3.2. Sistema de muestreo, recolección de datos socioeconómico y análisis

3.2.1. Socioeconomic data collection

The study population consisted of 464 farms that represented three edaphoclimatic conditions of the territory and all the land uses of the altitudinal gradient, where cattle raising in the Napo province (Ecuador) is representatively located. From these 464 cattle farms, 167 household were surveyed, by stratified randomized sampling with proportional assignation in the three elevational gradients: 57 farms in the low zone (Quijos canton), 57 in the middle zone (Archidona canton), and 53 in the high zone (Carlos J. Arosemena Tola canton) (Figure 1).

The non-probabilistic quota sampling technique was used (Grijalva et al., 2013; Izquierdo, 2015) with the conditions of, firstly, a herd of at least ten head of cattle, and secondly, more than three years of consecutive activity. The questionnaire was applied to the heads of households and had an average duration of 90 min. This allowed the collection of information, which was later subjected to analysis and validation. Socio-economic, demographic, livestock system management, land use, income, investment, and net benefits variables were evaluated.

For the calculation of livestock costs and income, all fixed costs (land rental, maintenance of facilities), financial expenses (payment of interest on loans), and variable costs (purchase of livestock, various inputs, and maintenance of pastures) were considered, thus determining the total cost per household. Net income per household was obtained from net income minus total costs. All data were processed using the statistical system IBM-SPSS version 22 (Izquierdo, 2015).

3.2.2. Calculation of revenues, investments, and net income

Fixed investments include: (a) live fixed assets (working animals, production animals, breeding animals, and animals of mixed aptitude), or “livestock” in the legal terminology, and (b) inanimate fixed assets (machines, tools, work utensils, vehicles, harnesses, and electrical appliances and utensils) (Grijalva et al., 2013).

Therefore, the precise identification of all the concepts that represent income and expenses in agricultural activity is essential. Outgoing payments can be classified as costs (expenses that will generate benefits in the future) and expenses (cash outflows that currently represent benefits), for example administrative, sales, marketing, and financial expenses (Rutter, 2006).

Cost-benefit analysis is a formal, personalized, clear, systematic technique for rational decisions. It is applied in the face of complex alternatives or uncertain times (Mogues, 2011).

3.2.3. Computing cattle ranching income and cost

For the calculation of cattle costs and income, we first considered all the fixed costs (land rental, maintenance of facilities) and financial expenses, which is the payment of interest on loans received, and the variable costs (purchase of cattle, various inputs, maintenance of pastures), thus determining the total cost per household (Bastanchury-López et al., 2022; Villarroel-Molina et al., 2021). The net profit per household was obtained from net income minus total costs. The benefit-cost ratio was obtained from the sum of net income divided by total costs using the following formula:

$$B/C_{cattle\_ha} = \sum_{i=1}^{N} \left[\frac{income\_ha_i}{cost\_ha_i} \right]$$

From the 167 cases (low, medium and high) 37 cases reported obtaining credit (86% from BNF) of which 11 are from the low zone with an average of USD 7,636 in credit received, 9 from the medium zone with an average of USD 8,816 and 17 from the high zone with an average of USD 13,480. This shows that the high zone has had an important flow of financial capital to their activity, which can be seen in the Benefit/Cost Ratio index.

Among these cases, 31 report a monthly payment value: 6 from the low zone with an average of USD 427, 9 from the middle zone with an average monthly payment of USD 188.26 and 16 from the high zone with an average of USD 944.

3.2.4. Computing grazing area opportunity cost

To measure the opportunity cost of the grazing area in hectare ($OpptCost_{grass\_ha}$), we first used the net benefit which is the result of income minus cost of the cattle ranching activity by hectare ($income_{\_ha} – cost_{\_ha}$). The complete formula applied in this paper is described as follows:

$$OpptCost_{grass\_ha} = \sum_{i=1}^{N} \left[\frac{(income\_ha_i) - (cost\_ha_i)}{grass\_ha_i} \right]$$

Where N is the number of cattle ranching household, $income_{\_hai}$ is the total household income from activity i (milk and meat production), $cost_{\_hai}$ is the total cost of cattle ranching activities and $grass_{\_hai}$ is the total grazing area in hectare. We found the annual opportunity cost for each hectare of pasture that a farmer has over along the altitudinal gradient studied. Considerando que es el beneficio neto que el productor renunciará por cada ha de pastoreo que libere para la restauración.

3.2.5. Statistical analysis

All data were assessed for normal distribution using a Kolmogorov–Smirnoff test and for homogeneity of variance with a Levene test. The elevational gradient factor was evaluated using the general linear model (GLM). When a significant effect was detected, the least-square means were compared using the Student–Newman–Keuls test (metric variables). Chi-square tests and contingency tables were used to determine associations between non-metric variables (Rangel et al., 2017). Differences were considered statistically significant when p was lower than 0.05. It is considered appropriate to use low–medium significance levels for both inputs and outputs in dual-purpose systems with high variability (Rangel et al., 2017). All data were processed using the IBM- SPSS (2013) statistical system (Version 22) on Windows.

3.2.6 Sistema de muestreo, recolección de datos para el análisis de capitales, inequidad y percepciones del cambio climático en pequeños ganaderos de los Andes Ecuatorianos

We conducted 197 surveys on small ranchers in four communities, from which those with between one and twenty head of cattle were chosen. A total of 19 producers that did not meet these characteristics were eliminated, and we finally continued with a sample of 178 cases. The selected small ranchers were distributed with 49 in Pilahuín, 45 in Tamboloma, 48 in San Rafael, and 36 in Chuquipogyo. For the grouping of small ranchers by poverty quintiles, the income and costs of the cattle-ranching activities at the household level were determined. Subsequently, the theory of capitals and climate change grouped by quintiles was analyzed. Thereafter, a total of 178 cattle farms were analyzed for a variety of parameters. Prior to the statistical analyses, the normality of the data distribution was evaluated by using the Kolmogorov–Smirnov test, including the Lilliefors correction (Lilliefors, 1967; Steinskog et al., 2007). For those variables that did not demonstrate normal distributions, the Bartlett test was applied in order to assess whether the data had equal variances (Lim & Loh, 1996). The quantitative variables were compared by using the analysis of variance (ANOVA) and establishing the Quintiles as a fixed effect (from 1 to 5 levels) (Kim, 2014). For the comparison of the means, the Tukey method was used. Likewise, the $\chi 2$ test ($p \leq 0.05$) was used for the qualitative variables. Statistical 12.0 for Windows software was applied to perform the statistical analyses, and the SPSS statistical program was used for the analysis of the descriptive statistics, such as the standard deviations, averages, percentages, and frequencies.

3.2.7 Determination of Net Income and Poverty Groups by Quintiles

To determine the net income, calculations were conducted of all the income from cattle activities at the household level, from which all of the costs that were incurred in activities related to cattle farming were subtracted. Furthermore, we used quintiles to group the subjects into several equal groups, as quintiles are frequently used in economic and social analyses and they allow the establishment of inequality metrics. The quintile facilitates the classification of the population according to income, with homogeneous values within the group, and heterogeneous values between them (Luna, 2020; Mújica & Moreno, 2019; Reddy, 2011). Thus, from all the households surveyed, the total net income of each household was calculated, and they were arranged into five groups according to their income, in ascending order. This occurred in such a way that Quintile 1 corresponds to the 20 percent of the people with the lowest income, and the fifth quintile to the 20% with the highest income.

- Quintile 1 (Q1): value that is higher than the 20% of the lowest samples.
- Quintile 2 (Q2): value that is higher than the 40% of the lowest samples.
- Quintile 3 (Q3): value that is higher than the 60% of the lowest samples.
- Quintile 4 (Q4): value that is higher than the 80% of the lowest samples.
- Quintile 5 (Q5): corresponds to the highest value.

$$Q_q = L_i + \frac{q\binom{n}{5} - Ni - 1}{n_i} * a$$

With q = 1,2,3,4

where:

L_i: Lower real limit of the class of quintile *(q)*.

N: is the number of data.

$Ni - 1$: Cumulative frequency of the class that precedes the class of quintile *(q)*.

n_i: Frequency of the class of quintile *(q)*.

a: Length of the class interval of quintile *(q)*.

In order to determine and categorize poverty, we used first the recommendation from the INEC (INEC, 2018), who suggest comparing the per capita household income with the poverty line and extreme poverty, which in the month of June 2018 were \$84.72 and \$47.74 per month per person respectively. In this framework, households with individuals whose per capita income is below the poverty line (\$2.82 per day) are reported and considered poor, and if it is below the extreme poverty line, they are considered extremely poor (\$159 daily). Secondly, we named the poverty groups according the five categories (quintiles) as extremely poor (Q1), moderate poor (Q2), not so well-off (Q3), moderately well-off (Q4), and well-off (Q5).

3.2.8 Income Inequality (Gini Index and Lorenz Curve)

For the determination of income inequality, the Lorenz curve was used as a general indicator of relative inequality (Atkinson, 1970; Bishop et al., 1997), allowing graphic representation of income distribution. The Gini coefficient (G) was also determined to support the results. The Gini measure is defined as the area closed by a diagonal, while the Lorenz curve is expressed as a proportion of the area under the diagonal (Lim & Loh, 1996), where a coefficient close to 1 means extreme inequality and 0 represents complete equilibrium, meaning that everyone earns the same.

The original formula appears in various forms, but it can be calculated from the Lorenz curve as the ratio, and represented in the following equation: G = Area A/(Area A + Area B). For the current study, we followed the following formula:

$$G = 1 - \sum_{i=0}^{N} (\sigma Y_{i-1} + \sigma Y_i)(\sigma X_{i-1} + \sigma X_i)$$

where, σX and σY are cumulative percentages of Xs and Ys (in fractions) and N is the total number of households.

For the study of income from cattle activity by quintiles, the following variables were analyzed: (1) Average income from milk sales, referring to the production for sale in the collection center,

(2) average valuation per calf, indicating the milk production for raising the calves owned by the rancher,

(3) average total cattle income, which is the sum of both the income from the sale of milk and the valuation per calf,

(4) average household size, which allows a reference to the amount of members that a household has living under the same roof,

(5) average per capita/daily income, referring to all the economic income received by a household;

(6) category according to the INEC (2018), being a variable that defines the grouping of the households surveyed and finally

(7) percentage of the sample.

3.3 Sistema de muestreo florístico y análisis de carbono

The criteria for the farm selection were pasture area ≥ 0.5 hectare, with at least a patch of pasture with dispersed trees, in a crown cover ≥ 10%. Thus, we installed a 26 circular temporary plot of 2826 m^2, in pasture with dispersed trees, distributed among the three zones. (Table 10).

Table 10. Characteristics of the three elevational gradients of the studied scattered tree on cattle farmland in the SBR, Ecuadorian Amazon.

Variables	Lowlands	Middle hills	High mountains	Sample mean
Elevation range (masl)	400-700	701-1600	1601-2000	800
Cattle system	meat and dairy	meat and dairy	dairy	meat and dairy
Number plots in PWT	12	8	6	26
Number plots in PM	15	15	15	45

PWT-Pasture with trees

3.3.1. Estimation of aboveground biomass and carbon content

Aboveground biomass and total carbon content was estimated directly from field data live stems with DBH larger than 10 cm to calculate the total basal area for each of the plots. Basal area is expressed in m^2 /ha and estimated by the following equation:

$$\text{Basal area } = \sum \pi * \left(\frac{\text{DBH}}{2}\right)^2 \text{divided by plot area}$$

Where DBH = Diameter at breast height (m).

Aboveground biomass was calculated for each plot using allometric equations developed by Chave et al. (2005) for wet tropical forest:

$$AGB = \sum \rho\, exp(-1.499 + 2.148\, ln(DBH) + 0.207(ln\, DBH))^2 - 0.0281(ln(DBH))^3)$$

Where AGB stands for aboveground biomass in kg dry mass, ρ is wood specific gravity in g/cm^3, and DBH is diameter at breast height in centimeters and include all trees having $DBH_{1.30} \geq 10$cm.

Wood specific gravity data for each species were based on Baker et al. (2004) In some cases where the specific gravity was not available, the suggested mean (ρ) for tropical secondary forests (McGroddy et al., 2015; Van Breugel et al., 2011) was used (0.47 g/cm^3). Total carbon content of the aboveground biomass (Mg ha^{-1}) was estimated by multiplying the average aboveground biomass estimated for each plot by a wood carbon value of 47%. Belowground biomass (BGB) (coarse roots) was indirectly estimated as 30% of aboveground biomass (McGroddy et al., 2015).

The biomass importance value (BIV) based on the methodology proposed by Torres et al. (2020) was calculated as follows: (N + BA + AGB)/ 3, where N is relative density, BA is relative basal area and AGB relative above ground biomass.

The Leaf litter (LL) was calculated within the subplots of 10 × 10 m with the help of a 0.25 m^2 quadrat; all the material corresponding to dead plant material (such as leaves, stems, stems, needles, and twigs) that have fallen to the soil and remains located within was collected. The quadrant was placed in the center of the subplot. It is marked as a green square in Figure 3. The collected material was weighed and placed in bags for drying at 105 ^{o}C for 24 hr, until a constant weight was obtained. The dry matter was calculated in megagrams per hectare.

3.3.2. Soil carbon stock

We use a systematic sampling method (Figure 16), identifying of traditional pasture with dispersed trees, along the elevational gradient and establishment of plots with five subplots. From each plot, we collected five soil cores from 0-10 and 10-30 cm depth and aggregate them into a composite sample for carbon analysis.

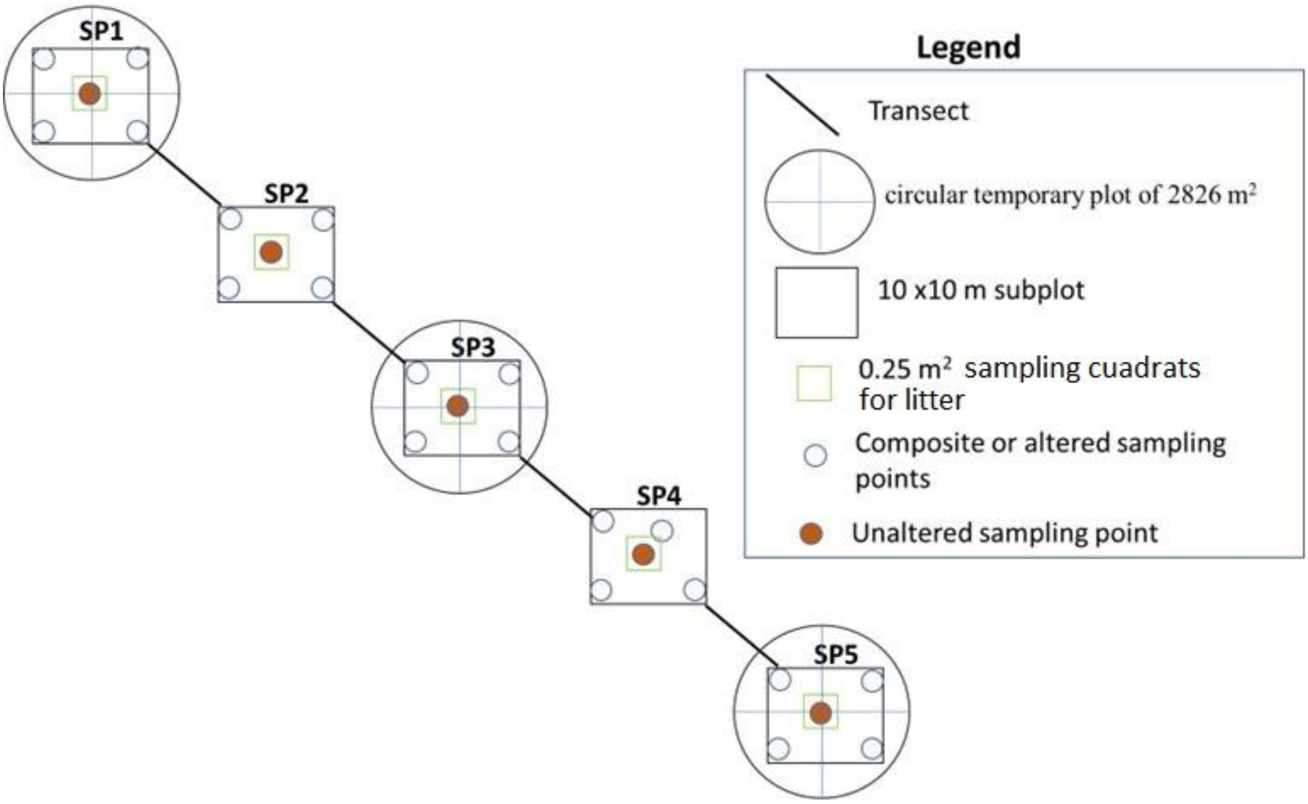

Figure 16. A schema of the sample collection procedure.

Soil organic carbon (SOC) was calculated using the following equation:

$\text{Mg C ha}^{-1} = (\text{BD} * (\text{TOC}/100) * \text{D} * 1000)$

where BD is the bulk density in Mg m^{-3}, TOC is the total organic carbon by percentage and D is the depth in m.

The bulk density (BD) of samples were determined by the cylinder method (Blake & Hartge, 1986), with cylinders 5 cm high and 5 cm in diameter collected with an Uhland-type sampler. In the laboratory, the samples were weighed and dried in a stove at 105 ^{o}C for 24 h to obtain the dry weight (Bravo et al., 2021). TOC was determined by the Walkley-Black wet digestion method (Nelson & Sommers, 1983), by oxidation with potassium dichromate

($K_2Cr_2O_7$) 1 N, with the addition of concentrated sulfuric acid (H_2SO_4), and subsequently, the amount of OC oxidized by chromium was measured by titration using a 0.5 N Morh salt solution (H_2SO_4 + F_eSO_4 +7H_2O).

The estimated carbon values in all its components were calculated per hectare. The mean stem density and basal area for one hectare at a specific elevation site was extrapolated, as well as the structural characteristics. Finally, all the resulting values along the gradient were compared using analysis of variance (one-way ANOVA) with SPSS software version 22).

3.4. Sistema de colección de datos para análisis de buenas prácticas ganaderas a través de actores

3.4.1. Designing best management practices (BMPs)

We developed best practices through an analysis of the literature followed by workshops with a multidisciplinary panel of fifteen stakeholders and researchers. It should be highlighted that for each suggested practice, a series of desirable and adaptable criteria were developed for each of the three zones (elevational gradients), based on several aspects including climatic conditions, culture, proximity to the road, and interest of local governments to contribute to the vision of the REDD+ action plan. Thirty-four potential BMPs were ultimately pre-selected (Table 11). The panel of stakeholders was selected intentionally to include livestock community leaders, extensionists, technicians, and scholars. All panel members have specialized interests and experience in sustainable cattle ranching systems, livelihoods, and climate change. Using this multidisciplinary panel of stakeholders and researchers, for each elevational gradient, we collected information to assess the best management practices (BMPs) recommended for livestock systems.

Table 11. Livestock best management practices (BMPs) pre-selected in the SBR, Ecuadorian Amazon

Components	No.	Best management practices (BMPs)
1. Improvement livestock management	1	Farm planning
	2	Implementation of accounting registers
	3	Implement compensation area: cutting grass (forage, legumes, gramineous)
	4	Implement compensation area: protein bank (legumes and/or shrubs)
	5	Elaboration of multi-nutritional blocks.
	6	Implementation of fences with shed
	7	Improvement of animal diet with salt minerals and dietary supplements
	8	Pasture rotation

	9	Artificial breeding/insemination
	10	Direct breeding
	11	Management of births
	12	Improvement of the development breeding system
	13	Genetic improvement
	14	Draining
2. Rehabilitation of pasturelands	15	Planting of new trees in degraded and not degraded pasturelands
	16	Establishment of tree nucleation around grazing areas
	17	Establishment of live fences around grazing areas
	18	Electric fence around grazing areas
	19	Association of grass with creeping legumes
	20	Association of pasture with tree and creeping legumes
	21	Redirection of production system
	22	Organic fertilization (phosphoric rock, compost...)
	23	Inorganic fertilization (chemical)
3. Pasture area restoration	24	Forest plantations
	25	Active restoration
	26	Passive restoration
	27	Agroforestry system (With cocoa, coffee, guayusa, naranjilla)
	28	Taungya system (With cocoa, coffee, guayusa, naranjilla)
	29	Chakra system (With cocoa, coffee, guayusa, naranjilla)
	30	Improved logging of dispersed trees
4. Implementation of waste-management systems	31	Artisanal lombriculture
	32	Biol production through biodigester
	33	Compost area
	34	Semi-artisanal biodigesters

Source: Author

3.4.2. Assessing best management practices (BMPs)

During the workshop with the 15 experts, each pre-selected BMP was analyzed and addressed according to its relevance in the dual-purpose system's context. Selection of the final BMPs started after ensuring the adequacy and appropriateness of the list of preselected BMPs. This way, the experts assessed each BMP on a Likert scale from one to five, where one was the least important, and five was the most important (Rivas et al., 2019). In the first round of assessment, the BMPs that obtained the maximum score (five) from nine or more experts were selected, and the BMPs that obtained the minimum (one) score from nine experts. were discarded. In the second round, descriptive information from the set of responses (concordance index and mean) was sent to each expert to re-examine and reconsider his or her decision. The Ishikawa index was utilized based on the concordance level (García-Martínez et al., 2016). We selected BMPs with over 60% of the concordance level and an average score over 3.5. Ultimately, 16 management practices (BMPs) were selected.

RESULTADOS Y DISCUSIÓN

4. RESULTADOS Y DISCUSIÓN

4.1. Productive livestock characterization and recommendations for good practices focused on the achievement of the SDGs in the Ecuadorian Amazon

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4.1.1 Introduction

The Sustainable Development Goals (SDGs) were adopted by all member states of the United Nations in 2015 and are valid until 2030 (Bexell & Jönsson, 2017; Fukuda-Parr, 2016; Opoku, 2016; Tsalis et al., 2020).They provide a shared agenda of peace and prosperity for people and the planet for the present and the future (ONU, 2021). The 17 SDGs are an urgent call to action by all countries in a global alliance, recognizing that ending poverty and other deprivation must go hand in hand with strategies to improve health and education (Kopnina, 2020; Kurth, 2017), minimize inequalities, stimulate economic growth considering climate change (Sanchez Rodriguez et al., 2018) and work to preserve the oceans and forests (Lu et al., 2015). In short, the SDGs exist within a common framework to overcome important interconnected challenges such as food supply, water scarcity, weak health systems, human nutrition, environmental pollution, and biodiversity loss (Foley et al., 2011; Landrigan et al., 2018). However, several authors state that achieving the SDGs is an ambitious and complex task (Nilsson et al., 2016; Obersteiner et al., 2016).

In 2020, the world population increased to 7.8 billion and is projected to be 9.8 billion by 2050 and 11.2 billion by 2100 (ONU, 2021). Of those 7.8 billion people, about 2 billion are undernourished due to protein, micronutrient, and vitamin deficiencies (FAO & UN, 2020; Ritchie et al., 2018). It is estimated that about 60 percent of rural households in developing countries depend wholly or partially on livestock for their livelihoods (Pica-

Ciamarra et al., 2011), which provide essential protein and micronutrients for poor populations (Cordain et al., 2002; Pica-Ciamarra et al., 2011). On a global scale, livestock farming is a key mechanism for reducing stunting and wasting (Grace et al., 2018; Mehrabi et al., 2020; Ritchie et al., 2018). Therefore, the livestock sector can play an important role in eliminating hunger, malnutrition, etc., and is able to be an engine for the fulfillment of various SDGs, if good livestock practices are incorporated using the approach of reducing emissions derived from deforestation and forest degradation (REDD+) in the Ecuadorian Amazon Region (EAR) (Krause et al., 2013; Torres et al., 2021a).

Due to the demands of a growing population, especially in developing countries, livestock management is shifting towards careful stewardship and sustainable intensification (Boval et al., 2017). This management seeks the integration of agriculture and livestock and may be part of the great challenge to advance towards the SDGs (Lal, 2020; Nalubwama et al., 2011). Sustainable livestock management can promote several of the SDGs, for example SDG 1 (No Poverty) because it generates income for smallholders (Wurzinger, 2019; Zezza et al., 2016). It also provides a balanced diet that includes beef to alleviate malnutrition that affects 2 billion people worldwide. Therefore, livestock farming is also critical to promoting SDG 2 (Zero Hunger) (Behera et al., 2019) and SDG 3 (Good health and well-being) (Jevtic et al., 2020).

Likewise, livestock activities strengthen SDG 4 (Quality education), since field schools can generate capacity development (Arnés et al., 2018; Heredia-R et al., 2020), and SDG 5 (Gender equality), as they are considered a key source of employment and self-employment for a large proportion of the world's rural populations (Yasmin & Ikemoto, 2015). In this regard, in small ranchers in the Ecuadorian Andes it was demonstrated that between 23% and 47% of cattle farms were managed by women (Torres, Andrade, et al., 2022).

However, the livestock industry consumes approximately 8% of the world's water supply (Schlink et al., 2010), with a strong impact on SDG 6 (Clean water and sanitation), so beef has a water footprint higher (Palhares et al., 2021) than poultry, pigs (Gerbens-Leenes et al., 2013), and many agricultural products (Lovarelli et al., 2016). Therefore, sustainable intensification and proper management of pastures are necessary to contribute to SDG 6 (Doreau et al., 2012; Palhares et al., 2021). Sustainable livestock production with a REDD+ approach can contribute to SDG 13 (Climate Action) and SDG 15 (Life on Terrestrial Ecosystems), due to the relationship between climate change and the livestock sector (Chiriacò & Valentini, 2021; León Alvear et al., 2020; Torres et al., 2021a).

One of the areas where the livestock frontier is expanding at the highest rate in Ecuador is in the EAR (Sierra, 2000; Suárez et al., 2009), becoming one of the main drivers of land use change and deforestation (Sierra, 2013a). In this region, there were an estimate 1.2 million hectares of grasslands in 2014 (MAGAP, 2015) dedicated to extensive cattle ranching (Lerner et al., 2015; MAGAP, 2015), providing meat and milk to satisfy the local demand and national markets (Knoke et al., 2014).

In a priority research framework for the SDGs (Rodriguez et al., 2018), the current study pursues three major objectives. The first is to analyse the main socioeconomic, demographic and land use characteristics, while the second seeks to describe the differences between the productive characteristics of livestock management in the Andean-Amazonian altitudinal gradient. The third objective realizes the comparisons of the levels of income, investments, and benefits of the rancher along the studied altitudinal gradient. Finally, the work concludes with recommendations for decision-making aimed at improving livestock systems in Andean-Amazonian ecosystems, as a contribution to the SDGs.

4.1.2 Results and Discussion

Sociodemographic characteristics

The results showed that livestock activity along the altitudinal gradient in Napo province began in different periods of settlement. The population first settled in the high zone (1601–2000 masl) approximately 70 years ago, then in the lower zone (400–700 masl) 45 years ago, and finally in the middle zone (701–1600 masl) some 35 years ago (Table 12).

Table 12. Characteristics of cattle producers along the altitudinal gradient, Napo, Sumaco Biosphere Reserve, Ecuadorian Amazon.

Variable	Altitudinal gradient (zone)			p value†
	Low	Medium	High	
Elevation range (masl)	400 – 700	701 – 1,600	1601 – 2,000	-
Average elevation (masl)	543.1 [a]	1,114.1 [b]	1,778.0 [c]	0.01
Year of settlement	1975	1984	1952	n.s

† ANOVA; $p < 0.01$; n.s.: not significant. Superscript letters denote significant differences between elevational gradients.

Regarding the socioeconomic and demographic characteristics, seven variables were studied, and it was identified that in the middle altitude region there are Kichwa households that manage livestock systems (56.1%) (Table 13). This provides evidence for the adoption of productive dynamics similar to those of migrant settlers (Rudel et al., 2002; Zimmerman et al., 2001), which could be due to the proximity to highways and access to markets (C. L. Gray et al., 2008). However, it has been demonstrated in this area that Kichwa households involved in livelihood strategies based on livestock obtain significantly lower income from this activity than migrant settlers due to scarce technical assistance, to having little or no formal or informal training in livestock production, and to sociocultural context (Heredia-R et al., 2020; Torres, Günter, et al., 2018). As for the size of the household, in the entire altitudinal gradient studied there is a range of 5.1 to 6.7 household members, similar averages (5.3) to those reported in the small Kichwa livestock producers of the RAE southern zone (Vasco et al., 2018) and in the Yasuní Biosphere Reserve (Heredia-R et al., 2020).

The average size of the households of small Kichwa cattle producers in the central Andes of Ecuador is smaller (3.8) (León Alvear et al., 2020). The average age of the head of household in the study areas is over 50 years old, which is similar to that of the producers who own small livestock species in the low areas of the province of Napo (Andrade-Yucailla et al., 2019).

A high level of illiteracy (15.8%) was observed among the heads of households of the middle altitude gradient, where 56.1% are Kichwas who have adopted a subsistence strategy based on livestock. In the lower zone there is a higher percentage (61.4%) of ranchers with primary education, which could be due to the fact that they live a shorter distance from educational centers and have easy access to them. However, in the high zone, the households are far from the schools, and 50% of household heads have secondary education; this dynamic could be explained by these household heads being settlers who migrated from the coastal lowland and Andean regions (Mogues, 2011).

In these territories, integration into society and the national economy in general has received little academic attention (Buitrón-Cañadas, 2017). This factor is reflected in the fact that many people migrated outside their places of origin to complete some level of study.

These characteristics make it possible to propose capacity development programs and sustainable training activities at the individual, family and community level (Heredia-R et al., 2020), as well as the development of academic and productive support programs aimed at young people in the area. The objective would be to minimize the effect of their leaving to study outside their towns or communities, which limits the generational change in agricultural tasks once the young people have obtained their degrees (Requelme & Bonifaz, 2012).

This information is important as both agriculture and the young rural population are in decline (Martín et al., 2019), given that the immersion of young farmers brings an increase in social, economic and human capital to a country (León Alvear et al., 2020).

Table 13. Average of the main sociodemographic characteristics of livestock producers along the altitudinal gradient, Napo, Sumaco Biosphere Reserve, Ecuadorian Amazon.

Variable	*Altitudinal gradient (zone)*			*p value*†
	Low	**Medium**	**High**	
Ethnicity (% kichwa)	*0.0* [a]	*56.1* [b]	*0.0* [a]	*0.001*
Household size (number of people)	*5.56* [a,b]	*6.70* [a]	*5.04* [b]	*0.01*
Household members who work on the farm	*2.63*	*3.00*	*2.32*	*n.s*
Head of household age (years)	*54.79*	*56.77*	*57.60*	*n.s*
Head of household without education (%)	*8.8*	*15.8*	*3.8*	*n.s*
Head of household with primary education (%)	*61.4*	*47.4*	*28.3*	*n.s*
Head of household with secondary education (%)	*22.8*	*24.6*	*49.1*	*n.s*

† ANOVA for continuous variables; and X^2 for discrete variables. $p < 0.01$; n.s.: no significance. Superscript letters denote significant differences between elevational gradients.

Land Use in Livestock Producers of the Altitudinal Gradient

Regarding the main uses of the land, the average surfaces of the farms are 47 ha, of which 62% are pastures for cattle in the lower zone, 62 ha with around 55% dedicated to pasture in the middle zone and 35 ha with 81% grassland in the upper zone. In absolute terms, there were no statistical differences in the average size of the pastures in the three zones, but there was a slightly significant difference ($p < 0.05$) in the total size of the farm area (Table 14). Producers in the middle zone have, by far, the largest total farm area and the largest amount of pasture, which is in line with the theory that producers with more land dedicate more hectares to pasture (Rivera et al., 2021).

The fact that the use of pastures does not present significant differences suggests that ranchers satisfy the demand for green forage of the animals. This is due to the fact that in the different altitude zones there is a different productive behavior in grasslands with vegetal biomass, coinciding with the finfing of Alemán-Pérez et al. (2020a), who mentioned that with a larger pasture the herd, availability, quality, and diversity can be increased. Persistence of forage biomass, especially when there is a combination of herbaceous and woody plants, is able to increase photosynthesis, nutrient recycling, biota recovery, soil fertility, and biodiversity. On the other hand, Rivera et al. (2019) reported that the expansion of forage species destined for animal feed significantly reduces the presence of secondary forests on farms with production systems, considering other aspects such as land use and deforestation on land.

This is especially true on land belonging to settler populations, which are associated with the opening of new roads, access to markets or changes in household life cycles (Mena et al., 2006) These dynamics produce a loss of forest cover in favor of other more intensive uses, especially pastures that constitute an essential production factor for farmers involved in livelihood strategies based on livestock (Buitrón-Cañadas, 2017).

Table 14. Average of the main characteristics of land use of livestock producers along the altitudinal gradient, Napo, Sumaco Biosphere Reserve, Ecuadorian Amazon.

Variable	*Gradiente altitudinal (zona)*						*p value*†
	Low		**Medium**		*High*		
	Avg (ha)	**%**	**Avg (ha)**	**%**	**Avg (ha)**	**%**	
Pasture land	*26.8 (19.2)*	*62*	*27.2 (28.6)*	*55*	*22.5 (17.2)*	*81*	*n.s*
Crop land	*1.6 [a] (1.9)*	*4*	*2.2 [a] (3.3)*	*5*	*0.4 [b] (1.1)*	*2*	*0.001*
Remnant Forest Land	*20.1 [a,b] (29.8)*	*34*	*32.9 [a] (56.2)*	*40*	*12.2 [b] (28.1)*	*17*	*0.05*
Total land	*47.3 [a,b] (42.1)*	*100*	*62.4 [a] (70.6)*	*100*	*35.2 [b] (40.2)*	*100*	*0.05*

† ANOVA; $p < 0.05$; $p < 0.001$; n.s.: not significant. Superscript letters denote significant differences between the altitude gradient. Values in parentheses are standard deviations from the mean.

Management of Livestock Systems in the Altitudinal Gradient

Livestock activity (Figure 17) in the high zone began in the 1950s due to the abundant presence of plant biomass for animal feed; in this area, livestock production is mainly dairy. Subsequently, livestock production began in the lower area in the mid-1970s, with meat and milk production. The same two products are produced in the middle zone, where ranching was established at a later date (the 1980s). This is due to various occurrences that arose during those periods, such as bovine diseases due to the entry of animals from different parts of the country (Ríos-Núñez & Benítez-Jiménez, 2015), precisely at a time when human settlement in the EAR was massive.

In tropical regions, sustainable livestock development is being promoted from an economic, social, and environmental point of view (Meunier, 2007). Ranching, in particular, offers an alternative source of capital that the rural poor can accumulate as a "savings account" to hedge against fluctuations in income (Meunier, 2007; Ness et al., 2007).

Therefore, raising livestock in rural households is considered an alternative form of insurance, allowing them to earn income from the sale of animals in times of crisis (Broom et al., 2013; Lemaire et al., 2014). Several authors have recently provided evidence that the welfare of ethnic minority households with livestock production was higher than that of those without livestock production (Hoddinott, 2006). The profitability of livestock systems depends on the grazing systems implemented (Hoddinott, 2006), management for environmental protection (T. L. Do et al., 2020), and availability of resources for transformation to agroforestry systems (Escobar et al., 2020).

Regarding grassland systems, Table 15 lists in order of importance the main forages, between grasses and legumes, along the altitude gradient. It is evident that throughout the studied gradient, grasses predominate. In the lower zone, marandú grass (Brachiaria brizantha), dallis grass (Brachiaria decumbes), and guinea grass (Panicum maximum) predominate. In the middle zone, the most important species are honey grass (Setaria splendida) and dallis grass, and the least predominant is German grass (Echynochloa polystachya).

In the low and middle zones, the use of imperial grass (Axonopus scoparius) is scarce. Meanwhile, in the highlands, the most important species are kikuyu grass (Pennisetum clandestinum) and honey grass (Setaria splendida), and the least used is ryegrass (Lolium multiflorum). In addition, along the gradient, forage legume species are the least used and have a lower number of species distributed by gradient. Specifically, in the low and middle zone, the forage peanut (Arachis pintoi) is the most common, while in the high zone, it is the lotus (Lotus pedunculatus) (Hassen, 2020; Martín et al., 2019) (Table 15).

Figure 17. Livestock systems distributed along the altitudinal gradient: A) low zone (meat and milk), B) middle zone (meat and milk) and C) high zone (milk).

Table 15. Distribution of forage species of livestock producers along the altitudinal gradient, Napo, Sumaco Biosphere Reserve, Ecuadorian Amazon.

Low zone 400 to 700 masl	**Middle zone 701 to 1,600 masl**	**High zone 1,601 to 2,000 masl**
	Grasses	
Marandu grass (*Brachiaria brizantha*)	Honey grass (*Setaria splendida*)	Kikuyu grass (*Pennisetum clandestinum*)
Dallis grass (*Brachiaria decumbes*)	Dallis grass (*Brachiaria decumbes*)	Honey grass (*Setaria splendida*)
Imperial grass (*Axonopus scoparius*)	Imperial grass (*Axonopus scoparius*)	Orchard grass / dactyl grass (*Dactylis glomerata*)
Savoy grass (*Panicum maximum*)	Guinea grass (*Panicum maximum*)	Ryegrass (*Lolium multiflorum*)
	German grass (*Echynochloa polystachya*)	
	Legumes	
Forage peanut *(Arachis pintoi)*	Forage peanut *(Arachis pintoi)*	Lotus (*Lotus pedunculatus*)
Bellflower (*Centrosema pubescens*)	Bellflower (*Centrosema pubescens*)	White clover (*Trifolium repens*)
		Buttercup (*Tithonia diversifolia*)

Pastures provide the largest volume of forage for animals throughout the gradient and, although they are rich in energy, they are poor in protein (Alvear et al., 2021a). On the other hand, the forage types with legumes are the least predominant: only 40% in the low zone, 13% in the middle zone, and 8% in the high zone reported the use of legumes in their paddocks (Figure 18).

This is an aspect to be improved throughout the entire EAR (Hassen, 2020; Martín et al., 2019), considering that legumes are usually used to increase the protein and mineral portion of calcium (Ca) and phosphorus (P), enhance the diet of animals, and fix nitrogen in the soil, from symbiosis with bacteria of the genus Rhizobium (Lopera-Marín et al., 2020). For the entire EAR, including the study area (Martín et al., 2019), agroecological management alternatives are recommended, such as agrosilvopastoral systems, protein banks, a combination of grasses and legumes, and the incorporation of native breeds, together with good agricultural and livestock practices.

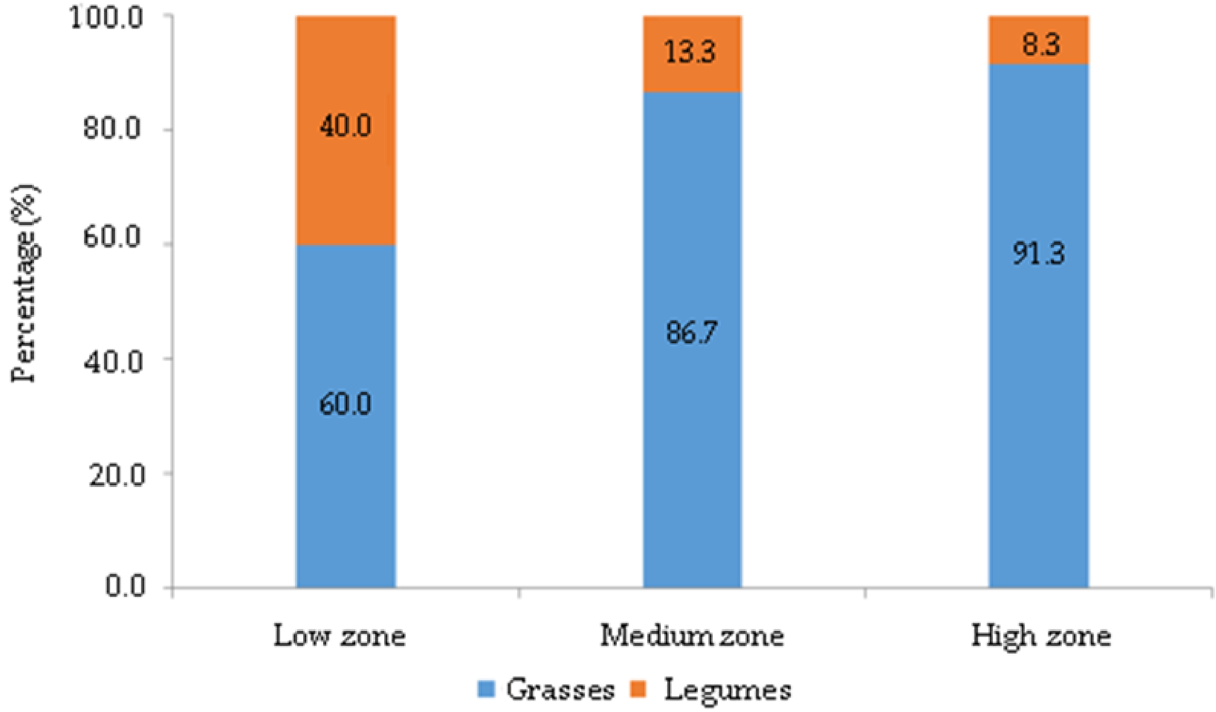

Figure 18. Types of pastures used by small ranchers in the Andean-Amazonian altitudinal gradient, Napo province, Ecuador.

Variation in Income, Investments, and Net Benefits in the Altitudinal Gradient

Regarding the economic analysis, considering the gross values of investment and income (Table 16), the three altitudinal zones differ in terms of animal stock and average of daily milk yield, with the high zone being the one with the highest average number of animals per producer (30.4 heads) and highest average daily milk yield by cows (7.2 L/cow). In terms of annual investment, there is a significant difference ($p < 0.001$) in the three areas studied. The high zone had the highest annual investment ($4307.3), and likewise, this zone reported the highest income, which is probably due to both the number of animals and the higher level of investment. Therefore, in the high zone, farmers are more successful and prefer to continue with this activity, since the income they obtain from raising livestock is greater than the cost of investing in livestock (Pérez, 2017). These results are similar to those obtained by (Martín et al., 2019), who realized that in the lower areas of the EAR there are fewer animals and low yields, which could be partly related to low investments and the low nutritional value of the pastures used, as well as the presence of parasites and diseases, such as mastitis and deficiencies in the reproductive process (Pérez, 2017).

Table 16. Average investments, gross income and annual net income in USD of livestock producers along the altitudinal gradient, Napo, Sumaco Biosphere Reserve, Ecuadorian Amazon.

Variable	*Altitudinal gradient (zone)*			*p value*†
	Low	**Medium**	**High**	
Total animals (heads)	*24.2* [a] *(13.8)*	*18.8* [a,b] *(17.1)*	*30.4* [b] *(21.8)*	*0.01*
Total investment (USD)	*1,709.9* [b] *(1,547.1)*	*1,555.8* [b] *(1,403.7)*	*4,307.3* [a] *(2,814.7)*	*0.001*
Total gross income (USD)	*2,762.7* [b] *(3,038.1)*	*3,415.1* [b] *(4,939.6)*	*19,042.6* [a] *(26,204.6)*	*0.001*
Net profit (USD)	*1,052.7* [b] *(3,259.3)*	*1,859.3* [b] *(4,682.1)*	*14,735.3* [a] *(25,120.3)*	*0.001*

† ANOVA ** $p < 0.01$; *** $p < 0.001$; n.s.: no significance. Superscript letters denote significant differences along the elevational gradient. Values in parentheses are standard deviations from the mean.

Good Livestock Practices Recommended for the Achievement of the SDGs

The resulting characterization of the livestock systems in the studied Andean-Amazonian gradient presents different dynamics for each area evaluated. Therefore, the following recommendations are considered to be of high priority along the studied altitudinal gradient, with a view towards sustainable intensification of livestock systems for decision makers (Table 17) and towards the achievement of the SDGs.

Table 17. Recommendations for strengthening the SDG indicators for livestock producers in the altitudinal gradient, Napo, Sumaco Biosphere Reserve, Ecuadorian Amazon.

Sustainable Development Goal (SDG)	**Recommendation**	**Examples**
SDG 1: End of poverty	Implement accounting records, productive and reproductive planning systems, among other aspects of good livestock management practices. As well as improving grazing systems and management of leguminous forage species to increase productivity.	(Martín et al., 2019; Torres et al., 2021a)
SDG 2: Zero Hunger	Diversify livestock systems with crops, fruit trees and timber (sustainable livestock intensification). Generate sustainable food-oriented production, implementing an animal-based diet, which could also alleviate malnutrition (hidden hunger).	(Burgos et al., 2013)
SDG 3: Good health and well-being	Promote a healthy human diet through precision farming and the incorporation of good farming practices that prevent diseases and promote product quality.	(Burgos et al., 2013)
SDG 4: Quality education	Propose field schools to promote good livestock practices aimed at making land use more efficient, freeing up pasture areas to promote reforestation and landscape restoration processes, as well as associativity and business development.	(Arnés et al., 2018; Torres et al., 2021a)

SDG 5: Gender equality	Promote greater participation and training of women in activities of good livestock practices to promote equal opportunities in sustainable societies.	(Torres et al., 2021a; Yasmin & Ikemoto, 2015)
SDG 6: Clean water and sanitation	Reduce the water footprint of livestock, considering sustainable intensification through good livestock practices that incorporate waste management, in order to obtain economic, environmental and social co-benefits from livestock activity.	(Burgos et al., 2013; Doreau et al., 2012; Torres et al., 2021a)
SDG 8: Decent work and economic growth	Identify resilience factors that promote the adaptation and buffering capacity of farms and that favor the adaptation capacity at the supply chain level. As well as economic analysis through poverty quintiles and capital theory to make extension and training programs more efficient.	(Torres et al., 2022)
SDG 10: Reduced inequalities	Promote research on inequities in livestock systems and policies to reduce inequity through animal breeding programs with solid agroecological principles and pasture technification, serving these vulnerable populations.	(Torres et al., 2022)
SDG 11: Sustainable cities and communities	Promote policies that encourage good livestock practices towards sustainable livestock landscapes at the community level, and that also add value to livestock products.	(Mehrabi et al., 2020)
SDG 12: Responsible Consumption and Production	Promote responsible consumption policies so that society insists on the consumption of products that do not cause negative environmental externalities throughout the production chain.	(Heredia et al., 2020; Heredia et al., 2020)
SDG 13: Climate Action	Promote public and private action policies with key actors to implement projects that promote good livestock practices with a REDD+ approach. Promote experimental research with the support of academia to facilitate technical assistance towards climate-smart livestock systems. As well as the implementation of waste management systems such as: artisanal vermiculture, composting and semi-artisanal biodigester.	(Burgos et al., 2013; Torres et al., 2021a)
SDG 15: Life on land	Promote policies to implement deforestation-free livestock systems and improve the ecosystem services of grasslands by implementing good livestock practices such as: passive and active restoration in degraded areas due to overgrazing, rehabilitation of grasslands with the inclusion of tree, fruit and forage species. Promote policies to implement deforestation-free livestock systems and improve the ecosystem services of grasslands by implementing good livestock practices such as: passive and active restoration in degraded areas due to overgrazing, rehabilitation of grasslands with the inclusion of tree, fruit and forage species.	(Torres et al., 2021a)
SDG 17: Partnerships for the goals	Promote policies for the organizational development of associations of livestock producers that promote cooperation, complementarity, solidarity, conflict resolution, the construction of local capacities and the necessary planning to achieve the SDGs.	(Heredia et al., 2020)

4.2. Livelihood Capitals, Income Inequality, and the Perception of Climate Change: A Case Study of Small-Scale Cattle Farmers in the Ecuadorian Andes

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4.2.1 Introduction

Livelihoods can be defined as a measure of the set of actions that are taken by people, within their capacity and capital, to earn a living by maintaining a highly diverse portfolio of activities, while livelihood capitals encompass the natural, physical, human, social, and financial resources that are critical to the survival of people in response to stresses and shocks, without damaging the natural resource base (Ansoms & McKay, 2010; Ellis, 2000; Mutenje et al., 2010; Scoones, 1998). Livelihoods involve not only the activities that shape the way that people live, but also the resources that ensure a satisfying life, the risk involved in managing those resources, and the policies that support or oppose the pursuit of livelihoods and good living (Mutenje et al., 2010). Subsistence capitals can be stored, exchanged, and transferred in the process of generating income for the household (Angelsen et al., 2014; Kibria et al., 2014; Scoones, 1998; van den Berg, 2010; Walelign, 2017; Walelign et al., 2017).

The important role of conventional agricultural strategies (e.g., agriculture, forestry, and livestock) in reducing poverty is pointed out by the authors of (Alary et al., 2011; Christiaensen et al., 2010; Hogarth et al., 2013; Reardon et al., 2000; C. M. Shackleton et al., 2007; Soltani et al., 2012), who argue that the increase in the area of arable land, the development of agricultural products with high added value, the adjustment of the structure of agricultural production, the improvement of the productivity of the land, and the fulfillment of the basic requirements for agricultural activities would produce less poverty. In the central Ecuadorian Amazon, it was determined that the livestock-based livelihood strategy was more successful in economic terms than others that are oriented towards agriculture and forest use (Torres et al., 2018; Torres et al., 2018), with the recommendation of 16 livestock best-management practices that are aimed at climate-change adaptation and mitigation as actions to strengthen the livelihoods of cattle-raising households (Torres et al., 2021b). In addition to the insights that are inherent in perception processes, climate-change impacts are increasingly recognized as important drivers of livelihood strategies that are, in particular, effective linkages with the livelihood vulnerability and the alleviation of poverty (Fang, 2013; Fang et al., 2011; Gentle & Maraseni, 2012). Climate change is an additional burden on poor people, who are already vulnerable and excluded, and there are predictions of additional risks to livelihoods and greater inequity in the future (Beverly, 2001).

Poverty is a complex economic phenomenon that occurs when the income of individuals or households falls short of basic living standards (Beverly, 2001; Hallegatte et al., 2018) because of the deprivation of access to social, economic, and political resources to achieve adequate food, the use of drinking water and sanitation, among many others (Anand & Harris, 1994; Guo et al., 2019). These circumstances may be divided into absolute and relative poverty (Foster, 1998; Liu et al., 2017), chronic or persistent and transitory poverty (Chen & Ravallion, 2007; Hulme & Shepherd, 2003), regional (place) and individual (people) poverty (Park et al., 2002; Powell et al., 2001; Ward, 2016), as well as urban and rural poverty (Amato & Zuo, 1992; Li et al., 2022). Regional poverty is a chronic or persistent poverty, while individual poverty is transitory (Anand & Harris, 1994). Individual poverty is closely related to regional poverty, and they influence and interact with each other. Regional poverty usually leads to the lack of an endogenous impulse for the individual development of a region; in turn, individual poverty translates into slow socioeconomic development and the lack of infrastructure and the guarantee of public services throughout the region, which accumulates as regional poverty (Anand & Harris, 1994; Ding & Leng, 2018; Du et al., 2005; Liu & Xu, 2016; Y. Zhou et al., 2018). Both individual and regional poverty are affected by human, social, financial, physical, natural, and livelihood capitals, as well as by their synthetic geographic capital, while these poverty-influencing factors vary across time scales and geographic regions (Du et al., 2005; Liu & Xu, 2016).

Approximately 80% of the world's poor live in rural areas (Y. Zhou et al., 2019). Reducing their multidimensional vulnerability needs to be a local, national, and international priority (Zhang et al., 2019), and, in this way, may comply with the indicators and goals of SDG 1, which shall lead to the eradication of poverty, and SDG 2, which may lead to the achievement of food and nutrition security and the end of hunger, as described in the UN Sustainable Development Goals for 2030 (Zhang et al., 2019). This accomplishes a better mitigation of the rural gap of urban contexts (Griggs et al., 2013; ONU, 2015).

A key route out of rural poverty is to improve the productivity, profitability, and sustainability of small-scale production systems (Fan et al., 2013; Grubbström & Sooväli-Sepping, 2012; Y. Zhou & Liu, 2019). Scientific evidence from specific geographic and social contexts is needed in order to inform the implementation of effective instruments that target vulnerable smallholder farmers (Alkire et al., 2015; Carney et al., 1999; Wegren & O'Brien, 2018). Human security relates to the social order in its concern for stability, as well as to the levels in the key dimensions of human development, which include freedom from misery and fear (Onyekwere & Nworgu, 2020).

The geographic elements that affect poverty include location, resource endowment, the ecological environment, public service, regional politics, and culture (Bigman & Fofack, 2000; Do & Iyer, 2010; Gasper, 2005). Previous studies have indicated that there is a "downward spiral" between regional impoverishment and environmental degradation (Barbier, 2014; Cao et al., 2009; Casillas & Kammen, 2010; Cavendish, 2000; Dasgupta et al., 2005; L. C. Gray & Moseley, 2005; Lufumpa, 2005; Luo & Li, 2014; Scherr, 2000).

The remote geographic location is often considered to be the main cause of the high incidence in the semiarid region of Zimbabwe (Watmough et al., 2016). Even in developed countries, such as the United States and Great Britain, rural impoverishment and geographic locations are closely related, and the incidence of poverty increases with the distance from metropolitan areas (Bird & Shepherd, 2003). In China, ecologically fragile areas largely overlap with poor areas (Partridge & Rickman, 2008).

In addition, the topographical conditions, the slope, the surface fragmentation, the distance/travel time to public resources or services, the elevation, and the type of land use are also closely related to poverty (Cheng et al., 2018; Gasper, 2005; Henninger & Snel, 2002; Okwi et al., 2007; Tian et al., 2022; Zhou & Xiong, 2018).

Complex topography has a positive driving effect on the spatial distribution of poverty-stricken countries (Cheng et al., 2018). Natural conditions play a scale independent role in the incidence of poverty (Okwi et al., 2007). Soil erosion can affect the quality of agricultural land, which forms a vicious cycle of ecological damage, soil erosion, the shrinkage of arable land, impoverishment, the reclamation of steep slopes, and ecological degradation (Amato & Zuo, 1992).

Natural disasters and climate change are also considered to be driving forces of rural impoverishment (Barbier, 2014; Hallegatte et al., 2017; Hertel & Rosch, 2010; Ma et al., 2018). Natural disasters perpetuate poverty and make it difficult for poor people to escape it (Akter &

Mallick, 2013; Datt & Hoogeveen, 2003; Hallegatte, 2013; Rodriguez-Oreggia et al., 2013; Rodriguez et al., 2017; Rozenberg & Hallegatte, 2016). Globally, natural disasters force around 26 million people into extreme poverty each year (Hallegatte, 2013; Shimada, 2022). By 2030, around 325 million extremely poor people are expected to live in the 49 most hazard-prone countries in the world, with most of them in South Asia, sub-Saharan Africa, Latin America, and the Caribbean (Echegaray-Aveiga et al., 2020).

In this context, the objectives of the current study were three-fold: to determine the poverty groups by quintiles through cattle income and inequality by using the Gini coefficient and the Lorenz curve in the households of small milk producers, to characterize rural livelihoods by using the theory of capitals and by evaluating the perception of climate change, and to evaluate the readiness to accept adaptation and mitigation measures.

4.2.2 Results and Discussion

Determination of Poverty Groups by Quintiles through Cattle Income

In relation to the first quintile (Q1), an annual average of USD 1174.26 was obtained, with a standard deviation of ±595.98. These were 103 households that were in a state of extreme poverty, which represented around 58% of the total of 178 households that were surveyed from the four communities that were studied in the provinces of Chimborazo and Tungurahua (Figure 19). Similar scenarios appear to the small ranchers of Puno (Peru) (Paredes & Escobar-Mamani, 2018), Ethiopia (Holden et al., 2004), and in the semiarid region of South Africa.

There poor households are trapped in a state of food insecurity and perpetual vulnerability because of poor asset endowments and a lack of markets, and especially capital, which prevents the necessary investment and the proper and productive use of assets (Jenkins, 1999; S. Shackleton et al., 2008).

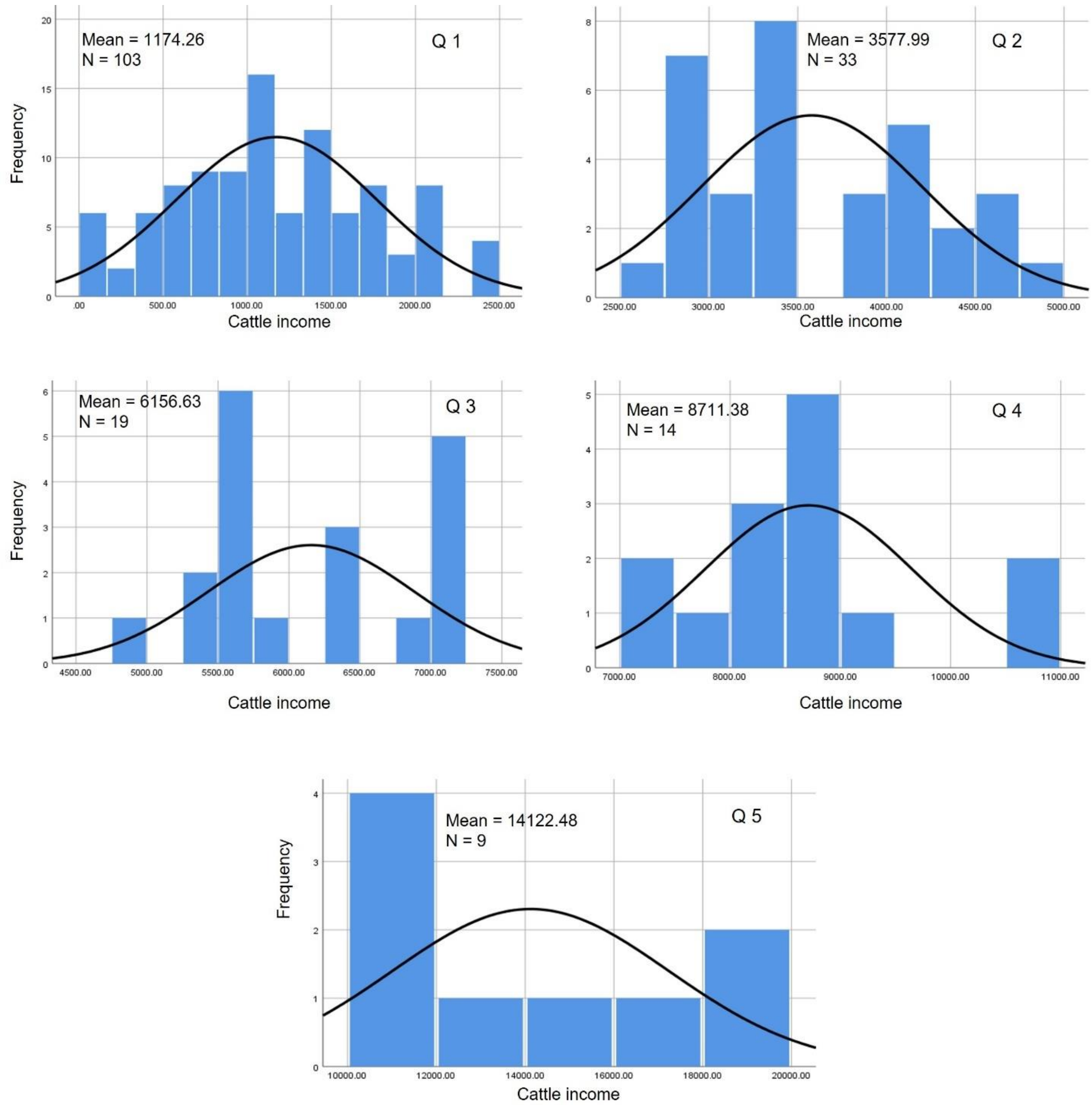

Figure 19. Total livestock income with respect to poverty quintiles in small ranchers in the Ecuadorian Andes.

With regard to the second quintile (Q2), an annual average of USD 3577.99 was obtained, with a standard deviation of ±624.30, which has been assigned to 33 individuals, who represent 18% of the total of the 178 households surveyed. With regard to the third quintile (Q3), an annual average of USD 6156.63 was obtained, with a standard deviation of ±727.35, which represents around 11%. In terms of the fourth quintile (Q4), an annual average of USD 8711.38 was obtained, with a standard deviation of ±940.03, which is 8% of the sample population, while, for the fifth quintile (Q5), an annual average of USD 14,122 was obtained, with a standard deviation of ±3115.40. In this quintile, there were nine of the wealthiest individuals, who only represent around 5% of the total of 178 households that were surveyed from the four communities that were studied in the provinces of Chimborazo and Tungurahua in central Ecuador.

This reflects an economic gap between small dairy farmers, for which it is essential to identify the critical points on productive sustainability (Torres et al., 2021b). To accomplish such a goal, we used methodologies such as RISE (Heredia-R et al., 2020), SAFA (Caicedo et al., 2019; Heredia-R et al., 2022; M. Heredia, Torres, et al., 2020; Weiler et al., 2019), or TAPE, where the environmental, social, economic, governance, health, and nutrition dimensions are evaluated (Mottet et al., 2020) in order to enhance the existing synergies between producers. It is also essential to identify the hot spots of land use and cover change (Heredia-R et al., 2021; Heredia-R, Torres, et al., 2021), to strengthen sustainable intensification programs with tools such as conservation psychology (Heredia et al., 2021), and to prevent the advance of the livestock frontier.

The classification into quintiles (groups from lower to higher incomes) is an effective tool since it could favor the implementation of policy strategies that are aimed at improving livelihoods, and the implementation of actions to mitigate and adapt to climate change. In this regard, according to Mujica et al. (2019) and Luna (2020), the use of quintiles facilitated the implementation of development policies to address the inequalities that were caused by COVID-19 in Latin America.

Inequity in Economic Income

The results of the Gini coefficient (0.52) and the Lorenz curve illustrate the income inequality of small-scale cattle producers in the Ecuadorian Andes. In this area, it is demonstrated that the poorest 20% of the population only obtain 3.40% of the income, while the 20% of the richest quintile obtain around 54% of the total income (Figure 20).

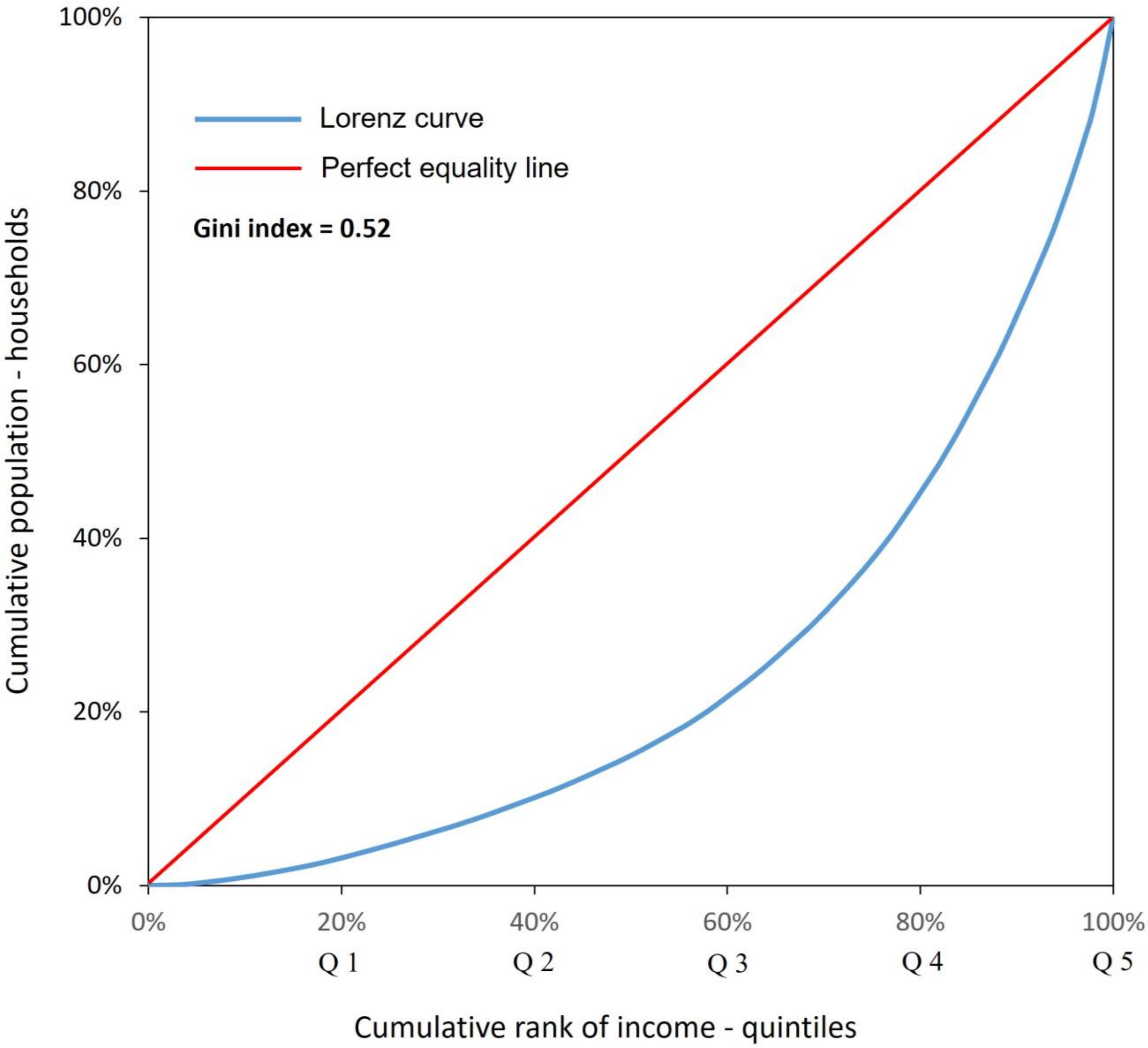

Figure 20. Lorenz curve of income distribution among small-scale dairy farmers in the Ecuadorian Andes.

Income from Cattle Activity by Quintiles

The average total cattle income was obtained by adding the income from production, the sale of milk, and consumption (milk) on the farm (Table 18). Between the quintiles, there are significant differences. In the first quintile (Q1), an income of USD 1174.26 was obtained; in the second quintile (Q2), USD 3577.99; in the third quintile (Q3), USD 6156.63; in the fourth quintile (Q4), USD 8711.38; and in the fifth quintile (Q5), USD 14,122.48. Therefore, in the first quintile (Q1), being the poorest, there is a lower average annual income compared to the fifth quintile (Q5), which represents the nonpoor.

Table 18. Mean and standard deviation in USD of income from livestock activity by quintiles in small livestock producers in Chimborazo and Tungurahua, 2018.

Variables	**Q1 <20% USD**	**Q2 20–40% USD**	**Q3 40–60% USD**	**Q4 60–80% USD**	**Q5 >80% USD**	**Average USD**	**Significance**
Average total livestock income	1174.26 (595.98)	3577.99 (624.30)	6156.63 (727.35)	8711.38 (940.03)	14,122.48 (3115.40)	3399.22 (3551.66)	***
Average household size	3.54	3.18	3.47	2.93	3.56	3.42	ns
Average income per capita/daily	0.91	3.08	4.86	8.15	10.87	2.72	***
Poverty category	Extremely poor	Moderately poor	Not so well-off	Moderately well-off	Well-off	Moderately poor	
Sample percentage	58%	18%	11%	8%	5%	100	

Values in parentheses are the standard deviation of the means. *** $p < 0.001$; ns = not significantly different.

In the analysis of the household size, there are no significant differences, while the average number of members per household was determined to range by three to four members, and a general figure between the households of the quintiles, Q1 and Q5. A similar scenario occurs in the Los Sainos microbasin, which is located in the municipality of El Dovio (Colombia), where the livelihood strategy of rural households is the production of cow's milk, on the basis of grazing (García & Brown, 2009). There, it has been stated that the household size is the most important determinant of the investment in labor for household farms, and that it also influences the need to increase milk production for domestic consumption, as well as for the free market (Ngongoni et al., 2006). The average income per capita/daily was obtained from the average total income from the cattle divided by the size of the household, and during the whole year. The resulting values present a significant difference between the quintiles, where the daily values were USD 0.91 in the first quintile (Q1), with increases of USD 2.17, USD 3.95, USD 7.24, and USD 9.96, which were distributed between the quintiles, Q1 to Q5, respectively. In the Andes region, it has been identified that the poorest households that are dedicated to milk production serve as assets for investments and sources of savings for household consumption (C. B. Valdivia & Quiroz, 2003). In rural areas of the departments of Puno and Cajamarca in Peru, cattle ranching has been demonstrated to be an effective strategy to reduce or to escape poverty (Kristjanson et al., 2007).

Furthermore, the category, according to the INEC (INEC, 2018), that belongs to the surveyed individuals was analyzed, where the first quintile (Q1) corresponds to the category of the extremely poor grouping of the largest number of cattle-raising households, while the second quintile to the fifth quintile were defined as moderately poor (Q2), not so well-off (Q3), moderately well-off (Q4), and well-off (Q5). Finally, the percentage of the sample that corresponds to each quintile was calculated, where, in the first quintile (Q1), it corresponds to

58%; in the second quintile (Q2), to 18%; in the third quintile (Q3), to 11%; in the fourth quintile (Q4), to 8%; and in the fifth quintile (Q1), to only 5%. There is scientific evidence that households that live in extreme poverty have few opportunities for productive work, little access to land that is suitable for agricultural and livestock use, erosion and progressive degradation, and their location in a fragile ecosystem, as represented by the paramo (Semplades, 2013). Consequently, these populations suffer not only from poverty, but also from food insecurity, despite the fact that they apparently have the natural resources that are necessary for their subsistence (FAO, 2019). Finally, some rural households respond to the income shock by migrating to seek work in non-agricultural sectors (Eche, 2018).

Characterization of Rural Livelihoods by Quintiles

In the following section, the characterization of rural livelihoods is indicated by using the theory of capitals, which includes the variable of the human, social, natural, financial, and physical capitals in small-scale cattle producers in the given study area of the Ecuadorian Andes.

Human and Social Capital

In relation to the ethnic variable, there are some significant differences. It was identified that out of all of the ranchers that were surveyed in the first quintile (Q1), 78.6% of them were of Kichwa nationality, and the residual 21.4% were Mestizos, while, in the quintiles (Q2), (Q3), and (Q4), there were less Kichwa and more Mestizos, which is in contrast to the fifth quintile (Q5), where all 100% were of Mestizo origin. In general, there were 11.2% more indigenous Kichwa than mestizo milk producers (Table 19). The results reaffirm the theory that social, productive, and labor inequalities will prevent the end of the poverty of indigenous peoples. Additionally, they could cause migration processes of indigenous women and men outside of their traditional territories, which, in some cases, can lead to work in the formal economic (Heredia-R et al., 2021). Furthermore, in order to face greater occasional dependency, they work in agriculture, construction, domestic work, or informal commerce (Dhir, 2015), where they obtain their livelihoods, which is also the result of the lack of opportunities in the formal economy (Morales, 2016).

Table 19. Average of the main variables that represent human and social capital in small livestock producers in Chimborazo and Tungurahua, Ecuadorian Andes.

Variables		**Quintiles**					**Average**	**Significance**
		Q1	**Q2**	**Q3**	**Q4**	**Q5**		
Ethnicity	Kichwa %	78.6	39.4	15.8	14.3	-	55.6	***
	Mestizo %	21.4	60.6	84.2	85.7	100	44.4	
Gender of household head	Man %	76.7	66.7	52.6	64.3	66.7	70.8	Ns
	Women %	23.3	33.3	47.4	35.7	33.3	29.2	
Age of household head	(years)	42.0	45.9	41.9	47.5	36.8	42.9	Ns

	Basic %	56.3	54.5	57.9	50.0	77.8	56.7	
Education of household head (years)	Medium %	19.4	18.2	21.1	28.6	11.1	19.7	Ns
	College %	5.8	30	5.3	-	11.1	5.1	
	None %	18.4	24.2	15.8	21.4	-	18.5	
Generational Replacement	Yes %	72.8	81.8	89.5	71.4	88.9	77.0	ns
	No %	27.2	18.2	10.5	21.4	11.1	22.5	
Belongs to an association	Yes %	38.8	57.6	78.9	71.4	55.6	50.0	***
	No %	61.2	42.4	21.1	286	44.4	50.0	

*** $p < 0.001$; ns = not significantly different.

In terms of the gender of the head of the household, and referring to all the quintiles evaluated, it was evidenced that men predominate, with 70.8%, which could be a constraint to local holistic development, since it has been proven that rural women (heads of household) play a key role in the promotion of pro-environmental behaviors in rural production (Balezentis et al., 2021). Several investigations have indicated the special bond between women and the environment (Balezentis et al., 2021; Dhir, 2015; Morales Ramírez, 2016; Qingqi, 2014). Early notions of women and the environment are primarily reflected in the ecofeminism theory from the 1980s, which suggests that women are especially "close to nature" in a spiritual or conceptual sense (Arora-Jonsson & Sijapati, 2018). Furthermore, some scholars suggest that women are imbued with a stronger ethical approach to environmental survival, which is fundamentally different from that of men (Irving & Helin, 2018). Consequently, women are more likely to protect natural resources for the continued survival of their families (Finzer, 2015).

With regard to the age of the head of household, it was determined that in the first quintile (Q1) and the third quintile (Q3), there is an average age of 42 years, and the fifth quintile (Q5) reveals a younger age (37 years), while the fourth quintile (Q4) yields a higher age (48 years), among the groups that were evaluated. The average age of the heads of households is about 43 years. In terms of the education of the heads of households (that is, the degree of educational instruction that he has received), we encountered that from the first quintile (Q1) to the fifth quintile (Q5), the majority of household heads have basic education, followed by secondary education, and the third level is the denomination of "none" (that is, they have no level of study). It is determined that the level of study or the educational system is extremely limited in its powers to reduce poverty and to increase intergenerational social mobility (Salleh, 2017). The standard policy formula—expanding access to education, increasing social mobility, and reducing poverty—does not stand up to close scrutiny, and it may have unintended consequences that serve to undermine the stated purpose of educational reform. This does not mean that education is a wasted investment (MacGregor, 2004), or that it is simply an institutional instrument for social reproduction (Brown & James, 2020). However, it does mean that education must be studied as an integral part of a more holistic and contextual theory that recognizes educational reform as a “complementary condition” (Loveday, 2019) for increasing social justice and individual well-being.

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<u>Natural Capital</u>

There is a significant difference between the groups of producers from Q1 to Q5 of 4.63 ha and 4.18 ha in the farm area and the pasture area, respectively (Table 20). Similar scenarios with regard to the livestock production in the highlands of Peru are largely based on pasture grazing, which is supplemented with crop residues, and particularly stubble, or agricultural byproducts and, in certain cases, with improved foraging resources. Thus, grasslands, with native grass species constitute the main food resource of mixed farming systems with ruminant species (León-Velarde & Quiroz, 2004). Small-scale pastoralist dairy farming in Zambia plays an important role in poverty reduction, employment opportunities, wealth creation, and household food, as well as in nutrition security (Mumba, 2012).

Table 20. Mean and standard deviation of the main variables that represent natural capital in small livestock producers in Chimborazo and Tungurahua in 2018.

Variables	Quintiles					Average	Significance
	Q1	Q2	Q3	Q4	Q5		
Total farm area (ha)	2.37 (2.12)	2.79 (1.99)	3.08 (1.65)	3.82 (1.49)	7.00 (5.07)	2.87 (2.45)	***
Pasture area (ha)	1.60 (1.52)	2.45 (1.65)	2.63 (1.38)	3.68 (1.51)	5.78 (2.99)	2.24 (1.91)	***
Cultivation area (ha)	0.77 (1.08)	0.33 (0.77)	0.45 (0.52)	0.14 (0.36)	1.22 (2.64)	0.63 (1.09)	ns

Values in parentheses are the standard deviation of the means. *** $p < 0.001$; ns = not significantly different.

Physical and Financial Capital

There are substantial differences in the "total cows" variable in the per capita production, where the values ranged from 2 in Q1 to 8 in Q5, which is a similar scenario as in Kilosa, Tanzania, where cattle contribute heavily to household livelihoods and food security, but fodder scarcity is a limiting factor (Ruvuga et al., 2020). In addition, it was identified that the producers in Q1 use 14.3% more water than the producers in Q5, and that only the producers that belong to Q3 have cement as the floor for milking. With regard to who performs the milking, it was identified that women predominate in this activity, and that they do not receive any economic bonuses at all, in all of the quintiles (Table 21).

Table 21. Average of the main variables that represent physical and financial capital in small livestock producers in Chimborazo and Tungurahua in 2018.

Variables		Quintiles					Average	Significance
		Q1	Q2	Q3	Q4	Q5		
Total cows in production per household	Cow unit	1.93	3.12	4.11	4.93	8.44	2.95	***
Milking water	*Yes %*	69.9	81.8	78.9	42.1	55.6	70.2	
	No %	30.1	18.2	21.1	57.9	44.4	29.8	
Milking floor type	*Earth %*	97.1	100	84.2	100	100	96.3	ns
	Cement %	-	-	10.5	-	-	2.1	
	Lacks of %	2.9	-	5.3	-	-	1.6	
Milk container	*AI drums %*	11.7	27.3	26.3	50.0	33.3	20.2	ns
	Aluminum drums %	64.1	60.6	68.4	14.3	44.4	59.0	
	Plastic tanks %	9.7	3.0	5.3	35.7	11.1	10.1	
	Others	14.6	9.1	-	-	11.1	10.7	
Who realizes the milking	*Man %*	21.4	9.1	15.8	14.3	-	16.9	ns
	Women %	73.8	87.9	73.7	85.7	100	78.7	
	Both %	4.9	3.0	10.5	-	-	4.5	
Receives bonus	*Yes %*	41.7	30.3	26.3	28.6	11.1	35.4	ns
	No%	58.3	69.7	73.7	71.4	88.9	64.6	

*** $p < 0.001$; ns = not significantly different.

Perception of Climate Change and Readiness to Accept Adaptation as Well as Mitigation Measures

With regard to the variables of the perception of climate change, there is evidence of heterogeneity in the responses (Table 22). It is fundamental to consider that the perception of climate change is a complex process that encompasses a variety of psychological constructs, such as the knowledge, beliefs, attitudes, and concerns about whether and how the climate is changing (Whitmarsh & Capstick, 2018). Perception is influenced and shaped by, among other things, the characteristics of individuals, their experiences, the information they receive, and the cultural and geographic contexts in which they live (Van der Linden, 2015; Whitmarsh & Capstick, 2018). Therefore, measuring the perception of climate change, and trying to find its determinants, is a rather complex task.

Table 22. Average of the main variables related to climate change and willingness to accept mitigation and adaptation actions in small livestock producers in Chimborazo and Tungurahua, 2018.

Variables		**Quintiles**					**Average**	**Significance**
		Q1	**Q2**	**Q3**	**Q4**	**Q5**		
Understanding about climate change	*Yes %*	27.2	25.0	31.6	42.9	44.4	29.4	
	No %	70.9	68.8	68.4	50.0	55.6	67.8	ns
	Some %	1.9	6.2	-	7.1	-	2.8	
Does the weather change in your area?	*Yes a lot %*	26.2	33.3	31.6	64.3	55.6	32.6	
	Yes a little %	44.7	27.3	42.1	7.1	33.3	37.6	ns
	No %	9.7	15.2	15.8	-	-	10.1	
	Unsure %	19.4	24.2	10.5	28.6	1.1	19.7	
Willingness to receive climate change training	*Yes %*	81.6	84.8	78.9	100	100	84.3	
	No %	18.4	15.2	21.1	-	-	15.7	ns
Willingness to adopt appropriate cattle management practices	*Yes %*	80.6	66.7	47.4	42.9	44.4	69.7	
	No %	19.4	33.3	52.6	57.1	55.6	30.3	ns
Access to climatological information	*Yes %*	10.7	15.2	15.8	28.6	22.2	14.0	
	No %	89.3	84.8	84.2	71.4	77.8	86.0	ns
In the last ten years have you adopted adaptive actions to climate change?	*Yes %*	5.8	12.1	-	14.3	11.1	7.3	
	No %	94.2	87.9	100	85.7	88.9	92.7	ns
Willingness to invest labor and materials to adopt actions adapting to climate change	*Yes %*	84.5	84.8	57.9	64.3	66.7	79.2	
	No %	15.5	15.2	42.1	35.7	33.3	20.8	***

*** $p < 0.001$; ns = not significantly different.

The producers of Q1 are those who least understand climate change, in general terms, while, in most of the quintiles that were evaluated, they do not understand climate change. This is worrying since it has been revealed that knowledge about climate change is a critical determinant of the behavior of rural producers, especially in order to achieve adaptation strategies (Leroy, 2019; Su et al., 2017). In addition, in the Ecuadorian Andes, there is a lack of thinking in terms of planning in the face of the existing and future scenarios of climate change (Alvear et al., 2021a;Heredia et al., 2020; Toulkeridis et al., 2020), considering that the increase in temperatures, the retreat of glaciers, and changes in the frequency and intensity of precipitation and frost have been documented in the Andean highlands over the past thirty years (Bradley et al., 2006; Perez et al., 2010; Thibeault et al., 2010; C. Valdivia et al., 2013; Vuille et al., 2008), which has coincided with greater uncertainty and the exposure to multiple climatic stresses in the northern highlands of Bolivia (Meldrum et al., 2018). This coincides with the results of a changing climate in the study area, where the producers from Q1 to Q5 responded more frequently to the option "Yes a little".

Adapting to climate change requires a change in people's behavior, knowledge, and abilities in order to help build their resilience. Typically, such learning is facilitated through informal and formal institutions (Nnadi et al., 2013). It has been demonstrated that rural farmers in the Peruvian Andes achieved significantly greater knowledge of integrated pest-management practices in the face of a changing climate than those in the comparison group of nonparticipants, and, consequently, significantly improved field productivity (Godtland et al., 2004), in such a way that similar results would be expected with the producers belonging to Q1 to Q5. This occurs since most of them are willing to receive training on climate change. As a consequence, there would be an increase in the awareness about the best local adaptations available that can be used to manage climate risks (Afsar & Idrees, 2019), while, at the same time, this would allow for the avoidance of maladaptation under a changing climate and, thus, of rebound vulnerability, shifting vulnerability, and the erosion of sustainable development (Antwi-Agyei et al., 2018; Juhola et al., 2016).

The management of good livestock practices leads to optimal productivity results, which increases the profits of the livestock producer and improves the quality of life of the peasant family under a changing climate (Vásquez et al., 2019). This is presented as an optimal scenario for producers who expect to conduct good livestock practices to face climate change (Table 7). There is a total average of 30% who are distributed among the quintiles of poverty, and who lack the desire to perform good livestock practices, which may be related to the low levels of education of the population studied and the age of the head of the household (Table 4). Among climate-smart approaches, climate information services (CIS) remain a credible option to increase productivity and to avoid losses in the agricultural and livestock sectors (Zhongming et al., 2013). CIS refers to the production, translation, transfer, and use of scientific information for decision making (Serra & McKune, 2016; Vaughan et al., 2019). It was identified that the access to and use of climate information helped Senegalese producers to formulate tactical decisions before, during, and after the agricultural and livestock management seasons (Ouedraogo et al., 2018). Therefore, it is essential to provide CIS to the assessed farmers, as 86% of the producers among the quintiles lacked access to climate information, and as there is no significant difference between the producers from Q1 to Q5. Therefore, the same adoption strategy may be considered. In the variable "willingness to invest labor and materials to adopt actions adapting to climate change", there is a significant difference between the quintiles, despite the fact that most answered affirmatively, with an average value of 79.2%. In this respect, farmers are willing to invest in household labor and farm materials in order to follow adaptation and mitigation actions if they receive support and training in this matter. These findings are important for the design of local adaptation and mitigation actions, such as those conducted in the Chilean and northern Ecuadorian Andes (Cayambe & Iglesias, 2020; Henry et al., 2018; Marchant Santiago et al., 2021).

4.3. Identification and assessment of livestock best management practices (BMPs) using the REDD+ approach in the Ecuadorian Amazon

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4.3.1 Introduction

The establishment of grazing lands for livestock accounts for 77% of the total farming land in the world (Ritchie & Roser, 2013) and produces 14.5% of global greenhouse gases (GHGs) (Gerber et al., 2013). This issue is particularly prominent in the tropics, where deforestation conventionally generates pasture for cattle-raising and other basic crops (Lerner et al., 2017). Thus, the global dilemma is determining how to improve productivity in a sustainable way (Foley et al., 2011). In terms of livestock production, an alternative could be "sustainable intensification" (Boval et al., 2017).

This option has gained substantial attention over the last few years under the global scenario of climate change. The Cancun Agreements, which resulted from the Conference of the Parties (COP 16), marked a milestone in international policy oriented to reduce emissions from deforestation and forest degradation (REDD+), thereby setting the definition of the REDD+ pillars and climate change mitigation efforts (MAE, 2016).

This research focuses on the Ecuadorian Amazon Region (EAR). In this region, the main drivers of deforestation and forest degradation are related to land-use change for agriculture and pastures (Sierra, 2013a; Wasserstrom & Bustamante, 2015), land clearing for the opening of oil and non-oil roads (Baynard et al., 2013), oil and mining exploitation (Finer et al., 2008; Leifsen, 2020; Suárez et al., 2009; Wasserstrom & Bustamante, 2015), population growth (C. L. Gray et al., 2008), and timber extraction (Mejia et al., 2015; Mena et al., 2006). The pastures for cattle-raising implemented in the EAR are extensive (Lerner et al., 2015; MAGAP, 2015; Torres, Günter, et al., 2018) and are the main causes of land-use change (Mena et al., 2006; R. Sierra, 2013a). Moreover, many cattle-raising practices are not aligned with the ecological reality of this region (Alemán-Pérez et al., 2020a; Bravo et al., 2017), threatening the conservation and sustainable use of Amazonian biodiversity. In 2014, about 1.2 million hectares of pastureland for cattle-raising were registered in the Ecuadorian Amazon (MAGAP, 2015), where landscape restoration actions could be promoted through the implementation of good cattle-raising practices in the context of REDD+ actions, such as technological innovation processes for managing the ecological system, the restoration of released areas, and productive reconversion.

Ecuador has carried out several efforts aimed at reducing emissions, including developing policy instruments such as the prime regulatory policies, which are at the core of the Environmental Organic Code (in the Spanish language: Código Orgánico del Ambiente— CODA (Official Gazette Supplement No. 983 on 12 April 2017 came into force on 13 April 2018). The CODA addresses issues such as climate change, protected areas, wildlife protection, forest heritage, environmental incentives, environmental quality, waste-management, access to genetic resources, biosecurity, and the bioeconomy, among other issues (MAE, 2017).

Furthermore, the CODA considers Agenda for Productive Transformation in the Amazon (ATPA) approaches (MAGAP, 2015). Through Ecuador's REDD+ Action Plan (MAE, 2016) and UNFCC (UNFCCC 2008), actions to achieve reductions in deforestation, conservation, and the sustainable use of biodiversity have been developed. Actions have been carried out to avoid deforestation/degradation, improve the soil carbon stock, reduce GHG emissions, improvement of soil carbon stock, and facilitate social and environmental co-benefits. Ecuador created the ATPA (MAGAP, 2015) as part of the solution to reduce the expansion of the agriculture frontier. The main aim of ATPA was to convert 300,000 hectares of pastureland to agroforestry, silvopastoral, and forestry-integrated mixed systems (MAE, 2016; MAGAP, 2015).

The Chakra, a traditional agroforestry system characterized by its high levels of timber content (Jadán et al., 2015), fruit trees, diversity (Jadán et al., 2016; Torres et al., 2015; Vera et al., 2017), and promotion of food sovereignty and social and cultural benefits (Coq-Huelva et al., 2017, 2018), was also considered.

Therefore, the implementation of ATPA approaches requires an understanding of both the livelihoods of local populations and the best management practices (BMPs) that could release pasture areas for restoration or the implementation of silvopastoral systems. Silvopastoral systems, or grasslands with dispersed trees, contribute to carbon sequestration (Lerner et al., 2015; Rudel et al., 2015) and are key elements in international discussions where REDD+ strategies aim at mitigating environmental stressors. In this regard, the success of adopting BMPs in the transition to sustainable livestock production depends on appropriate knowledge of the local realities of livestock production systems (De-Pablos-Heredero et al., 2020).

Therefore, this study has a double objective: first, to characterize the farms along the elevational gradient in the upper Ecuadorian Amazon; and second, to identify and assess the best management practices (BMPs) in each ecological zone that help foster sustainable production using the REDD+ approach and environmental and economic co-benefits. The research questions were evaluated by applying a mixed methods approach, combining qualitative and quantitative methodologies. Using the quantitative methodology, according to social, structural, and technical characteristics, the farms were characterized for each altitudinal gradient of Amazonia. Later, considering the qualitative methodology with a panel of 15 experts, BMPs were selected for sustainable production using the Ecuadorian REDD+ action plan. This research was developed in the buffer and transition zone of the Sumaco Biosphere Reserve (SBR), located in the northern and central part of the EAR.

4.3.2 Results

Characterization of Farms in Three Elevational Gradients

In the results, the ethnicity of the household heads presented statistically significant differences. Most of the Kichwa population were found to live in the medium zone (56.1%). Moreover, the household size in the medium zone (6.7) was greater than that in the other two zones. The year of settlement did not allow us to obtain significant differences in management or economic performance.

The medium zone presented a higher percentage (78.9%) of households with generational replacement. Furthermore, access to credit for the dairy cattle system was higher in the high zone (24.5%) than in the other zones (Table 23).

A high level of illiteracy and a high number of heads of households without formal education (15.8%) were observed in the medium elevational gradient, where 56.1% were Kichwa with livestock-based livelihood strategies. In the low zone, there was a higher percentage (61.4%) of cattle ranchers with a primary school education, which could be due to their shorter distance to educational centers and the easy access of those centers. In the high zone, 50% of the heads of households had a secondary education.

Table 23. Characteristics of livestock producers along elevational gradients, Napo, SBR, Ecuadorian Amazon, 2015.

Variables	***Elevational gradients (zones)***			***Statistical test***	
	Low	*Medium*	*High*	*F-Snedecor*	*p-value*[1]
Sociodemographic characteristics					
Average elevation, masl	*543.1*^{a}	*1,114.1*^{b}	*1,778.0*^{c}	816.58	*0.001*
Settlement, y	*1975*	*1984*	*1952*	0.58	*n.s.*
Ethnicity, %	*0.0*	*56.1*	*0.0*	*0.43*	*0.001*
Household size, n°	*5.56*^{a,b}	*6.70*^{a}	*5.04*^{b}	*1.04*	*0.01*
Household labor, n°	*2.63*	*3.00*	*2.32*	*0.75*	*n.s*
Generational replacement (Yes, %)	*56.1*^{a,}	*78.9*^{b}	*56.6*^{a}	*8.73*	*0.01*
Age of household head, y	*54.79*	*56.77*	*57.60*	0.71	*n.s*
Without regulated education, %	*8.8*	*15.8*	*3.8*	*4.83*	*n.s*
Primary education, %	*61.4*	*47.4*	*28.3*	*12.46*	*0.002*
Secondary education, %	*22.8*	*24.6*	*49.1*	*11.57*	*0.003*
Land use					
Pastureland, ha	*26.8 + 19.2*	*27.2 + 28.6*	*22.5 + 17.2*	18.49	*0.001*
Crops land, ha	*1.6* ^{a} *+ 1.9*	*2.2* ^{a} *+ 3.3*	*0.4* ^{b} *+ 1.1*	17.32	*0.001*
Remaining forest land, ha	*20.1* ^{a,b} *+ 29.8*	*32.9* ^{a} *+ 56.2*	*12.2* ^{b} *+ 28.1*	*22.35*	*0.05*
Total land, ha	*47.3* ^{a,b} *± 42.1*	*62.4*^{a} *± 70.6*	*35.2* ^{b} *± 40.2*	0.73	*0.05*
Forage					
Grasses, %	*60*	*86.7*	*91.7*	*77.82*	*0.05*
Legumes, %	*40*	*13.3*	*8.3*	*12.10*	*0.05*
Economic performance					
Total animal unit, UA	*24.2* ^{a} *± 13.8*	*18.8*^{a,b} *± 17.1*	*30.4* ^{b} *± 21.8*	5.82	*0.01*
Breeds	*Creole, Charoles, Santa Gertrudis and Jersey*	*Creole, Brown Swiss, and Brahman*	*Holstein and Normando*		
Total investment, $	*1,709.9*^{b} *± 1,547.1*	*1,555.8*^{b} *± 1,403.7*	*4,307.3*^{a} *± 2,814.7*	32.42	*0.001*
Total gross income, $	*2,762.7* ^{b} *± 3,038.1*	*3,415.1*^{b} *± 4,939.6*	*19,042.6* ^{a} *± 26,204.6*	20.11	*0.001*
Net profit, $	*1,052.7*^{b} *± 3,259.3*	*1,859.3*^{b} *± 4,682.1*	*14,735.3*^{a} *± 25,120.3*	15.15	*0.001*

[1] *ANOVA for continuous variables and* X^2 *for discrete variables; n.s. p > 0.05-no significance. Letters in superscript denote significant differences among elevational gradients.*

The comparative results of land-use and farm size among the three groups shown in Figure 21 indicate that, from the 62.4 hectares in the medium zone, on average, 55% of the land is used for growing pastures, 40% is covered by forest, and the rest is dedicated to crops. Subsequently, 62% of the average hectare in the low zone is pastureland, 34% is forest land, and 5% is crop land. Land in the highland area is mostly used to produce pastures (81%), while 17% is covered by forest, and only 2% is used for crops. Farms in the three zones were focused on raising cattle, particularly in the high (dairy and meat) and low (meat and dairy) zones, while the medium zone was found to feature a greater area of forest. However, the availability of agricultural land in the three zones was very low.

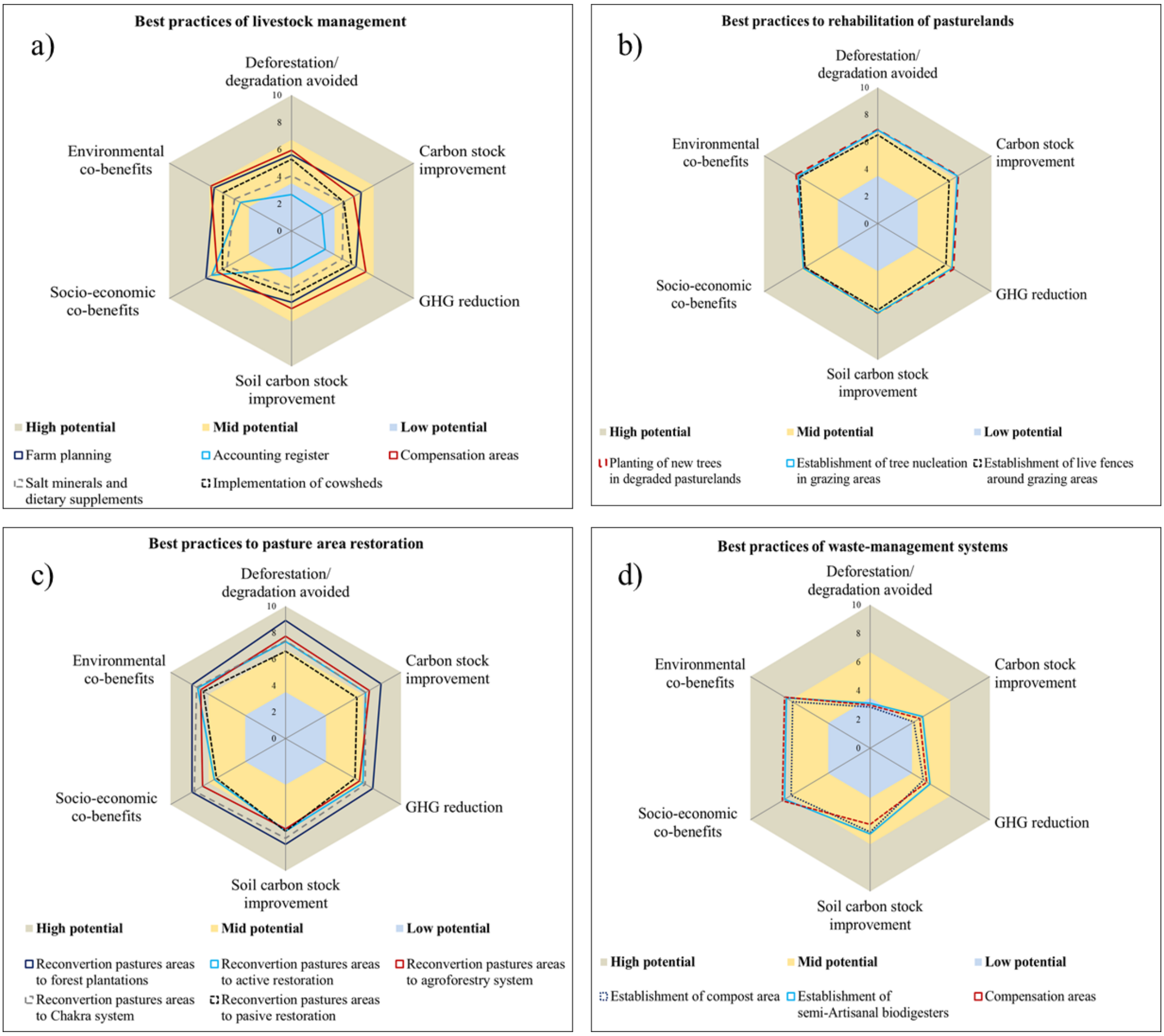

Figure 21. Assessment of BMPs identified as having potential for: a) livestock management, b) the rehabilitation of pasturelands, c) pasture area restoration, and d) waste-management systems. Napo, Ecuador.

The total stock of cattle was significantly greater in the low zone (30.4 animal units) than in the other research sites. Nevertheless, the annual net benefit was the lowest ($1053). The existing climatic variables in the 400–700 masl zone play an important role in the adequate management of cattle production, which is reflected in the annual income ($1053). If this value is transformed into a monthly income, farmers in this zone earned an Figure 2. Assessment of BMPs identified as having potential for: (a) livestock management, (b) the rehabilitation of pasturelands, (c) pasture area restoration, and (d) waste-management systems. Napo, Ecuador. The total stock of cattle was significantly greater in the low zone (30.4 animal units) than in the other research sites. Nevertheless, the annual net benefit was the lowest ($1053). The existing climatic variables in the 400–700 masl zone play an important role in the adequate management of cattle production, which is reflected in the annual income ($1053). If this value is transformed into a monthly income, farmers in this zone earned an average of USD 87.75, while households in the high zone, with an average of 24.3 animal units, annually earned USD 14735, which represents a monthly income of $ 1228 (Figure 2).

Identification of Best-Recommended Livestock BMPs

Table 24 shows the 16 BMPs evaluated under the six REDD+ actions and grouped by their contribution to improving livestock management (1), rehabilitating pastureland (2), promoting the reconversion of pasture areas (3), and implementing waste-management systems (4) in the three zones (Table 3). Likewise, the measures were classified as having high, medium, or low potential impacts. Thus, a practical and direct guide was proposed, where the higher-impact BMPs could be visualized (Figure 19).

Table 24. Livestock BMPs recommended and assessed along the elevational gradient.

Components	Best management practices (BMPs)	Low zone	Medium zone	High zone
1.Improvement of livestock management	Farm planning	✓✓✓	✓✓✓	✓✓✓
	Implementation of accounting registers	✓✓	✓✓	✓✓
	Implement compensation area	✓	✓	✓
	Implementation of fences with sheds	✓✓	✓✓	✓✓
	Improvement of animal diet with salt minerals and dietary supplements	✓✓✓	✓✓✓	✓✓✓
2. Rehabilitation of pasturelands	Planting of new trees in degraded and non-degraded pasturelands	✓✓✓	✓✓✓	✓✓✓
	Establishment of tree nucleation around grazing areas[1]	✓✓	✓✓	✓✓
	Establishment of live fences around grazing areas	✓	✓	✓
3. Pasture area restoration	Forest plantations	✓✓✓	✓✓✓	-
	Active restoration	✓✓	✓✓	-
	Passive restoration	✓✓	✓✓	-
	Agroforestry system	✓	✓	-
	Chakra system	✓✓✓	✓✓✓	-
4. Implementation of waste-management systems	Artisanal lombriculture	✓	✓	✓
	Compost area	✓✓✓	✓✓✓	✓✓✓
	Semi-artisanal biodigesters	✓✓	✓✓	✓✓

✓✓✓ High potential; ✓✓ Medium potential; ✓Low potential. [1]Vegetative propagation technique to speed up the process of succession through the use of tree and shrub stakes, creating vegetation clusters inside pasture areas.

Figure 2a shows that farm planning and accounting registers have high potential to achieve socio-economic benefits. The BMPs of the compensation areas present medium potential to achieve environmental co-benefits, avoid deforestation/degradation, reduce GHG emissions, and improve the soil carbon stock. The building of fences with sheds has medium potential to achieve all six benefits, particularly those related to deforestation and avoiding degradation.

Figure 2b shows that the rehabilitation of the pastureland component by planting new trees in degraded pasturelands has medium potential for all six benefits. The establishment of live fences around grazing zone areas has high to medium potential to achieve environmental, soil carbon stock, and socioeconomic benefits; improve the carbon stock; and reduce GHGs.

The component of pasture area restoration that includes the BMPs for promoting the reconversion of pasture areas to forest plantations has high potential to avoid degradation and deforestation. Likewise, the reconversion of pasture areas to chakra systems has high potential to contribute to all six benefits but primarily provides socioeconomic co-benefits. Finally, the reconversion of pasture areas to passive restoration has high potential to provide environmental co-benefits and improve the soil carbon stock (Figure 2c).

Among the BMPs related to the implementation of the waste-management system component shown in figure 2d, the compensation areas and the establishment of semi-artisanal bio-digesters have high potential to achieve environmental and socioeconomic co-benefits and low potential to avoid deforestation and degradation. Furthermore, the establishment of the compost area has medium potential for environmental and socio-economic co-benefits and, like other BMPs, low potential to avoid deforestation and degradation.

4.3.3 Discussion

Indigenous populations, who have experienced almost 60 years of colonization, ancestrally inhabited the area, which is considered to be a biodiversity “hotspot” under severe threat (Mittermeier et al., 1998; Myers et al., 2000). The current protection of the SBR promotes biodiversity conservation, sustainable development, education, and research as a means of reconciling humans and nature. The first settlements appeared 70 years ago in the high zone, 45 years ago in the low zone, and 35 years ago in the middle zone. The average age of the head of the household in the study area was over 50, a similar value to that of land-owning producers of small livestock species at low altitudes in Napo Province (Torres et al., 2018). The adoption of unsustainable productive dynamics similar to those of migrant settlers was observed (Sellers &

Bilsborrow, 2019; Vasco et al., 2018), which could be due to the proximity to roads and the market economy (Godoy et al., 1998; Vasco et al., 2018). However, it is important to consider the results of Torres et al. (2018), who reported that Kichwa households involved in livestock-based livelihood strategies obtain significantly lower incomes from this activity than migrant settlers. For household size, the values (5.3) were similar to those reported by Kichwa smallholders in the southern EAR (Vasco et al., 2018) and those reported in the Yasuni Biosphere Reserve (Heredia-R et al., 2020). These values were higher than those reported for Kichwa smallholder cattle ranching households in the central Andes of Ecuador (3.8) (Alvear et al., 2021b).

Sustainable production improvements have been widely studied (Boval et al., 2017; Foley et al., 2011; McGroddy et al., 2015). In this context, understanding the Best Management Practices (BMPs) for controlling and reducing natural resource degradation (forest, land, and water) is essential to design more sustainable systems. In Latin America, land-use change to grasslands has become one of the main causes of tropical forest destruction (Rodríguez et al., 2016). Through our analysis, we compared the livestock farming systems among different ecological zones in the Ecuadorian Amazon Region, linking these systems to economic performance. Then, we identified the best practices selected for each region. Lastly, we will discuss the assessment of best practices related to land-use changes, REDD+ actions, restoration of pasturelands, and co-benefits.

How and to What Extent BMPs Contribute to the REDD+ Approach and the Conversion of Pasturelands to Other Sustainable Uses

The BMPs were selected based on the following factors: (a) current deforestation trends considering increased demand for agricultural products (De-Pablos-Heredero et al., 2020); (b) the priorities of the Ministry of Environment and Water (MAAE) within the framework of the REDD+ action plan (MAE, 2016); and (c) the different incentive programs in Ecuador, such as ATPA, the MAAE's Socio Bosque Program, the MAAE, and MAG's program (ProAmazonia). All the identified BMPs were proposed based on their applicability and technical feasibility in the area, the availability of the facilities on their farms, the observation of major impacts from greenhouse gas reductions and carbon sequestration, and the presence of a direct contribution to economic and environmental co-benefits. These BMPs were divided into the four components assessed (Table 3) for improving livestock management. For BMP studies of cattle ranching, combining BMPs yielded the greatest change, since a combination of BMPs is always better than using a single type (Kroll & Oakland, 2019). In this context, farm planning and the implementation of accounting registers, compensation areas, cowsheds, and improvements in animal diet with salt minerals and dietary supplements should be most effective if a whole-farm management plan cannot be implemented with all the necessary BMPs. In the cattle ranching sector, the main contributions to sustainability come from the adequate use of economic and natural resources and the implementation of effective feeding strategies (Makkar, 2016). Sustainable development is important to understand the trade-off between farming profitability and environmental protection (Bardos et al., 2016).

Considering the best management practices to improve cattle-raising will contribute to the long-term sustainable development of farming (Martinho, 2019).

BMPs for the Rehabilitation of Pasturelands

We recommend improving grasslands using the BMPs, including planting trees, as well as using tree nucleation models and live fences to increase production and profits and reduce damage to the environment among households engaging in livestock-based livelihood strategies(Torres et al., 2018). On this issue, the livelihood approach could be used to identify the acceptance of producers to convert less efficient or abandoned pasture areas into more sustainable production systems, as proposed by Torres and others (Torres et al., 2018) in the same study area. The benefits of BMPs were related to increased pasture resistance, a greater number of animal units per hectare, higher cattle weight, the presence of continuous pasture, decreased feeding costs, and soil erosion (Borges et al., 2016). Using the recommended BMPs to recover pasturelands in the Amazon could help deflect the current pressure of establishing farmland, reduce deforestation and the emissions of GHGs, and increase the carbon stock.

These results are consistent with those of Fernandes and others (Fernandes et al., 2006), who highlighted the importance of rehabilitating pastureland based on its value for human use and ability to provide ecosystem services and carbon sinks.

Applying nucleation as a reforestation strategy can significantly improve forest diversity and structure, thereby increasing many ecological services (Corbin et al., 2016). For instance, by 2040, the adoption of sustainable pasture management in Brazil is projected to increase the productivity of pasture-based products by up to 50% (Strassburg et al., 2014).

Furthermore, the implementation of live fences to protect grazing areas as a BMP have productive and ecological benefits. Live fences can be a source of fodder, wild fruits, firewood, and carbon sequestration, while providing resources and acting as habitat for other animals.

As shown in similar studies in Central America (Harvey et al., 2005), the joint utility of live fences for production and biodiversity conservation should be the subject of greater research attention as a sustainable management strategy. An understanding of these factors could help policy makers to design new policies regarding the rehabilitation of pasturelands to improve socioeconomic constraints and handle degradation phenomena.

BMPs for Forest Restoration

Local people plant trees in association with food crops, thus creating resource agroforestry islands in open degraded pastures with more than 100 species (Fernandes et al., 2006) and reducing the amount of land in the livestock system—not only via intensification, as suggested by Green et al. (2005) and Phalan et al. (2011), but also due to soil impoverishment and degradation. Reforestation can, moreover, introduce economic development to deprived rural areas and create lasting livelihood benefits (Simo, 2020).

The BMPs suggested to promote the reconversion of pasture areas are recommended in the low and medium zones due to the socioeconomics and cultural characteristics of the areas. In these zones, the traditional agroforestry system known as Chakra uses locally adapted patterns of sustainable development and a strong interaction of cultural, biosocial, and environmental aspects embedded in the traditional Kichwa worldview (Coq-Huelva et al., 2017, 2018). However, rapid deforestation and a significant loss of biodiversity threaten the indigenous agroforestry systems and modify their socioeconomic and environmental conditions (Sherman et al., 2015).

Therefore, the restoration of pasture areas by afforestation as a BMP strategy in the framework of REDD+, and payment for ecosystem services (PES) provide an opportunity to improve the capacity of landscape carbon storage and create the conditions for re-establishing ecosystem services. In this regard, Knoke et al. (2014) suggested afforestation as the best option for local farmers to effectively integrate abandoned pasturelands into the production cycle with high socioeconomic and ecological value in southern Ecuador. Therefore, the prioritization of pasture areas for restoration is urgently needed; otherwise, due the lack of sustainable management, the degradation process will continue (Sattler et al., 2018).

Finally, in light of the results (Table 3 and Figure 2), we suggest the following: In the high zone, it is recommended to start with BMPs that contribute to improving livestock management and the rehabilitation of pasturelands. Additionally, in the medium and low zones, it would be easier to start with BMPs, with a focus on promoting the restoration of pasture areas and improving livestock management.

BMPs for Implementing Waste-Management Systems

The findings in this study show that the establishment of artisanal lombriculture, compost areas, and semi-artisanal biodigesters are BMPs that allow for adaptions able to improve the socioeconomic and environmental co-benefits for farm households. Furthermore, adaptive management allows the conservation of forests (Wilmer et al., 2018) and contributes to resilience towards adverse economic conditions (Sánchez-Romero et al., 2021). The best practices of waste-management systems are built from knowledge from social networks within and among communities (Bennett et al., 2017). However, livestock BMP research does not often integrate social or human factors. This study contributes to the understanding that socioeconomic and environmental benefits emerge from knowledge that allows adaptive learning, which influences farmers' decisions to implement different BMP strategies that can facilitate sustainable livestock intensification.

Policy Implications for Implementation

The evaluated BMPs could facilitate the development of mechanisms to improve existing national financial incentive programs related to livestock, as well as encourage public–private partnership structures and the roles they play as key local actors in potential REDD+ projects. Our findings could also facilitate discussions between impact investment funds and multilateral funders that have committed to support REDD+ projects. To this end, it will be necessary to develop partnerships for specific interventions among several stakeholders (Knoke et al., 2013; Santos Martin & van Noordwijk, 2011). However, it is also necessary to consider other factors such as technical assistance, livestock technologies, local capacity building, and off-farm employment to achieve the dual objectives of improving productivity through increased yields and releasing land for restoration purposes. The effectiveness of BMPs is often dependent on other factors, including proper installation and maintenance and the selection of appropriate practices for a given combination of households and farm characteristics. The development of a technical assistance package is proposed to ensure the full implementation of the 16 recommended BMPs.

Additional long-term analyses will be required to validate these assumptions and assess the technical and financial feasibility of implementing and monitoring these practices. In addition to their impacts on land-use change, a thorough analysis of the impact of changes in animal diet, as the most significant source of greenhouse gases (GHGs) from livestock activity, should be conducted.

4.4. Carbon stock assessment in silvopastoral systems along an elevational gradient: A study from cattle producers in the Sumaco Biosphere Reserve, Ecuadorian Amazon

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4.4.1 Introduction

Currently, silvopastoral systems (SPS) are the subject of multiple economic and conservation initiatives aimed at increasing the percentage of forest cover globally (Chapman et al., 2020; Munsell et al., 2022; M. M. Smith et al., 2022). This interest is associated with the fact that SPS contribute to greenhouse gas (GHG) reduction (Cusack et al., 2021). It is estimated that pasture lands account for around 3.87 Pg C in 1.89 billion ha, contributing significantly to mitigating the effects of climate change (Chapman et al., 2020).

Moreover, it provides economic benefits to low-income rural and peri-urban populations (da Silveira Pontes et al., 2021; M. M. Smith et al., 2022), and the potential related to timber sales, improving soil productive yields, ensuring access to food security in a climatically changing future and reducing deforestation rates (Conway & Nieman, 2022; Ferreiro-Domínguez et al., 2022).

However, mean surface temperature has increased by an average of 0.66 °C over the last 60 years (Valipour et al., 2021). This gradual increase has caused both humans and animals (cattle) to become susceptible to heat stress (McManus et al., 2022; Thornton et al., 2021), being this exposure strongly negative for the cattle production sector (Choudhary & Sirohi, 2022). In this sense, (Zeppetello et al., 2022) suggests that SPS contribute to temperature regulation through an average cooling between −0.32 °C to −2.4 °C in tropical areas used for these activities. Additionally, it has also been evidenced that cattle raised under a SPS exhibit better animal quality and body weight indexes compared to those managed under a traditional system

(Huertas et al., 2021). This is related to the fact that the SPS allows cattle to have space for shelter in extremely hot days, resulting in low exposure to heat stress and increased grazing and browsing activity (Huertas et al., 2021; McManus et al., 2022).

This research focuses on the Ecuadorian Amazon Region (EAR) in the Andean Amazon hotspot of biodiversity and endemism (Myers et al., 2000), with a high potential to provide ecosystem services to local populations (Mejía et al., 2015; Raven et al., 2020).

Nevertheless, the EAR has experienced significant deforestation process related to land use change for agriculture and pastures (Mena et al., 2006; R. Sierra, 2013b). Within the boundaries of the EAR, is located the Sumaco Biosphere Reserve (SBR), which is considered a biodiversity hotspot (Trew & Maclean, 2021). Large areas of native forests are found within the buffer and transition zones of the SBR, nonetheless, significant areas of pastureland in agricultural systems are also evident (Torres, Andrade, et al., 2022; Torres, Günter, et al., 2018).

Due to the ecological and cultural relevance of this area, it has been suggested to assess the implications of cattle ranching systems related to climate change mitigation, to promote incentives for best management practices (BMP) (Torres et al., 2021a; Torres, Andrade, et al., 2022).

Therefore, the main objective of this research was carbon stock assessment in silvopastoral systems in Ecuadorian Amazon, with three specific objectives: The first was quantify the soil and tree biomass carbon stored in traditional pasture with dispersed trees, along elevational gradient in the Ecuadorian Amazon. In the second objective the variation of the carbon stock in different components along elevational gradient was determined. Meanwhile, the third objective focused on determine the biomass Important Value (BIV) of dominant tree species in pasture systems along elevational gradient. Finally, the paper concludes with recommendations for decision-making aimed at improving livestock systems through a silvopastoral approach to contribute to nationally determined contributions (NDC) to the Paris Agreement goal of constraining global warming to less than 2 °C.

4.4.2 Results

The following sections describe the resulting values of (1) Floristic composition in pastures with dispersed trees, (2) Carbon stock in pastures with dispersed trees and pastures in monoculture system and (3) Biomass Importance Value (BIV) of the dominant tree species in the pasture systems, distributed along the elevational gradients.

Floristic Composition in Pasture with Dispersed Trees

Table 2 shows that mean tree species richness decreased significantly with increasing elevation, but significant differences ($p < 0.01$) were only detected between the lowlands and high mountains. The average tree density (Trees ≥ 10 cm DBH per ha^{-1}) along gradients ranged from 193 (lowlands) to 83.25 (middle hills), with significant differences ($p < 0.01$) registered between lowlands and middle hills, high mountains (Table 2). Both basal area and average DBH showed no significant variation along the gradient. In the lowlands basal area was the highest (8.67 m^2) and high mountains average DBH was 22.85.

Carbon Stock in Pasture with Dispersed Trees and Pasture in Monoculture System

In the pastures with trees scenario (Table 25), there were significant differences at $p < 0.01$ between lowlands and high mountains, in the variables AGB_{trees}, AGC_{trees}, BGB_{tres}, BGC_{trees} y C_{Soil} 10–30 cm, with values of 51.84 (Mg ha^{-1}), 24.35 (Mg ha^{-1}), 15.56 (Mg ha^{-1}), 7.31 (Mg ha^{-1}) and 11.97, respectively, and there were no significant differences (0.01%) in lowlands and middle hills for the variables $AGB_{Pasture}$ y $AGC_{Pasture}$; while the variables C_{Soil} (0–10 cm) and total carbon stock showed no significant differences among the altitudinal gradient.

Table 25. Means (±standard deviation) aboveground biomass (AGB), aboveground carbon (AGC), belowground biomass (BGB), belowground carbon (BGC), aboveground biomass of pasture (AGBPasture), aboveground carbon of pasture (AGCPasture), and total carbon pools along the elevational gradient of the SBR, Ecuadorian Amazon.

Variables	**Lowlands N = 27**	**Middle Hills N = 23**	**High Mountains N = 21**	**Total Average N = 71**	[1] ***p*-Value**
		Pasture with trees (PWT)			
AGB_{trees} (Mg ha^{-1})	87.57 ± 45.31 ^{a}	56.47 ± 43.57 ^{ab}	35.73 ± 29.93 ^{b}	66.03 ± 45.67	**
AGC_{trees} (Mg ha^{-1})	41.14 ± 21.30 ^{a}	26.54 ± 20.48 ^{ab}	16.79 ± 14.07 ^{b}	31.03 ± 21.46	**
BGB_{roots_trees} (Mg ha^{-1})	26.27 ± 13.59 ^{a}	16.94 ± 13.07 ^{ab}	10.71 ± 8.97 ^{b}	19.81 ± 13.70	**
BGC_{roots_trees} (Mg ha^{-1})	12.34 ± 6.39 ^{a}	7.96 ± 6.14 ^{ab}	5.03 ± 4.22^{b}	9.30 ± 6.44	**
$AGB_{litter+pasture}$ (Mg/ha^{-1})	6.55 ± 1.53 ^{a}	6.92 ± 2.53 ^{a}	2.85 ± 0.31 ^{b}	5.80 ± 2.36	***
$AGC_{litter+pasture}$ (Mg/ha^{-1})	3.27 ± 0.77 ^{a}	3.46 ± 1.26 ^{a}	1.43 ± 0.15 ^{b}	2.90 ± 1.18	***
C_{soil} 0–10 cm	35.44 ± 9.57	42.94 ± 13.85	35.52 ± 16.11	37.76 ± 12.58	n/s
C_{soil} 10–30 cm	20.60 ± 12.67 ^{a}	28.10 ± 6.02 ^{ab}	32.57 ± 12.10 ^{b}	25.67 ± 11.64	**
Total carbon stock	112.80 ± 41.51 ^{a}	108.99 ± 31.43 ^{a}	91.34 ± 28.46 ^{a}	106.67 ± 35.68	n/s

Pasture in monoculture (PM)					
$AGB_{litter+pasture}$ (Mg/ha^{-1})	8.36 ± 2.65 [a]	4.54 ± 2.41 [b]	3.68 ± 1.95 [b]	5.52 ± 3.08	***
$AGC_{litter+pasture}$ (Mg/ha^{-1})	4.18 ± 1.33 [a]	2.27 ± 1.21 [b]	1.84 ± 0.97 [b]	2.76 ± 1.54	***
C_{Soil} 0–10 cm	30.08 ± 7.63	40.13 ± 16.15	31.61 ± 13.89	33.94 ± 13.52	n/s
C_{Soil} 10–30 cm	18.27 ± 6.48 [a]	35.41 ± 11.82 [b]	37.60 ± 16.95 [b]	30.42 ± 15.01	***
Total carbon stock	52.53 ± 13.55 [a]	77.80 ± 21.09 [b]	71.04 ± 29.23 [ab]	67.12 ± 24.26	**

[1] *p*-Value: ** $p < 0.05$; *** $p < 0.01$; n/s = not significantly differences. [a, b] Within row, averages with different superscript differ significantly

In the monoculture pasture scenario, there were significant differences ($p < 0.01$) in the variables $AGB_{litter+pasture}$, $AGC_{litter+asture}$ and C_{Soil} (10–30 cm); the average $C_{\mathbf{Soil}}$ (0–10 cm) was 33.94 with no significant difference among altitudinal gradients, but total carbon stock showed a significant difference ($p < 0.05$) of 25.27 between lowlands and middle hills and an overall average of 67.12.

Variation in Carbon Stock in Different Components along the Elevational Gradient

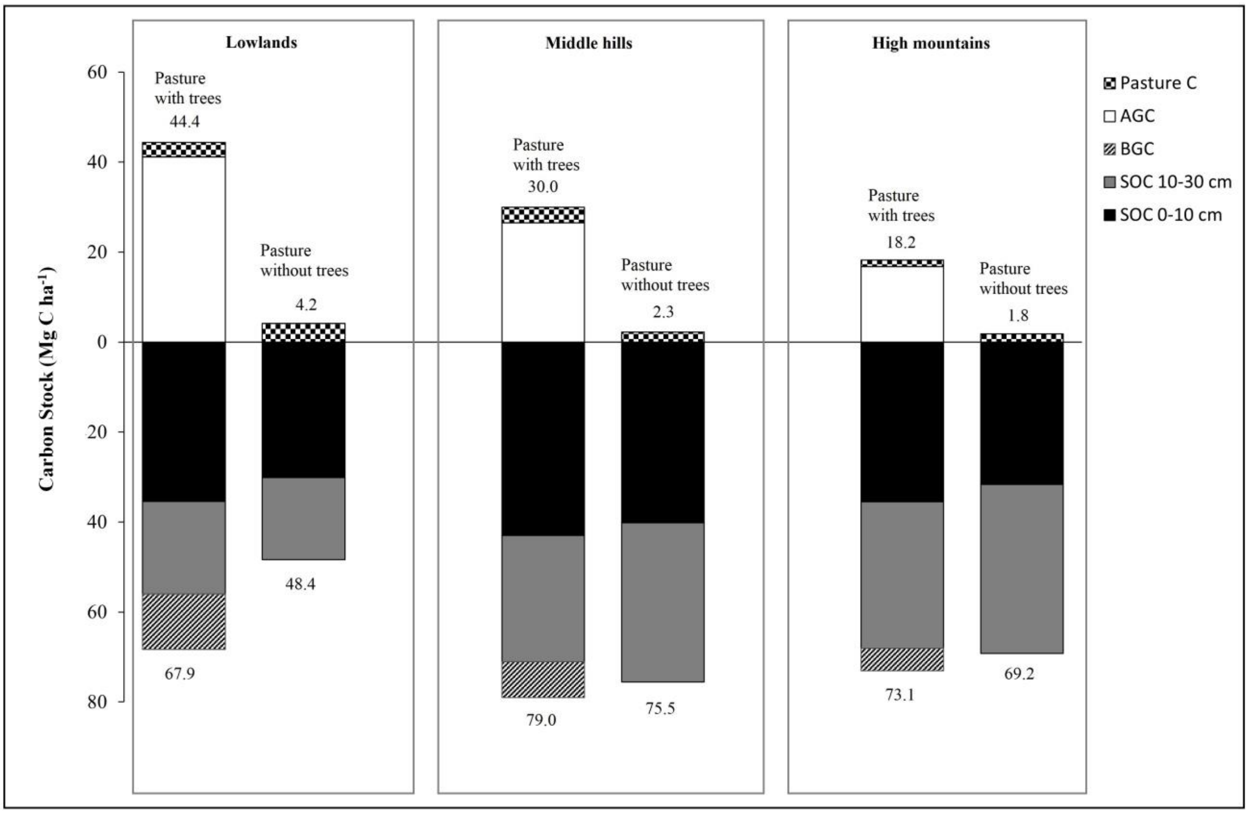

Figure 22. Total carbon stock (Mg ha−1) for each of the three elevational gradient studied pasture systems.

Table 25 and Figure 22 show that in the superficial horizon pastures with trees, the average carbon sequestration ranged from 35.44 to 42.94 Mg C ha^{-1} along the altitudinal gradient without significant differences ($p < 0.05$), while for the second horizon (10–30 cm) a decrease was observed with respect to the superficial horizon with significant differences ($p < 0.005$) along the altitudinal gradient and with higher values in the high zone (32.57 Mg C ha^{-1}).

Regarding the pasture without trees or monoculture, the carbon stored both in litter and pasture shows a slight decrease as the altitudinal gradient increases. While carbon sequestration in the first horizon (0–10 cm) reached 30.08, 40.13 and 30.61 Mg C ha^{-1} for lowlands, middle hills, and high mountains, respectively. In the second horizon (10–30 cm depth), the middle hills and high mountains showed the significantly higher values with respect to the lowlands with ranges of carbon stored from 20 to 32 Mg C ha^{-1} (Table 3).

Furthermore, it was found that the carbon stored in the soil (0–10 and 10–30 depth) in pastures with trees represents between 49 and 74% of the total carbon stored (TCS), while for pastures without trees it represents between 92 and 97%, evidencing the role of the soil resource in providing regulating ecosystem services.

Biomass Important Value (BIV) of Dominant Tree Species in Pasture Systems

Along the grandient, Jacaranda copaia (lowlands), Nectandra spp. (middle hills), Ficus sp. (high mountains); were the most abundant species and the BIV values were ascending (11.66%, 12.41% and 22.96%), with respect to elevation (Table 4).

Some of the less abundant tree species contributed a high percentage of the AGB (carbon stock): Cordia alliodora 11.47% (400–700 masl), Ficus maxima 18.45% (701–1600 masl) and Ficus sp. 27.35% (1601–2000 masl) (Table 4). The results also showed that the 10 species with the highest BIV contributed between 69.59% (lowlands), 75.81% (middle hills) and 85.34% (high mountains) of the total AGB stored in the altitudinal gradient studied (Table 26).

Table 26. Density, basal area, live above-ground biomass (AGB) and Biomass Importance Value (BIV) of the most frequent tree species in pasture with trees along the study gradient. Napo, RBS, Ecuadorian Amazon.

Family	Species	N (%)	BA (%)	AGB (%)	BIV* (%)
		Lowlands (400–700 masl)			
Bignoniaceae	*Jacaranda copaia*	18.40	11.34	5.24	11.66
Cordiaceae	*Cordia alliodora*	1.74	8.09	11.47	7.10
Vochysiaceae	*Vochysia braceliniae*	9.72	6.36	4.52	6.87
Myrtaceae	*Psidium guajava*	5.56	6.95	7.66	6.72
Melastomataceae	*Miconia* spp.	4.17	4.85	5.93	4.98

Myristicaceae	*Virola flexuosa*	3.47	4.89	6.33	4.90
Fabaceae	*Piptadenia pteroclada*	2.78	3.74	4.74	3.75
Urticaceae	*Cecropia membranacea*	2.78	4.43	3.39	3.53
Meliaceae	*Cedrela odorata*	0.69	3.76	5.30	3.25
Lauraceae	*Ocotea* spp.	2.43	3.81	2.72	2.99
Subtotal		71.88	72.01	69.59	71.16
Middle hills (701–1600 masl)					
Lauraceae	*Nectandra* spp.	8.66	10.82	17.74	12.41
Moraceae	*Ficus maxima*	1.40	11.93	18.45	10.59
Cordiaceae	*Cordia alliodora*	6.42	14.39	6.63	9.15
Lauraceae	*Ocotea* spp.	6.98	6.64	11.43	8.35
Asteraceae	*Piptocoma discolor*	8.94	7.21	7.60	7.91
Fabaceae	*Inga* spp.	11.17	5.75	3.55	6.83
Burseraceae	*Protium nodulosum*	3.91	4.94	4.67	4.51
Burseraceae	*Dacryodes peruviana*	4.47	4.77	3.70	4.31
Meliaceae	*Cedrela odorata*	8.66	2.82	1.39	4.29
Myrtaceae	*Psidium guajava*	5.59	0.97	0.66	2.41
Subtotal		66.20	70.24	75.81	70.75
High mountains (1601–2000 masl)					
Moraceae	*Ficus* sp.	3.52	38.02	27.35	22.96
Lauraceae	*Nectandra* spp.	10.56	12.62	17.75	13.64
Malvaceae	*Heliocarpus americanus*	12.61	11.81	10.73	11.72
Myrtaceae	*Psidium guajava*	19.06	3.52	3.15	8.58
Fabaceae	*Inga* spp.	13.49	4.89	4.80	7.73
Lauraceae	*Ocotea* spp.	6.74	4.96	6.29	6.00
Burseraceae	*Dacryodes peruviana*	5.57	3.52	4.39	4.49
Meliaceae	*Cedrela montana*	1.17	4.34	6.13	3.88
Moraceae	*Brosimum* sp.	0.59	2.36	4.48	2.47
Arecaceae	*Wettinia* sp.	5.87	0.57	0.26	2.23
Subtotal		79.18	86.61	85.34	83.71

N = Density. BA = Basal area. AGB = Above-ground biomass. * Biomass importance value (BIV) = relative mean of (N+BA+AGB)/3 (Torres, Vasseur, et al., 2020)

4.4.3 Discussion

Regardless of the altitudinal gradient, the results of this study reflect the existence and permanence of the main tree species (Table 4) and the strong potential of silvopastures throughout the EAR for carbon sequestration in both soil and biomass, which is associated with different factors such as climate (tropical hyper-humid) (Phillips et al., 2019; Salinas et al., 2011), vegetation (Pietsch et al., 2014), biogenic macroaggregates (Silva Neto et al., 2016) and some land uses prevailing in this area such as traditional agroforestry systems (chakra and pasture with trees) that maintain high concentrations of organic carbon in the soil (Bravo et al., 2021; L. Rodríguez et al., 2021; Torres, Andrade, et al., 2022; Torres, Vasseur, et al., 2020). However, it is important to consider that the altitudinal gradient studied presents high precipitation with average values ranging from 2025 to 5209 mm (Figure 2) without any seasonality. This situation, unlike other typical lowland tropical ecosystems, ensures that fire in this area is not used as a pasture management practice (McGroddy et al., 2015), which is considered an advantage in the ecosystems studied, since fire minimizes carbon stocks mainly in soils (Mataix-Solera & Cerdà, 2009; Y. Zhou et al., 2022).

Carbon Biomass

We documented high richness and density of tree species in Lowland zone with respect to the Middle hill and High mountain zones. With the exception of the lower zone where we obtained the highest richness, this was similar with the species richness found in four communities in Southeastern Ecuador (McGroddy et al., 2015). But this decreasing pattern of tree species richness is opposite to the patterns found in a forest in the same area specifically in the Ecuadorian Amazonian Andean evergreen forest (Torres et al., 2020). This could be due to management activities (Feliciano et al., 2013), and the fact that in the high zones cattle ranching started over 70 years ago and ranchers have smaller parcel sizes using more intensive cattle ranching, leaving few trees for cattle shade; in comparison to the middle and low zones where cattle ranching started around 40 and 50 years ago respectively and producers experiment a very extensive cattle ranching allowing more trees in pastures (Torres et al., 2022).

The difference in species richness and tree density along the altitudinal gradient has resulted in significant differences in the amount of AGC_{trees} in the studied silvopastoral systems (Table 3), showing similar patterns to tree abundance, with the highest carbon stocks (41.14 Mg ha^{-1}) in the lower zone compared to 26.54 and 16.79 Mg ha^{-1} in the Middle and High mountain zones respectively, these quantities are similar to those found in SPS in Southeastern

Ecuador between 6.8 to 40.8 Mg ha^{-1} (McGroddy et al., 2015), as well as in Mexico (29.1 Mg ha^{-1}) by López-Santiago et al. (2019) and in Colombia (31 Mg ha^{-1}) (Aynekulu et al., 2020). AGC_{trees} sequestration potential of silvopastoral systems depends on the plant characteristics (tree species, age, crops, biodiversity, and tree density), structural characteristics and management factors such as regeneration and harvesting regimen, etc. (Feliciano & Sobenes, 2022; Yang et al., 2019), and for this case the historical and current land use surrounding the silvopasture also plays an important role in carbon sequestration. Thus, the carbon stored in these SPS, especially in lowland and middle hill zones, corresponds to approximately 28% and 18% respectively of the total carbon stored in a primary forest in the same area, reported in a range of 124 to 160 Mg ha^{-1} (Torres et al., 2020).

This study has found that the transition from pasture monoculture to silvopasture has great potential for accumulate and sequester carbon in all components of the system. This benefit for increasing carbon stocks is very clear for above and bleove ground carbon, where further research is needed, given that our study was carried out in a single determined period, it is recommended to perform longitudinal studies in order to determine how much time tree species need to regenerate in these systems, as well as the carbon accumulation rates. These systems must be reinforced with technological alternatives and best management practices (BMPs) (Torres et al., 2021a) to reduce deforestation in tropical areas (Murthy et al., 2013) and might also bring important benefits in terms of climate change adaptation (Feliciano & Sobenes, 2022).

Dominant Tree Species

Using the biomass importance value index (BIV) proposed by (Torres et al., 2020), it is evident that the species Jacaranda copaia, Cordia alliodora, Vochysia braceliniae, and Psidium guajava obtained the highest BIV in the lowland zone, the first three species are of high commercial value and the fourth are of high nutritional value (Álvarez et al., 2021; Jernigan, 2006; Montagnini et al., 2003). In the middle hills zone, the species with the highest BIV were Nectandra spp. Ficus maxima, Cordia alliodora and Ocotea spp., the four species are of high commercial value and the last one high potential for the extraction of essential oils (Oza & Kulkarni, 2017; Passos et al., 2021; Salehi et al., 2021) as well. In the High mountain zone, the species with the highest VIB were Ficus sp., Nectandra spp., Inga spp., and Ocotea spp. (Table 4).

These are also species of high commercial value, while the Inga spp. provide food and incorporate nitrogen into the soil (Duchicela et al., 2022; Huera-Lucero et al., 2020; Palacios

Bucheli et al., 2021); evidencing that the most common tree species found throughout the altitudinal gradient are of interest to provide shade, food and commercial timber similar to the findings of (Lerner et al., 2015), and they are part of the native tree diversity, this could be due to the fact that the producers in the study area still have between 17% and 40% of remaining forests in the surroundings of the pastures (Torres et al., 2022).

Our study however indicated that the least abundant tree species in silvopastoral systems, such as Ficus sp., Cedrela odorata, Cedrela montana, Cordia alliodora, Nectandra spp., Brosimum sp. at the various elevations, could significantly contribute to the aboveground biomass and consequently to carbon storage along the elevation gradient.

Soil Organic Carbon Pools

Landscape variability in the evaluated gradient also shows different levels of biodiversity and carbon stored, which is associated with organic matter content, climatic conditions, soil texture, site management, vegetation type, land use history, etc. (Deng et al., 2016). In this study, pastures with trees presented a greater amount of leaf litter, which is associated with a greater contribution of organic matter, which reaffirms the theory that the quantification of the organic matter cycle is an important indicator of the agricultural potential of soils (Tiessen et al., 1994), given the identification of soil quality, structural indices such as bulk density, hydraulic conductivity and aeration porosity (Bravo et al., 2021).

Concerning EAR, some studies in pasture with and without trees report values ranging from 36 to 49 Mg C ha^{-1} (Bravo, Torres, Alemán, Changoluisa, et al., 2017) in depths up to 30 cm, although some studies found that soil organic carbon stocks ranged from 85.0 to 97.6 Mg ha^{-1} (McGroddy et al., 2015), which is associated with the historical use of the forest where high biomass content has been generated, fertility improvement that has allowed a high accumulation of organic matter (Bravo et al., 2021; Torres et al., 2020). Despite the background of forested areas in the EAR, the conversion of forests to livestock systems represents a decrease in soil carbon stocks, with a higher proportion in those pasture systems without trees (29%) with respect to pastures with trees (4%) (Bravo, Torres, Alemán, Changoluisa, et al., 2017). Similar results have been reported by other researchers who found a decrease in soil carbon stock from 8 to 42% when conversion occurs from forest to livestock and cropping systems (Bravo et al., 2021).

Globally, it has been noted that soil carbon sequestration shows a negative correlation with initial carbon stocks and the effects of climatic factors (mean annual temperature and mean annual precipitation) on C sequestration may vary among land use conversion types (Deng et al., 2016). In this regard, it has been noted that the critical level of C input requirements to maintain SOC at levels above 10 Mg C ha^{-1} ranges from 1.1 to 3.5 Mg C/ha/yr and differs according to soil type and production systems (Lal, 2015).

Importantly, that similarities in underlying parent materials, topography, soil textures, bulk densities, as well as the fact that differences were most pronounced in the shallow horizon (0–10 cm depth), support the notion that management activities constitute the most relevant factor for the observed differences in soil carbon (Yang et al., 2019).

The soils of the Ecuadorian Amazon region are relatively undeveloped with a predominance of the Inceptisols and Andisols orders, with high organic matter content (Bravo, Torres, Alemán, Changoluisa, et al., 2017), the climate exerts on edaphogenesis a primary influence that favors the leaching of bases (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}), which induces a predominance of poorly alterable minerals and simple clays such as quartz, kaolinite, gibbsite and iron oxides, conferring them certain morphological characteristics and the decrease of parameters associated to fertility with low cation exchange capacity, poor in phosphorus and mainly acid pH with high potential for aluminum toxicity (Bravo et al., 2021; Custode & Sourdat, 1986; Gardi et al., 2014). These soil conditions are also characteristic of highly weathered Oxisols and Ultisols that dominate the Neotropics (McGroddy et al., 2015).

In this context, given the size of soil organic carbon stocks in these systems, a better understanding of how human activities influence soil carbon concentrations and stability would be essential to manage carbon balances more accurately.

4.5. Structure and above ground biomass along an elevation small-scale gradient: case study in an Evergreen Andean Amazon Forest, Ecuador

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4.5.1 Introduction

The Amazon Basin is a reservoir with great ecological diversity. It constitutes 50% of existing forests and plays a strategic role in carbon sequestration. Due to its quantitative and qualitative importance, any type of disturbances to the ecosystem generates environmental damage and affects the carbon cycle (Wang et al., 2014). Tropical forests have high biomass productivity and represent a significant fraction of total stocks of carbon and nutrients (I. F. Brown et al., 1995; Y. Pan et al., 2011; Phillips et al., 1998). There are still insufficient studies on their production and their influence on carbon stock (Chave et al., 2005). Biomass is a key ecosystem function (Fahey & Knapp, 2007) that results from the mass balance between productivity (photosynthesis and seed germination) rate and loss through respiration and mortality (Keeling & Phillips, 2007). The level of tree biomass production is unknown in most tropical regions, which limits the valuation and conservation efforts of these ecosystems. This may be partly due to the scarcity of estimates of live biomass and their high level of variability among regions (Houghton et al., 2009).

In this context, quantification of biomass provides important information for understanding the responses of vegetation to local and global climate and environmental changes (Eisfelder et al., 2017; Verón et al., 2011). Biomass estimates in tropical forests, like the Amazon, can help assess forest carbon reserves and emissions to the atmosphere during deforestation and changes in land cover as well as implications at the global level (Malhi & Grace, 2000). Studies have shown that estimating carbon reserves, for example, can help define sensitive indicator of environmental change and ecological functioning (Cardinale et al., 2011; Poorter et al., 2015).

Moreover, it is well reported that the structure and biomass of tropical rainforests greatly vary due to ecological, physical, and chemical factors, especially at the microscale (Moser et al., 2011). Increased elevation can affect tree growth rates and biomass production because of decline in temperature at higher elevation, changes in precipitation, and variation in soil nutrient composition (Coomes & Allen, 2007; Körner, 2007; Moser et al., 2011).

Studies conducted along tropical mountain slopes have indicated a decrease in tree height (Aiba & Kitayama, 1999) and an increase in tree density with elevation (Moser et al., 2011). Most of these studies, however, targeted a relatively large scale gradient: for example, from 1050 to 3060 m along an altitudinal transect in the South Ecuadorian Andes (Leuschner et al., 2007), and in the northeast region of Ecuador (Kitayama & Aiba, 2002; Leuschner et al., 2007; Moser et al., 2011).

Very few studies have examined the variation in tree communities and their contributions to biomass and carbon storage at the small-scale elevation gradient. In that vein, this study was carried out in an important ecosystem in the Amazonian foothills, situated in the province of Napo from 601 to 1000 m above sea level (m.a.s.l.).

The study area is considered to be a mega diverse site as it is part of the hotspot called the Uplands of Western Amazonia (Myers, 1988; Myers et al., 2000). Unfortunately, the area is under severe threats (Mittermeier et al., 1998) due to colonisation leading to high rates of deforestation and land use changes including road construction that facilitates agriculture and livestock expansion in frontier forest areas (Torres et al., 2018a,b), band timber logging (Mejía et al., 2015; Vasco et al., 2017). Oil exploration and exploitation in the northern Ecuadorian Amazon region (Bilsborrow et al., 2004; Finer et al., 2008; Mena et al., 2017; Torres et al., 2014) and exploitation of gold mines further threatens this fragile ecosystem. As a result of these activities, whilst from 1990 to 2000 deforestation rate in the province of Napo increased by 0.47%, between 2000 and 2008 this rate increased to 0.83% (MAE, 2013).

Given the ecological changes and increased deforestation rate occurring in this region, our main objective was to better understand the contribution of these forests to the country's and world carbon storage by analysing tree richness by family, community structure, and above-ground tree biomass along a small-scale elevation gradient in an evergreen forest in the foothills of the Ecuadorian Amazon region (EAR). The expectation was to contribute data that can support the conservation efforts necessary for the protection of native tree species and carbon storage in this fragile.

4.5.2 Results

Floristic composition

A total of 1378 trees (C 10 cm in DBH) corresponding to 50 families and 177 tree species were recorded in these 20 plots. Families of trees with highest species richness along the entire small-scale gradient were Moraceae (17 species), Fabaceae (16), Meliaceae (10), Cecropiaceae (10), Euphorbiaceae (9), Arecaceae (7), Annonaceae (7), Clusiaceae (6), Rubiaceae (6), and Myristicaceae (6). No species was found to be present in all four elevations, suggesting that even at the micro-scale, species diversity can greatly vary.

As depicted in Table 27, mean tree species richness appeared to increase with increasing elevation although significant differences (P \0.01) were only detected between EAAF1 and EAAF4. Mean stem density (stems C 10 cm in DBH per ha-1) along the gradient ranged between 576 (EAAF1) and 772 (EAAF3), with significant differences (P \0.05) recorded between EAAF1 and, EAAF3 and EAAF4 (Table 2). The tree biomass (AGB) along the elevation small-scale gradient ranged from 246.8 to 320.9 Mg ha-1 (Table 2) and did not significantly vary along the gradient.

Table 27. Means and standard deviations of richness, forest structural characteristics and total live above-ground biomass (AGB), along the small-scale elevation gradient.

Variable	m.a.s.l					
	EAAF1	EAAF2	EAAF3	EAAF4	F value	*P*
Richness (S) (0.1 ha^{-1})	23.80 ±4.08^{a}	28.00 ±3.08^{ab}	27.40 ±0.89^{ab}	32.00 ±3.39^{b}	5.860	0.007
Stem density (1 ha^{-1})	576.0 ±8.73^{a}	676.0 ±13.06^{ab}	772.0 ±11.60^{b}	732.0 ±7.72^{b}	3.273	0.049
Basal area (m^2 ha^{-1})	27.39 ±0.88	34.11 ±0.91	34.52 ±0.67	31.24 ±0.44	0.941	0.437
Average DBH (cm)	21.80 ±1.70	22.13 ±2.87	20.65 ±0.90	20.51 ±1.38	0.949	0.440
Maximal DBH (cm)	84.99	108.00	124.77	69.07	-	-
Total AGB (Mg ha^{-1})	246.80 ±104.94	320.92 ±97.45	307.06 ±77.42	291.88 ±64.04	0.677	0.579

Values within a row with different letters indicate significant differences (P<0.05) between elevations (601 to 1000 m.a.s.l.) according to a Tukey post-hoc test.

Structural characteristics and Above-Ground Biomass (AGB)

Irrespectively of altitude, and as expected, trees of smaller diameters (10 to ≤30 cm) had the highest densities (Figure 23A). The three classes of diameters showed no significant variation along the elevation gradient. As well, the average AGBs calculated by diameter class did not significantly vary along the four elevations (Figure 23B).

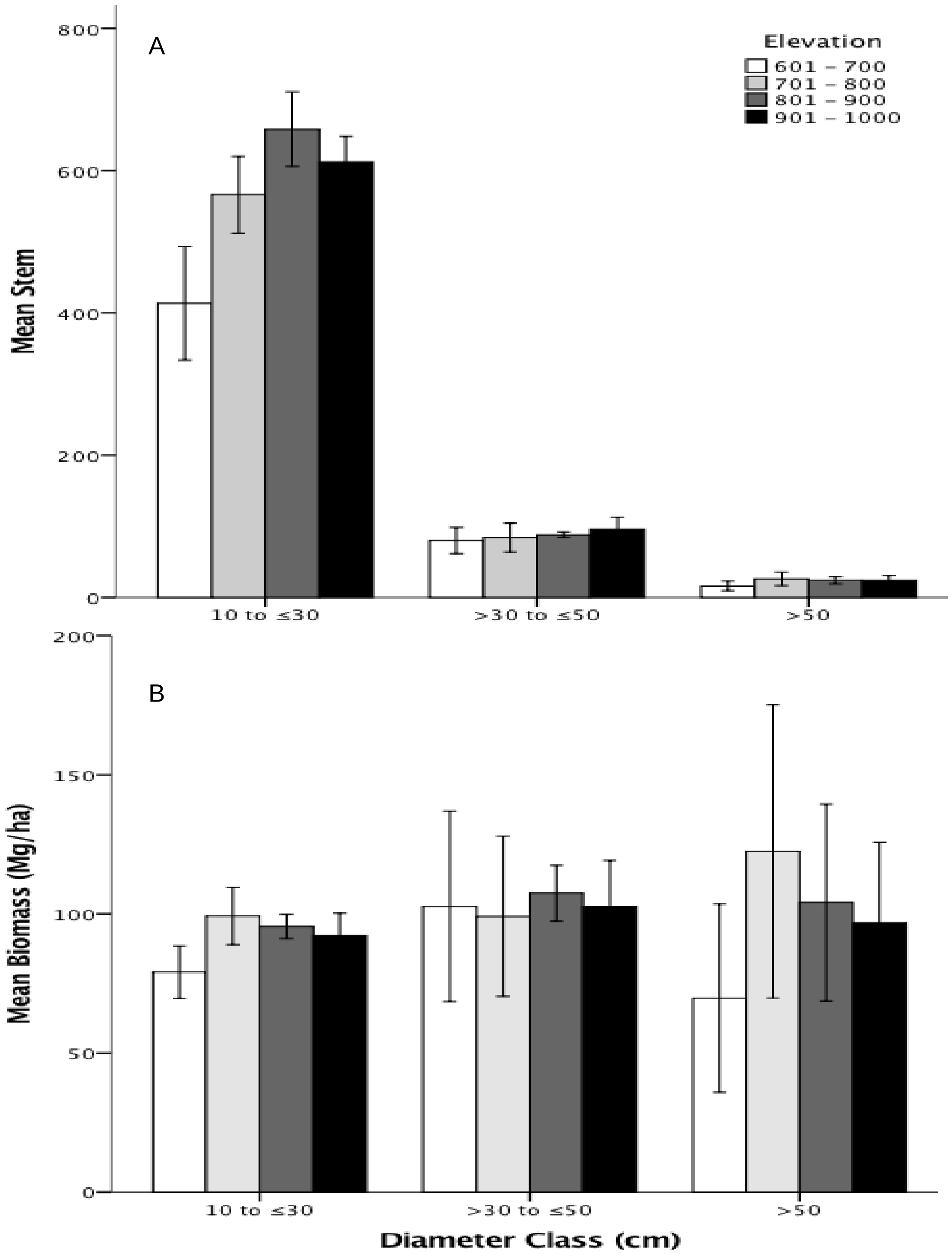

Figure 23. Means of: (A) stems (ha-1) and (B) Above ground biomass (Mg ha-1) by groups of diameter sizes (DBH cm) along the elevation small-scale gradients.

Biomass Importance Value (BIV)

In three of the four elevations, *Irealtea deltoidea* was the most abundant species in three of the four elevations and had the highest BIV with values varying from 11.66% in EAAF1 plots (600-700 m.a.s.l.) to 4.64% in EAAF4 plots (901-1000 m.a.s.l.).

Some of the least abundant tree species contributed with a high percentage of the AGB (carbon stock) in this survey: *Sterculia* sp. 11.4 % (601-700 m.a.s.l.) *Nectandra* sp. 12.1 % (701-800 m.a.s.l.), *Ficus* sp. 15.4 % (801-900 m.a.s.l.), and *Inga* sp. 9.3 % (901-1000 m.a.s.l.) and therefore had high BIV values along the gradient. Results showed that the 10 highest AGB species contributed between 41.5 and 55.7% of the total AGB stored in this Evergreen Andean Amazon forest (Table 28).

Table 28. Density, basal area, live above-ground biomass (AGB) and biomass importance value (BIV) of the most important tree species along the study gradient, ordered according the BIV in each elevation.

Family	Species	N (%)	BA (%)	AGB (%)	BIV* (%)
EAAF1 (601-700 m.a.s.l.)					
Arecaceae	*Iriartea deltoidea*	18.40	11.34	5.24	11.66
Malvaceae	*Sterculia* sp.	1.74	8.09	11.47	7.10
Lauraceae	*Ocotea aciphylla*	9.72	6.36	4.52	6.87
Lauraceae	*Nectandra* sp.	5.56	6.95	7.66	6.72
Myristicaceae	*Otoba parvifolia*	4.17	4.85	5.93	4.98
Vochysiaceae	*Erisma uncinatum*	3.47	4.89	6.33	4.90
Meliaceae	*Guarea macrophylla*	2.78	3.74	4.74	3.75
Vochysiaceae	*Vochysia ferruginea*	2.78	4.43	3.39	3.53
Myristicaceae	*Virola* sp.	0.69	3.76	5.30	3.25
Urticaceae	*Cecropia obtusifolia*	2.43	3.81	2.72	2.99
Subtotal		33.34	58.22	57.3	55.75
EAAF2 (701-800 m.a.s.l.)					
Arecaceae	*Iriartea deltoidea*	18.34	9.89	4.41	10.88
Lauraceae	*Nectandra* sp.	2.96	8.61	12.16	7.91
Urticaceae	*Cecropia sciadophylla*	4.44	7.13	4.55	5.37
Euphorbiaceae	*Croton matourensis*	0.89	4.61	6.01	3.84
Moraceae	*Ficus* sp.	1.18	4.33	4.68	3.40
Fabaceae	*Inga* sp.	4.14	2.28	1.87	2.76
Fabaceae	*Dussia* sp.	0.30	2.80	4.93	2.68
Myristicaceae	*Virola* sp.	4.14	1.92	1.28	2.45
Compositae	*Pollalesta discolor*	1.78	2.26	2.54	2.19
Fabaceae	*Pterocarpus* sp.	1.48	2.31	2.58	2.12
Subtotal		21.31	46.14	45.01	43.6
EAAF3 (801-900 m.a.s.l.)					
Arecaceae	*Iriartea deltoidea*	15.63	10.69	5.80	10.70
Moraceae	*Ficus* sp.	3.65	11.43	15.42	10.16
Myristicaceae	*Otoba glycycarpa*	3.91	5.51	4.02	4.48
Lauraceae	*Nectandra* sp.	3.65	3.55	3.59	3.59
Myristicaceae	*Virola* sp.	1.82	3.38	4.10	3.10
Urticaceae	*Cecropia sciadophylla*	3.65	3.32	1.93	2.96

Meliaceae	*Guarea* sp.	2.34	2.72	3.53	2.86
Rubiaceae	*Psychotria* sp.	2.60	1.39	1.03	1.67
Vochysiaceae	*Vochysia* sp.	1.30	1.91	1.43	1.55
Burseraceae	*Protium* sp.	1.82	1.30	1.04	1.39
Subtotal		24.74	45.2	41.89	42.46
EAAF4 (901-1000 m.a.s.l.)					
Arecaceae	*Oenocarpus bataua*	4.92	9.06	5.40	6.46
Fabaceae	*Inga* sp.	3.01	6.75	9.27	6.34
Myristicaceae	*Otoba glycycarpa*	6.56	7.80	4.51	6.29
Compositae	*Pollalesta discolor*	1.91	6.00	8.32	5.41
Fabaceae	*Dussia* sp.	1.09	5.20	7.96	4.75
Arecaceae	*Iriartea deltoidea*	7.92	4.26	1.74	4.64
Meliaceae	*Guarea* sp.	2.19	2.97	4.33	3.16
Burseraceae	*Dacryode* sp.	0.55	1.94	2.70	1.73
Euphorbiaceae	*Croton matourensis*	0.27	1.80	2.27	1.45
Lauraceae	*Nectandra* sp.	2.19	1.03	0.72	1.31
Subtotal		25.69	46.81	47.22	41.54

N = Density. BA = Basal area. AGB = Above-ground biomass
*Biomass importance value (BIV) = relative mean of (N+BA+AGB)/3

4.5.3 Discussion

The floristic and structural characteristics of this forest along a small-scale elevation gradient showed a great level of spatial heterogeneity. Moraceae and Fabaceae were the most species-rich families in our study. This was consistent with ter Steege et al. (2000) and Gentry (1988) who report that Leguminosae is a species-rich family in neotropical primary forests, whilst on rich soils, Moraceae becomes very diverse (Gentry, 1988).

Forests situated between 500 and 3,500 m in elevation (Killeen, 2007), especially and lower montane forest communities (Gentry, 1988, 1992), are considered the most biologically diverse habitats within the Andes Mountains. The tree floristic composition recorded in this study confirmed this report, with a significant increment in tree species richness along the small-scale elevation gradient. However, this high level of diversity is threatened by increased deforestation and forest fragmentation strongly related to the expansion of the extractive frontiers (Finer et al., 2008; Mena et al., 2017; Pan et al., 2007), as well as for timber logging (Mejía et al., 2015; Vasco et al., 2017). In this scenario, it is necessary to promote forestry planning oriented towards the conservation of sites considered the most species-rich in the Neotropical rainforests(Valencia & Balslev, 1994).

We found that small diameter trees (10 to 30 cm) had the highest densities and this was true at all elevations. Leuschner et al. (2007) state that with higher altitude, tree density increases across an elevation gradient from 1050 to 3060 m, but in our case, being at a smaller scale, this was not found. The presence of many small trees and few large trees leads to the formation of primary and secondary canopies (Lamprecht, 1990). This system is common and can also found in many forests in the world, including the Peruvian Amazon (Nebel et al., 2001). There are several reasons for the presence of smaller trees in this area, including the high rate of regeneration due to high winds causing landslides and mortality of the largest trees, thus opening the canopy for the advanced regeneration to occur. This is a distinctive characteristic of this type of forest near the ridges (Tanner et al., 2014).

Above ground biomass

We obtained AGB values in the range of 200-300 Mg ha^{-1}. These values are common for Amazonian forests (Baker et al., 2004; Unger et al., 2012). According to the analysis by Keeling and Phillips (2007), the world's tropical forests do not usually have AGB values above 350 Mg ha^{-1}. However, Nascimento and Laurance (2002) report values of nearly 400 Mg ha^{-1} in undisturbed central Amazonian rainforests. Another notable exception is the Southeast Asian dipterocarpaceas forests with AGB values above 450 Mg ha^{-1} (Slik et al., 2009, 2010). It is important to note that these values remain conservative since most studies only target tress with diameter greater than 10 cm (Nascimento & Laurance, 2002). Despite not having below ground values, the results, like those of Nascimento and Laurance (2002), suggest high potential for carbon storage. There was no significant variation in AGB along our small-scale elevation gradient. Similarly, no significant differences have been found in AGB between 500 and 2000 m.a.s.l. in the northeast region of Ecuador (Kitayama & Aiba, 2002; Leuschner et al., 2007; Moser et al., 2011). Changes in tree size and species composition along a short elevation gradient do not appear to influence total AGB (Culmsee et al., 2010; Unger et al., 2012). Furthermore, Kirby and Potvin (2007) show a disproportionate contribution of a number of species to biomass and carbon stocks in Panamá, as we have also seen in our study.

Biomass importance value

Irealtea deltoidea had the highest BIV values in the first three elevation levels whilst *Oenocarpus bataua* in the highest elevation had the highest abundance. Both species are included in the list of the 20 most abundant tree species of Amazon (Fauset et al., 2015). Our study however indicated that the least abundant tree species, such as *Sterculia* sp., *Nectandra* sp., *Ficus* sp., and *Inga* sp. at the various elevations, could significantly contribute to the aboveground biomass and consequently to carbon storage along the elevation small-scale gradient. This is an important result for future inventories since these were not reported among the top 20 most dominant species by AGB in Fauset et al. (2015), the usual reference for AGB in this region. Our results indicate that abundance alone may not be enough to predict the contribution to forest biomass of a species. The least abundant species can contribute through basal area and thus AGB values to the BIV. Lewis et al. (2013) indicate that the basal area is a better predictor of above-ground biomass than stem density. As suggested by Ruiz-Jain and Potvin (2010), it is possible that both mass ratio hypothesis (control of dominant species) and niche complementarity hypothesis are not mutually exclusive and may explain the current results. The age of these forests may also possibly influence the contribution of these two hypotheses in explaining the values obtained in this study.

Conservation effort for tree species and carbon storage and cycling

It has been suggested that, as a biodiversity *hotspot*, the Uplands of Western Amazonia may significantly contribute to the carbon storage of the world (Myers, 1988; Myers et al., 2000). Our study suggested that remarkably few species, 10 most dominant, might contribute to aboveground biomass. Fauset et al. (2015) also report the contribution of few species to AGB in the Amazonian forests and suggest that these forests may be less resilient to environmental change compared to more diverse forests where more species contribute to the total AGB. Therefore, these species should be warranted special attention in conservation efforts for their potential contribution to greenhouse gas emission mitigation measures, and for its contribution for ecosystem functions (Ruiz-Jaen & Potvin, 2010). In addition, we suggest that species-level management can be important to avoiding C-impoverishment through selective logging in these forests, as well as to consider these species during reforestation and restoration process, both for conservation purposes and for commercialization, due to preferences for timber species important to carbon stored (Bunker et al., 2005).

Our study contributes to the improving knowledge of the importance of tropical forests as a major potential for carbon storage. They will represent an important carbon sink under climate change mitigation schemes (Nascimento & Laurance, 2002). Considering the current trends in greenhouse gas emissions there is an urgent need to promote conservation of these forests for future buffering of this changing climate. Governments and organizations may have to not only encourage their protection but also support through schemes such as payment for ecosystem services if we want to have them protected. Land use changes due to resource exploitation remain a serious threat in Ecuador, a country that is trying to transition towards modern wealthy society. Such pressures must be considered when discussing and implementing development and conservation plans.

4.6. Livelihood capitals and opportunity cost for grazing areas restoration: A sustainable intensification strategy in Ecuadorian Amazon

Under review:

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4.6.1 Introduction

Cattle ranching has a fundamental role on rural household livelihoods and in the economy of households from developing countries (Acosta et al., 2021; Myeki & Bahta, 2021; Torres, Cayambe, et al., 2022). This activity is considered a source of future capital savings for rural households, allowing them to generate income by trading animals in times of economic uncertainty (Benti et al., 2022; Ibrahim, 2022; Torres et al., 2021a). In this context, for example, beef exports exceeded 153.1 billion lbs worldwide in 2018. Of this value, 25.7% was produced in Latin America (Smith et al., 2018; Williams & Anderson, 2020). In tropical areas, pastures are the main source of feed for ruminants, which has encouraged farmers to implement large extensive livestock grazing (Bailey et al., 2021; Lerner et al., 2015) to meet the feed demand of these livestock (Bukoski et al., 2022). However, these practices are considered the main drivers of tropical deforestation and high impact related to soil degradation and loss of local biodiversity (Bardgett et al., 2021; Clark et al., 2011). In addition, it is also estimated that livestock farming contributes approximately 15% of global greenhouse gas emissions (Crippa et al., 2021; Munidasa et al., 2021; Rosenzweig et al., 2020).

The world faces the challenge to encourage best management practices (BMPs) for livestock-oriented activities (Torres et al., 2021a) to mitigate climate change(Torres et al., 2023), given that cattle-raising activities are the main cause of the increase in land use change at the global level (Winkler et al., 2021). In this sense, the shifting use intended for pastoral purposes has been very intense in recent decades (Habel et al., 2019; Trew & Maclean, 2021), with about 178 million hectares (ha) of forest being lost from 1990 to 2020, at a rate of 7, 8 million ha/year in the period 1990-2000, 5.2 million ha/year in 2000-2010 and 4.7 million between 2010-2020 (FAO & UN, 2020). Currently, approximately 37% of the global area is known to be under livestock grazing activities (Shukla et al., 2019).

This contribution focuses on the Ecuadorian Amazon Region (EAR), where the agricultural frontier is expanding at an unprecedented rate (Kleemann et al., 2022; Torres et al., 2020), with cattle pastures being one of the main drivers of land use change and deforestation (Sierra, 2000, 2013; Torres et al., 2020). It is estimated that in this region, in 2014, there were approximately 1.2 million hectares of pasture for extensive livestock grazing (Lerner et al., 2015), contributing to meeting the national and international demand for animal protein and milk (Doelman et al., 2020). On the other hand, despite the low income from agricultural activities in general in the rural EAR, the livestock-based livelihood strategy is the most economically profitable source of income for households compared to other strategies based on crops and forestry activities at household level (Torres et al., 2022; Torres et al., 2018). Particularly, in the SBR it is estimated that 56.1% of the productive activities carried out by local settlers are based on subsistence methods focused on cattle ranching (Torres et al., 2021a).

The Ecuadorian government launched the Amazonian Productive Transformation Agenda - (ATPA, for its Spanish acronym). The main objective of the ATPA was to convert 300,000 hectares of pasture into silvopastoral systems (SPS), integrated forestry and mixed agroforestry systems (MAGAP, 2015). This initiative is aligned with other global restoration efforts such as the Bonn Challenge (Verdone & Seidl, 2017) and the UN Decade of Restoration (ONU, 2021), which aim to reforest 350 million hectares by 2030 (Romijn et al., 2019; Stanturf, 2021). In this context, a growing interest is evident in the search for various forms of financing at the global level to implement these practices (Bosshard et al., 2021; Löfqvist & Ghazoul, 2019; Nazareno & Laurance, 2020). However, it is necessary to explore appropriate approaches to successfully implement these actions at the local level. In this framework, this research is aimed to propose a strategic program to promote sustainable intensification in the Ecuadorian Amazon., with the following steps: a) identify and access to livelihood capitals along the altitudinal gradient; b) opportunity cost estimation of the grazing area ($OppCost_{grass\_ha}$) through the cost-benefit ratio / grazing area (ha), and c) design of strategic measures for sectoral policy mix between land sparing and land sharing approaches, according to ethnicity and gradient range.

4.6.2 Results

Cattle strategies, ethnicities, and location

Cattle ranching systems were established at different times along the altitudinal gradient throughout the current Sumaco Biosphere Reserve, which corresponds to the Napo province (Table 1). Thus, ranchers initially colonized the high mountain zone (1601-2000 masl) 70 years ago, followed by the lowland zone (400-700 masl) approximately 47 years ago, and then, they settled in the middle hill zone (701-1600 masl) about 38 years ago (Figure 2). Only in the middle hill zone indigenous cattle ranchers were registered. In this zone, 56.1% of the cattle ranchers are of the Kichwa nationality, who have adopted a subsistence strategy based on cattle ranching. Conversely, in both the lowland and high mountain zones, only mestizo cattle ranchers were recorded (Table 29).

Table 29. Characteristics of cattle ranching farms along altitudinal gradients, Napo, SBR, Ecuadorian Amazon, 2015.

Variables	Altitudinal gradients			Overall (n=167)	*p*-Value [1]
	Lowlands (n=57)	Middle hills (n=57)	High mountains (n=53)		
Ethnicity and location					
Ethnicity (% Kichwa)	0,0 [a]	56,1 [b]	0,0 [a]	19,2	***
Elevation range (m.a.s.l.)	400-700	701-1600	1601-2000	800	n/s
Average elevation (m.a.s.l)	543,11 [a]	1114,16 [b]	1778,02 [c]	1129,93	***
Year of settlement (farm)	1975	1984	1952	1971	n/s
Slope in pastures (%)	26,81 [a]	38,79 [b]	24,91 [a]	30,29	***
Cattle strategies					
Dual purpose cattle system	meat- dairy	meat and dairy dairy-meat	dairy	meat and dairy	n/s
Forrage types					
Grasses (%)	60	86.7	91.7		*
Legumes (%)	40	13.3	8.3		*

[1] *p*-Value: *** $p < 0.01$; n/s = not significantly differences between elevations gradients from 400 to 2000 m.a.s.l; [a, b] Letters in superscript denote significant differences among altitudinal gradients.

Cattle raising strategies used in both the lower and middle zones are focused on meat and milk sales, while only in the high mountain zone the activities are associated with milk production. With respect to the feeding system, grasses were predominant in comparison to leguminous plants. In this context, the high mountain zone was highlighted with 91.7% of grasses, followed by 86.7% in the middle hill zone and 60% in the lowland zone. However, the percentage of legumes was higher in the lowland zone with 40%, while the middle hill was

13.3% and only 8.3% in the high mountain zone. A wide description of the productive systems in the study area can be found in Torres et al (Torres et al., 2021a; Torres et al., 2022).

Main livelihood capitals

Human Capital

The size of cattle-raising households throughout the studied gradient was from 5.04 to 6.70 household members, with an average of 5.78. The age of the head of household was over 54 years old. However, it was found that an average of 2.66 household members work directly in livestock activities as their main source of income. An average of 2.59 household members work in off-farm activities. It was also observed that cattle ranchers in the middle hills have the highest percentage of illiteracy (15.8%), compared to the lowlands (8.8) and high mountains zone (3.8). The highest levels of secondary and university education were observed among households in the high mountains (Table 30).

Social Capital

With regard to social capital, an average of 51.5% of the households (in all three zones) belong to a producers' association, with the highest percentage of associates in the middle hills zone (61.4%). On the other hand, an average of 46.7% of the associates participate actively and 85% feel satisfied with their livestock activities. Furthermore, it is important to recognize that in the middle zone, almost 80% of the households have replacement generation (household members interested in continuing with these activities), while in the low and high zones, only 56% and 64% have been found, respectively.

Natural Capital

The results show an average farm area of 48.59 ha, with range of approximately 35 to 62 ha for all the cattle ranching households sampled. However, the greatest amount of pasture areas were found in the middle hill zone with a mean of 27.20 ha, followed by the lowland zone with 26.81 ha and the high mountain zone with 22.52 ha, without significant differences along the gradient analyzed. In addition, it was found that in the high zone around 80% of the pasture areas are compatible with grazing. On the other hand, the average percentage of forested land within the cattle farms was higher in the middle hill zone with 33 ha, compared to 20 ha and 12 ha for lowlands and high mountain zone respectivelly. Crops areas of these producers is reduced with an overall average of 1.41 ha of land under agricultural crops.

Physical and Financial Capital

In this regard, it was found that the high mountain zone has a larger percentage (47.20%) of farmers specialized in dairy farming. It was also found that 37.70% of the farmers in this zone count on with appropriate infrastructure and animal facilities.

In terms of financial capital, the results indicate an average of 15.6% of farmers in the three zones analyzed have access to credit to develop productive activities. However, the animal stock and average annual milk production differ significantly, with the high mountain zone having the highest average number of animals (30.4 head) and the highest average annual milk production yield (32,654.21 l/farm and year L/year). This yield is related to the investment because the greatest annual investment was identified in the high zone with $ 4,307.38.

Table 30. Mean of the main capitals (human, social, natural, financial and physical) of cattle ranching systems along altitudinal gradients, Napo, SBR, Ecuadorian Amazon, 2015.

Variables	Altitudinal gradients			Overall (n=167)	*p*-Value [1]
	Lowlands (n=57)	Middle hills (n=57)	High mountains (n=53)		
Human capital					
Household size (n)	5.56 [a,b]	6.70 [a]	5.04 [b]	5.78	**
Household members working in farm (n)	2.63	3.00	2.32	2.66	n/s
Household members working in out farm (n)	2.12	2.68	3.00	2.59	n/s
Age of household head (y)	54.79	56.77	57.60	56.36	n/s
Household head without Education formal	8.8	15.8	3.8	9.6	n/s
Household head with elementary school	61.4	47.4	28.3	46.1	n/s
Household head with secondary	22.8	24.6	49.1	31.7	n/s
Household head with university level	7.0	12.3	17.0	12.0	n/s
Social capital					
Member of association (Yes, %)	45.6	61.4	47.2	51.5	n/s
Actively participates in association (Yes, %)	45.6	54.4	39.6	46.7	n/s
Feel satisfaction on the farm (Yes, %)	87.7	82.5	84.9	85.0	n/s
Replacement generation (Yes, %)	56.1 [a]	78.9 [b]	56.6 [a]	64.1	*
Production Certification (Yes, %)	3.5	1.8	1.9	2.4	n/s
Natural capital					
Total land (ha)	47.30 [a,b]	62.36 [a]	35.16 [b]	48.59	*
Pasture land (ha)	26.81	27.20	22.52	25.58	n/s
Pasture land compatible with grazing (%)	75.00 [a]	54.12 [b]	78.21 [a]	68.89	***
Total forest land (ha)	20.01 [a,b]	32.99 [a]	12.16 [b]	21.95	*
Total agricultural land (ha)	1.64 [a]	2.17 [a]	0.35 [b]	1.41	***
Financial capital					
Access to credit for cattle system (Yes, %)	8.8 [a]	14.0 [a,b]	24.5 [b]	15.6	*
Annual investment in cattle farm (USD)	1,709.96 [b]	1,555.81 [b]	4,307.38 [a]	2,481.68	***

Physical capital					
It has cattle infrastructure (Yes, %)	8.80 [a]	15.80 [a]	47.20 [b]	23.40	***
Infrastructure with health animal (Yes, %)	3.50 [a]	7.00 [a]	37.70 [b]	15.60	***
Total stock of cattle (heads)	24.2 5 [a]	18.84 [a,b]	30.43 [b]	24.4	**
Cows in production (heads)	12.36 [a,b]	8.47 [a]	15.08 [b]	11.9	**
Productivity (l/farm and year)	1,926.40 [a]	2,720.46 [a]	32,654.21 [b]	11,949.3	***

[1] *p*-Value: *** $p < 0.01$; n/s = not significantly differences between elevations gradients from 400 to 2000 m.a.s.l; [a,b] Letters in superscript denote significant differences among altitudinal gradients.

Opportunity cost of grazing area

The results show an average gross annual income of USD 8,152.03 from meat and milk sales along the altitudinal gradient studied, with the high mountain zone having the highest productivity with values above USD 19,042. Within this context, it was evident that there is greater profitability in the high mountain zone with a net profit of USD 14,735.36, compared to USD 1,859.32 in the middle hill zone and USD 1,052.77 in the lowland altitudinal gradient. Moreover, the average benefit-cost ratio was USD 3.23 in all zones; however, this ratio was higher in the high mountain zone at USD 5.21. Finally, the opportunity cost of the grazing area was significantly higher in the high mountain zone with USD 672.36, followed by USD 58.85 for farmers located in the middle hill zone and USD 37.08 for farmers located in the lowland altitudinal gradient (Table 31).

Table 31. Mean of annual gross and net incomes; and opportunity cost of grazing area along altitudinal gradients, Napo, SBR, Ecuadorian Amazon, 2015.

Variables	Altitudinal gradients			Overall (n=167)	*p*-Value [1]
	Lowlands (n=57)	Medium hills (n=57)	High mountains (n=53)		
Gross income of meat and dairy (USD/farm)	2,762.71 [b]	3,415.02 [b]	19,042.63 [a]	8,152.03	***
Net benefit (USD/ farm)	1,052.77 [b]	1,859.32 [b]	14,735.36 [a]	5,670.44	***
Benefit cost rate B/C_{cattle}	2.29 [b]	2.34 [b]	5.21 [a]	3.23	**
Opportunity cost of grazing area ($OpptCost_{grass\_ha}$) (USD/ha)	37.08 [a] (±145.1)	58.85 [a] (±189.2)	672.36 [b] (±1,098.8)	246.13 (±694.62)	***

[1] *p*-Value: *** $p < 0.01$; n/s = not significantly differences between elevations gradients from 400 to 2000 m.a.s.l; [a,b] Letters in superscript denote significant differences among altitudinal gradients.

4.6.3 Discussion

Livelihoods capital and opportunity cost for grazing areas restoration

The pasture systems are considered the main drivers of tropical deforestation (Noh et al., 2022; Sierra, 2013; Torres et al., 2020), especially because of their extensive use due to the low net income per hectare obtained by producers in some areas (Sekaran et al., 2021; Torres et al., 2021b). Therefore, the promotion of public policies to encourage the restoration of ecosystems in the Amazon through economic valuation of ecosystem services should be of particular interest (Bardgett et al., 2021; Buisson et al., 2022; Török et al., 2021). In addition, payments for environmental services could be linked with the development of sustainable intensification practices (Hua et al., 2022; Li et al., 2022; Yan et al., 2021) aimed at promoting restoration in agricultural and livestock systems. In this research, according to Reyes (2019), Börner & Wunder (2008), Leguia & Moscoso (2014) the opportunity cost was quantified through the valuation of land use and the provision of market products (meat and milk). The methodology was adapted according to the livelihood capitals, production systems and the grazing area from the altitudinal gradient in a zone of high diversity and endemism in the EAR (Barbier & Burgess, 2017; Delgado-Aguilar et al., 2017; Lozano et al., 2020; Torres et al., 2018).

The findings suggest that the lowland and middle zones are appropriate to promote restoration, considering the high natural capital (including grazing areas) in these zones, whereas the opportunity cost of each hectare of pasture are particularly low with averages of USD 37.08 and USD 58.85 per year respectively; while in the high mountain zone the opportunity cost of the grazing area had an average of USD 672.36 per year, where any compensation option could be less attractive, challenging and expensive (Figure 4). In this respect, we support the use of opportunity cost to establish environmental payment policies and development of BMPs for sustainable intensification (Bastanchury-López et al., 2022; Leguia, D. Moscoso, 2014; Reyes, 2019).

Considering the theory of natural resource valuation (FAO., 2007; Tisdell, 2010), based on these results, the impact of land use change is valued and contributes to the planning of its optimal use and the development of programs for payments for environmental services.

Figure 24 shows the variation of the opportunity cost according to altitudinal gradient and grazing area. In this regard, Reyes (Reyes, 2019) indicated that agricultural productivity responds inversely proportional to the slope in an altitudinal gradient; thus, the higher the gradient, the lower the opportunity cost of land. Our results presented opposite patterns, the zones in the highest gradient specialized in dairy production showed a high opportunity cost. On the contrary, as the altitudinal gradient decreases, the systems evolve to dual purpose (meat-milk), in an extensive way, presenting lower stocking rate and lower opportunity cost.

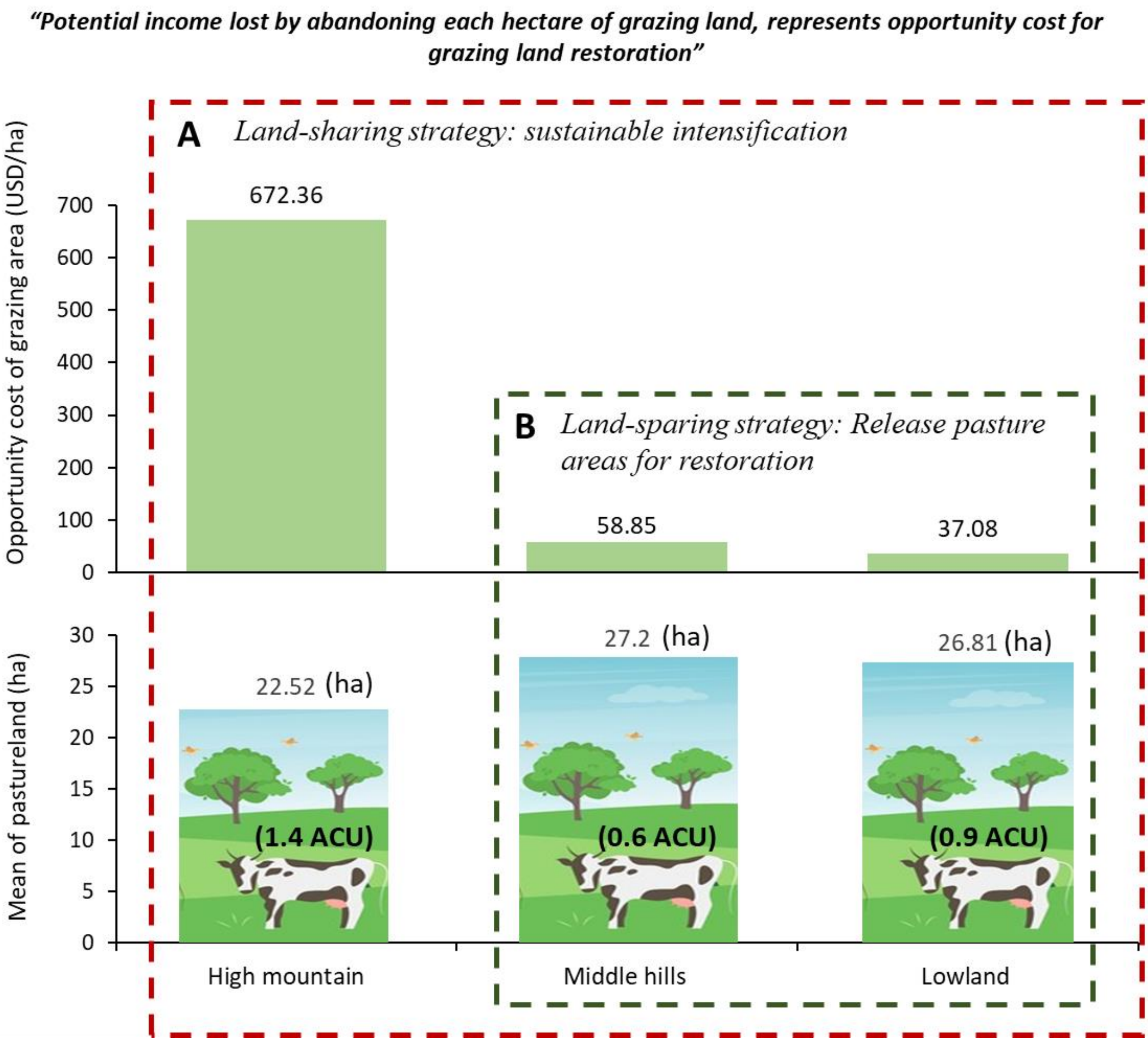

Figure 24. Opportunity cost of grazing area, represented by potential income lost by abandoning one hectare of grazing area. And suggested intensification strategies: A) Potential for land-sharing and B) potential for land-sparing approach along altitudinal gradients pastoral systems. Napo, Ecuador. (ACU, is the Adult Cattle Unit).

If the opportunity cost and capital variables vary along the altitudinal gradient, these results could be used to optimize land use and promote the Sustainable Development Goals (SDGs) and the REDD+ methodology (Leguia & Moscoso, 2014; Reyes, 2019; Torres et al., 2021a; Torres et al., 2022). Thus, considering the opportunity cost curve and the natural capital variable related to pasture area (Figure 4), in high mountain zones the systems could be focused on food production contributing to (SDG 1) using the *land-sharing* approach, on the contrary, in middle hill and lowland zones, with low opportunity cost; the land could be destined to the production of ecosystem services (SDG 13, SDG 15) based on the *land-sparing* approach. The combination of these two strategies favors sustainability (Tälle et al., 2022) and is compatible with the achievement of the 2030 Agenda goals (Barbier & Burgess, 2017; Tisdell, 2010; Vatn, 2010).

However, a limitation of the use of opportunity cost in the valuation of ecosystem services is the variability of productivity and prices over time, so it is necessary to promote longitudinal studies or, alternatively, probability models that simulate the behavior of these parameters.

Opportunity cost to release pasture areas for restoration (land-sparing)

The results using the livelihood and opportunity cost approaches of the grazing area suggest the strategy of the *land-sparing* approach, which is oriented to release pasture areas for the protection of local biodiversity through active or passive restoration processes. This is recommended mainly in the lowland and middle hill zones (Figure 4), due to the low opportunity cost that makes it easier for producers to accept to initiate restoration processes, if human, natural and financial capitals are also valued (Torres et al., 2022). Therefore, the plantation of forests can bring economic development in deprived rural areas and create lasting livelihoods benefits (Van Der Meer Simo, 2020).

Beneath this approach, the implementation of BMPs oriented to pasture area restoration could be financially promoted through an incentive program (Torres et al., 2021a). It is suggested larger incentives for forest plantations and "Chakra" system (traditional agroforestry system characterized by its high levels of timber and fruit trees content), moderate incentives for activities promoting active and passive restoration, and smaller incentives for agroforestry practice. Likewise, operational investments need to be calculated, which would be added to the opportunity cost and thus, its minimum value would be the cost associated with the adoption of the BMPs (Rivas-Torres et al., 2018).

In particular, this strategy facilitates the creation of incentives to promote and enable the sustainable intensification of livestock production in small areas, converting such areas into highly profitable areas, allowing: (a) restore degraded areas in livestock landscapes, conserving the biodiversity surrounding the protected areas considered a *hotspot* of biodiversity and endemism (Myers, 1988; Myers et al., 2000), contributing to the stability and resilience of the ecosystem and consequently to a decrease in GHG emissions and carbon sequestration (Torres et al., 2023) from cattle production; b) this approach could also contribute to reduce deforestation and habitat fragmentation in an area of high diversity (Ceddia et al., 2014; Luskin et al., 2018), which is essential to avoid species loss; c) the *land-sparing* approach and complementary public policies such as incentives, technical assistance, access to flexible credit would allow greater efficiency (Luskin et al., 2018; Mertz & Mertens, 2017) in this case in livestock production, since both the release areas for restoration and the areas destined for production could be used intensively, maximizing their yields, to benefit the households and the landscape. These processes could help to meet the growing demand for food from deforestation-free areas in an increasingly populated world (de Alcantara et al., 2021; Edwards et al., 2021; B. T. Phalan, 2018) with sustainable development objectives.

Opportunity cost for cattle sustainable intensification (land-sharing)

Land-sharing could be a suitable option for the Amazon region. Local producers have planted trees or allowed trees to be regenerated naturally in pastures, and in association with food crops, creating resource agroforestry-islands in open degraded pastures with more than 100 species (Fernandes et al., 2006), reducing the amount of land in livestock system not only by intensification as suggested by Green et al. (2005) and Phalan et al. (2014), but also due to soil impoverishment and degradation.

Our results indicated that *land-sharing* can be implemented in the three study zones (Figure 4), albeit with different strategies. According to Torres et al. (2021a), this could be the case for the three zones with grassland rehabilitation; with higher incentives in BMPs oriented to planting new trees in pastures and establishment of tree cores around grazing areas, and lower incentives in establishment of live fences around grazing areas. Additionally, in high mountain areas the objective should be to improve livestock with BMPs, such as: farm planning, establishment of accounting registers, establishment of compensation areas, establishment of enclosures with sheds, improvement of the animal diet with mineral salts and dietary supplements. Due to the pasture areas in this zone, they are more efficient in terms of income and livelihoods, so producers would not be very motivated to release areas for restoration, given that any type of incentive would have to be equal or greater than the USD 672.36 that they receive per hectare annually.

Opportunities for sectoral policy development

In this study, the opportunity cost for restoration appears as the loss of income for reducing grazing areas, as demonstrated by several studies that have identified more efficient and adaptable conservation strategies with this approach (Naidoo et al., 2006; Polasky et al., 2004, 2008). The *land-sparing* and *land-sharing* strategies facilitates reflection to promote incentive policies as compensation for those who decide to restore or intensify their agricultural systems (Salles et al., 2017), thus encouraging producers to accept such policies, and also improve ecosystem functions towards the goals of not exceeding a 1.5 °C temperature increase (Arndt et al., 2022; Costa et al., 2022) and contributing to the SDGs (Kozicka et al., 2022; Torres, Andrade, et al., 2022). Simultaneously, the opportunity cost method can also be useful for designing research strategies for the adoption of BMPs (Bailey et al., 2021; Torres et al., 2021a) as well as for the adoption of new technologies (Akhigbe et al., 2021; Vaintrub et al., 2021) and the analysis of social networks in cattle smallholders that are involved in restoration processes (Villarroel-Molina et al., 2021), which can be promoted through the enactment of a portfolio of incentives through sectoral policies or new political frameworks encouraging productive restoration (de Oliveira Silva et al., 2017; Harrison et al., 2021; Yan et al., 2021).

Thus, to promote pasture restoration areas (Buisson et al., 2022; Török et al., 2021), policy strategy should aim to maximize net benefits by unit area (ha) and increase livelihoods (Alva & Rojas, 2022; Baltenweck et al., 2020; Y. Ma et al., 2022). This could be achieved by estimating the opportunity cost of the grazing area, which as evidenced in this study, even in the same region are not homogeneous, indicating that any type of intervention must be treated in a differentiated way to facilitate public policy. This is relevant, considering that under the Paris Agreement, countries have to submit their Nationally Determined Contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC) (Samaniego et al., 2019), which, in the case of Ecuador, its first NDC submitted in 2019 (MAE, 2019) included mitigation and adaptation plans determined in the National Climate Change Strategy (ENCC, for its Spanish acronym) 2012-2025 (MAE, 2012). The ENCC includes land use change generated by the expansion of the agricultural frontier, with initiatives quantifying the potential for climate change mitigation such as livestock restoration and intensification. All these restoration mechanisms would be more effective if only the opportunity costs of the pasture area were considered and treated in a differentiated manner.

In terms of research policies, these processes require monitoring not only in the adoption of new policies or technologies, but also in opportunity cost modeling at the level of species appropriate for restoration, predictions of possible environmental changes, and optimization of land use oriented to climate risks. Finally, agricultural lands are also at the frontier of deforestation (Baumann et al., 2022; Pendrill et al., 2022); however, these results support other studies suggesting that moderate intensification coupled with technological improvements could meet future food demands while avoiding the emissions typically associated with land clearing (Henchion et al., 2021; Moran & Blair, 2021; Tilman et al., 2011).

DISCUSION GLOBAL

5. DISCUSIÓN GLOBAL

The global discussion has been based on the essential considerations and implications drawn from each of the sections. Therefore, we have respected the order of the publications maintained throughout the manuscript.

a) *Considerations regarding bibliometric analysis:*

The evolution of the number of scientific publications in the field of agrosilvopastoral systems has shown a sustained growth over the last 39 years. With an exponential growth in the last 20 years, which was adjusted to a S-curve function. On the other hand, with respect to the number of citations, two periods were significantly differentiated: the interval 1983-2003 vs. 2004-2022.

Researchers' interest in the knowledge of silvopastoral systems has also evolved; initially focused on the characterization of silvopastures and soil physical factors: on the contrary, in the last decade, research has been directed towards the search for strategies to improve the sustainable use of these systems; from ecosystem restoration to the implementation of good practices. Most of the scientific production is focused on a few countries, mainly those using mixed agrosilvopastoral systems.

In the Americas: The United States, Brazil, Mexico, Colombia, and Argentina; in Asia, China and India stand out. Finally, in Europe, the three most relevant countries were Spain, Germany, and the United Kingdom.

The publications were distributed among different journals, but in terms of the number of documents published, the publishers that accounted for most of the publications were: Springer, Elsevier and MPDI.

In the case of Ecuador, the 10 most cited documents referring to the country's silvopastures were shown. This facilitates the visibility of a group of prestigious experts, according to bibliometric indexes, so that they can collaborate in the design of public policies and help develop the country's guidelines for ecosystem conservation.

In this group, 4 of the most cited publications were in journals of the MPDI group (Sustainability, Forest, Agronomy and Agriculture) in the Open Access system.

Future studies should consider the moderating role of the "h-index" in the results and the disruptive contribution of Open Access systems in the global dissemination of knowledge, breaking economic constraints of countries, universities, and researchers.

b) Concerning the productive characterization of farming along altitudinal gradient:

Livestock activities throughout the Andean-Amazonian altitudinal gradient studied began approximately seventy years ago in the high zone, with the presence of migrant settlers. However, in the middle zone, there are reports of Kichwa households involved in life strategies based on livestock, who maintain large family nuclei with household heads over fifty years of age and low educational levels.

On average, cattle farms along the altitudinal gradient are more than 35 ha, with more than 50% of the farm area dedicated to pasture. The high zone stands out with little presence of forest on the farms, but with the highest economic income.

It is necessary to complement the efforts between public and private entities and academia to develop applied research that facilitates the identification of appropriate combinations of good livestock practices towards sustainable intensification to simultaneously increase productivity without affecting the environment. This also allows the development of new products through bioenterprises derived from small- and middle-scale livestock systems.

Furthermore, it generates research and development of local governance models in order to optimize the supply of products provided by sustainable livestock. Finally, it leads to an evaluation of the dynamics and environmental and climate change impacts of the livestock sector.

c) Regarding to livelihood capitals and perception of climate change:

The quintiles were determined on the basis of the total income of the livestock activity of a sample of 178, being the total number of the surveyed households, where there are 103 households in the first quintile (Q1), which represents 58%; 33 households representing 18% in the second quintile; 19 households representing 11% in the third quintile (Q3); 14 households representing 8% in the fourth quintile (Q4); and 9 households representing 5% in the fifth quintile (Q5).

Through an analysis by quintiles, it was determined that the households that are part of Q1 are most of the inhabitants in the entire sample (58%), who obtain an average per capita/daily income of USD 0.91. Therefore, they are the households that are categorized in “extreme poverty” by the Ecuadorian INEC. In this category, the largest number are of the Kichwa ethnic group (78%), where 61% of these families do not belong to any association of producers. In addition, 70% of these households mentioned a lack of any knowledge about climate change.

In Q5, they are the most economically well-off, earning an average of USD 14,122.48 per year, which represents an average per capita/daily income of USD 10.87. Therefore, they are the households that are categorized as “well-off”. However, only 5% of the households in the entire sample fall into this category.

With regard to climate change, in the entire study area, only 29% of the population were aware of climate change, while Q4 and Q5 included the ones who understand climate change the most, and those who have realized that the climate is changing.

The entire number of households in this quintile were willing to receive training on climate change. About 70% of the entire population of the study area was willing to adopt appropriate cattle-management actions that are adapted to the climate, and around 80% are willing to invest labor and materials from the farm to implement adaptation and mitigation actions if they receive support and training on climate change.

Finally, the study suggests that the quintile classification in groups that ranges from lower to higher incomes favors a more effective implementation of development policies at the local level in high-poverty areas that are located in fragile ecosystems.

d) Regarding to best management practices (BMPS) and REDD+ approach:

This research contributes to a characterization of the farms along the elevational gradient in the upper Ecuadorian Amazon. Cattle specialized in milk production predominate in the upper area, and dual-purpose cattle (meat and dairy) are most common in the lower area.

The Kichwa population was found to be concentrated in the middle zone and presented a livelihood system with agricultural, forestry, and livestock activity. This study provides an evaluation of 16 BMPs oriented to improve the sustainability of farms in the upper Ecuadorian Amazon along an elevation.

The application of BMPs by stakeholders contributes to various REDD+ objectives for restoring and enhancing pasturelands, and many of these practices will influence climate change mitigation.

e) Related to carbon stock in silvopastoral systems:

The main findings indicate that along the altitudinal gradient, traditional pasture systems with dispersed trees reflect a high potential for carbon sequestration in the Ecuadorian Amazon.

Therefore, considering the capacity of these systems to absorb and store carbon in vegetation and soils, they can be considered a fundamental component for climate change mitigation strategies in tropical countries. Additionally, the traditional pasture with scattered trees system of the EAR offers a high potential to contribute to climate change mitigation as well as to the adaptation of small farmers to the conditions of a changing climate.

These systems should be managed by applying the best livestock management practices (BMPs) to avoid deforestation caused by the advance of the agricultural frontier, and in this sense could be linked to the REDD+ approach of Ecuador, contributing to nationally determined contributions (NDCs for the AFOLU sector) to the Paris Agreement goal of constraining global warming to less than 2 °C.

However, understanding tree structure and diversity is important to promote practices that contribute to carbon sequestration and provision of other economic services, in this regard it is necessary encourage further research on tree structure, as well as diversity indices and the ecological importance of the species present in pasture with dispersed trees, using long term methodological approaches, to observe carbon accumulation rates and regeneration potential.

f) Regarding carbon stock in Andean-Amazon Forest:

In order to relate the amount of carbon stored in silvopastoral systems, we also analyzed the amount of carbon found in the biomass of a forest in a evergreen forests in the EAR in the Napo province, which vary in composition and structural characteristics but not in terms of aboveground biomass along a small-scale elevation gradient of 601–1000 m.a.s.l.

The results show that forests can be largely determined by the changes in species composition and tree density that along the elevation gradient. The abundance of small trees represents a great potential for carbon capture over time.

The value index as a function of density, abundance and biomass is a good indicator for recognising potential species in carbon capture and therefore for biomass production. The disproportionate contribution of few species to maintain the level of AGB/carbon stocks suggests that future intensification of selective logging biased towards trees with high C storage potential could lead to the carbon impoverishment of Amazonian forests. Decision making in terms of deforestation and reforestation programs should consider the consequences of these tree values.

g) Regarding to livelihoods and opportunity cost of grazing areas:

Livelihoods and opportunity cost are two important approaches to understand and promote restoration strategies in smallholders. These household-level approaches could serve as strategies to identify areas and fair trade-offs to promote restoration processes.

The study shows that opportunity cost, linked to net benefit from grazing area (ha), was a robust, direct, and simple and appropriate indicator. It was used to value the indirect use and hence the ecosystem services of ecosystem restoration. Thus, the opportunity cost could be used as a method to determine public policies for environmental payments and the development of best management practices for sustainable intensification.

Following the above assumptions, BMPs in land-sparing are oriented fundamentally in middle hill and lowland zones, promoting ecosystem restoration through environmental payments. Furthermore, BMPs in land-sharing would focus on high mountain farms with a strategy of sustainable intensification and food security.

However, both strategies should complement actions to concentrate conservation efforts especially in areas of high biodiversity (hotspots) conserving as much as possible the ecological dynamics through restoration strategies where it is most appropriate, considering the livelihood outcomes and opportunity cost of grazing areas in pastoral regions.

CONCLUSIONES

6. CONCLUSIONES

1. La investigación en sistemas agrosilvopastoriles ha mostrado un interés creciente en los últimos cuarenta años, y de carácter exponencial en los últimos veinte años. El número de citas mostró un comportamiento decreciente en el periodo 2004-2022. En este último periodo la investigación se ha orientado a la búsqueda de estrategias para mejorar el uso sustentable de los sistemas; desde la restauración hasta la implementación de buenas prácticas.

Las publicaciones se distribuyeron entre diferentes revistas, pero en cuanto a la cantidad de documentos publicados, las editoriales que concentraron la mayor parte de las publicaciones fueron: Springer, Elsevier y MPDI.

2. Respecto a la caracterización productiva según el gradiente altitudinal andino-amazónico. Destaco la zona media donde se concentra la mayor parte de la población indígena de la nacionalidad Kichwa de la Amazonía quienes han adoptado estrategias de vida basadas en la ganadería de doble propósito. Mientras que en la zona alta se destaca la especialización de ganadería lechera; sin embargo, también se destaca que en las zonas media y baja los existen sistemas mixtos de carne-leche que se combinan con otras actividades agrarias y forestales.

3. Se realizó un análisis de los capitales de vida y la percepción del cambio climático. Mediante un análisis por quintiles se determinó que los hogares que forman parte del Quintil Primero son la mayoría (58%), con un ingreso per cápita/diario promedio de USD 0,91. Fueron los hogares categorizados en “pobreza extrema” por el INEC ecuatoriano. En esta categoría, el mayor número son de la etnia Kichwa (78%), donde el 61% de estas familias no pertenecen a ninguna asociación de productores.

Además, el 70% de estos hogares mencionaron la falta de conocimiento sobre el cambio climático. Mientras que en el Quintil Quinto (5%) se localizaron las explotaciones con mayores ingresos, con un resultado promedio de USD 14.122,48 por año, lo que representa un ingreso per cápita/diario promedio de USD 10,87. Hogares catalogados como “acomodados”.

Con respecto al cambio climático, en toda el área de estudio, solo el 29% de la población estaba consciente del cambio climático, mientras que Q4 y Q5 incluyeron a los que más entienden el cambio climático y a los que se han dado cuenta de que el clima está cambiando.

4. Respecto a las mejores prácticas de gestión (BMPS) y enfoque REDD+:

La población Kichwa se encontró concentrada en la zona media y presentan un sistema de subsistencia con actividad agrícola, forestal y ganadera. Este estudio proporciona una evaluación de 16 buenas prácticas de manejo (BPM) orientadas a mejorar la sostenibilidad de las fincas en la alta Amazonía ecuatoriana a lo largo de una elevación. La aplicación de BPM por parte de los actores interesados contribuye a varios objetivos de REDD+ para restaurar y mejorar los pastizales, y muchas de estas prácticas influirán en la mitigación del cambio climático.

5. Respecto a las reservas de carbono en los sistemas silvopastoriles:

El sistema tradicional de pastos con árboles dispersos de la EAR ofrece un alto potencial para contribuir a la mitigación del cambio climático en la Amazonía ecuatoriana, así como a la adaptación de los pequeños agricultores a las condiciones de un clima cambiante. Estos sistemas podrían gestionarse aplicando las mejores prácticas de manejo ganadero (BPM) para evitar la deforestación.

En ese sentido podrían vincularse al enfoque REDD+ de Ecuador, contribuyendo con contribuciones determinadas a nivel nacional (NDCs, por sus siglas en inglés) en los sectores agropecuarios, forestales y de cambio de uso del suelo, al objetivo del Acuerdo de París de limitar el calentamiento global a menos de 2 °C.

6. Respecto al stock de carbono en la Selva Andino-Amazónica:

Los resultados mostraron que la cantidad de carbono almacenado en la biomasa de los bosques andinos estaban determinados en gran medida por los cambios en la composición de especies y la densidad de árboles a lo largo del gradiente de elevación. La abundancia de árboles pequeños representa un gran potencial para la captura de carbono a lo largo del tiempo.

El índice de valor en función de la densidad, abundancia y biomasa constituye un buen indicador para reconocer especies potenciales en la captura de carbono y por lo tanto para la producción de biomasa. Asimismo, la contribución desproporcionada de pocas especies para mantener el nivel de reservas de carbono sugiere que la intensificación futura de la tala selectiva sesgada hacia árboles con alto potencial de almacenamiento de C podría conducir al empobrecimiento de carbono de los bosques amazónicos.

7. Respecto a las oportunidades de restauración e intensificación sostenible:

Los resultados muestran que el análisis de las variables de capitales de los medios de vida y del coste de oportunidad del área de pastoreo pueden orientar a tomadores de decisiones en determinar áreas para restaurar paisajes productivos e intensificar sosteniblemente sistemas ganaderos. También se muestra que el enfoque *land-sparing* y *land-sharing* se complementan con estos análisis facilitando el uso de estas estrategias, especialmente en zonas donde se requiere por un lado mayores esfuerzos de conservación y por otro lado mejorar los ingresos rurales y demás factores necesarios para avanzar hacia los objetivos del desarrollo sostenible (ODS).

RESUMEN

7. RESUMEN

El resumen de todo el trabajo se ha organizado considerando las partes esenciales de cada uno de los apartados. Por ello, hemos respetado el orden de las publicaciones mantenido a lo largo del manuscrito.

a. Resumen del análisis bibliométrico:

Los sistemas silvopastoriles se encuentran en permanente cambio y en estado de crisis y riesgo de desaparición dados los cambios en la ciencia y las prioridades estratégicas. En este trabajo se ha realizado un análisis bibliométrico con el fin de identificar los cambios asociados a los diferentes sistemas silvopastorales (mixtos de cultivo, forestal, ganadero y otros usos). Se ha aplicado la herramienta Bibliometrix en R para analizar 5.708 documentos publicados entre 1983 y 2022, incluyendo los términos "silvopastoral" y "silvopasture" entre otros. Los resultados muestran un aumento longitudinal y exponencial de los estudios sobre silvopastoreo en los últimos 20 años. El crecimiento se ajustó a una función S, con un R2 del 96,06%. El interés de los investigadores por el conocimiento del silvopasto ha evolucionado; inicialmente se centra en la caracterización del silvopasto y recientemente, se enfoca en la búsqueda de estrategias para mejorar el uso sostenible del silvopasto; incluyendo la restauración de ecosistemas y la implementación de buenas prácticas. En América: Estados Unidos, Brasil, México, Colombia, Ar-gentina); En Asia: China e India; En Europa: España, Alemania y Reino Unido destacan como los países con mayor producción científica en el estudio del silvopastoreo. En el caso de Ecuador, los líderes en silvopastoreo están incluidos en las citaciones, lo que facilita la construcción de un grupo de expertos que contribuyen al desarrollo de políticas públicas. Las publicaciones más citadas tuvieron lugar en revistas del grupo Springer, Elsevier y MPDI (revistas de Sostenibilidad, Forestal, Agronomía y Agricultura), en su mayoría en sistemas de Acceso Abierto. En el futuro, deberá evaluarse la contribución disruptiva de los sistemas de Acceso Abierto a la difusión global del conocimiento científico

b. En relación con la caracterización productiva a lo largo del gradiente altitudinal

El incremento de la producción ganadera en la Región Amazónica Ecuatoriana ha provocado un aumento de la deforestación y el avance de la frontera agrícola. El objetivo del presente estudio fue realizar una caracterización socioeconómica y productiva en los sistemas ganaderos andino-amazónicos de Ecuador. El área de estudio formó parte de la

Reserva de la Biosfera Sumaco (RBS) y de otras tres zonas: baja (400 a 700 msnm), media (701 a 1600 msnm) y alta (701 a 1600 msnm). Se recogieron datos de 167 hogares ganaderos. Hay diferencias significativas ($p \leq 0,001$) en los resultados. Se identificó que el 56,1% de los productores de la zona media son indígenas (Kichwa). En la misma zona se encontró el mayor ($p \leq 0,01$) tamaño promedio del hogar (6,7 miembros del hogar) y el mayor nivel de jefes de hogar sin escolaridad (16%). Los cabezas de familia mayores de 54 años se registraron en todo el gradiente. Las explotaciones más grandes también se encontraron en la zona media, con una media de 62,3 ha, de las cuales una media de 32,9 ha son bosque nativo, 2,1 ha son tierras agrícolas y 27,2 ha son pastos para el ganado. La economía familiar está impulsada por una mayor inversión en ganadería en la zona alta, por lo que su ingreso bruto anual tiene un alto impacto en su economía. Con estos resultados, este estudio presenta recomendaciones para alcanzar los Objetivos de Desarrollo Sostenible

c. *En relación con los medios de subsistencia y la percepción del cambio climático*

Los Objetivos de Desarrollo Sostenible (ODS) de 2015 identifican la pobreza, el crecimiento y la desigualdad como tres áreas clave de intervención hacia la Agenda 2030 de la ONU para el bienestar humano y la sostenibilidad. En este sentido, los objetivos predominantes son: (a) Determinar los grupos de pobreza por quintiles a través del ingreso ganadero en hogares de pequeños productores de leche; (b) Caracterizar los medios de vida rurales utilizando la teoría del capital; y (c) Evaluar la percepción del cambio climático (CC) y la disposición a aceptar medidas de adaptación así como de mitigación. El presente estudio se realizó en comunidades ubicadas en los Andes ecuatorianos, donde se aplicaron 178 encuestas a jefes de hogar indígenas kichwas y mestizos. A partir de los ingresos netos totales determinados, se organizaron cinco grupos. Se aplicó la curva de Lorenz como indicador general de la desigualdad relativa, así como el coeficiente de Gini (G). Con base en la teoría del capital, se determinaron las características humanas, sociales, naturales, físicas y financieras, y se consideraron siete variables para evaluar la percepción y disposición a aceptar acciones de mitigación y adaptación de los quintiles determinados. El resultado del coeficiente de Gini fue de 0,52, lo que indica que el 20% más pobre de la población sólo recibe el 3,40% de los ingresos, mientras que el 20% más rico del quintil obtiene alrededor del 54% de los ingresos totales. Es evidente que la mayoría de los productores saben poco sobre CC, pero que están dispuestos a recibir programas de fortalecimiento. Por lo tanto, es fundamental establecer lineamientos estratégicos desde la política pública para reducir la desigualdad y mejorar el bienestar social de los productores, con un eje transversal en el fortalecimiento de las capacidades sobre el impacto, mitigación y adaptación al CC, así como la provisión de diversas herramientas, como el acceso a la información climática.

d. En relación con las mejores prácticas de gestión y el enfoque REDD

La deforestación es una grave amenaza para la diversidad en la Región Amazónica Ecuatoriana (RAE). Para mitigar la deforestación, es necesario conocer los roles e interacciones de los actores relevantes y profundizar nuestro conocimiento de los medios de vida locales, objetivos, potenciales, limitaciones y "derechos de ser" entre las fincas, así como las mejores prácticas de manejo (BMPs). En este estudio, nuestro objetivo era identificar y evaluar las BMP ganaderas a lo largo de un gradiente elevacional para fomentar la producción sostenible y reducir las emisiones derivadas de la deforestación y la degradación forestal (REDD+). Este enfoque podría ser beneficioso desde el punto de vista medioambiental y económico. Se recopilaron datos de 167 hogares a lo largo de tres gradientes elevacionales, así como de 15 entrevistas realizadas entre un panel multidisciplinar de partes interesadas clave e investigadores de la AER. Los resultados mostraron que la mayoría de la población kichwa vive en la zona media, que presenta una mayor superficie agrícola y forestal. Por el contrario, en las zonas baja y alta predomina la ganadería, donde la zona alta está especializada en la producción de leche y la baja en la ganadería de doble propósito (carne y leche). La evaluación de las partes interesadas proporcionó varios resultados clave: (a) los factores sociales, estructurales y técnicos tienen efectos complementarios en la adopción de las BMP; (b) las dieciséis BMP evaluadas facilitaron la aplicación de los programas de incentivos financieros existentes y permitieron la creación de asociaciones público-privadas para desarrollar proyectos REDD+. También se analizan las implicaciones políticas de la aplicación de estos enfoques.

e. En relación con las reservas de carbono en los sistemas silvopastorales

El sistema silvopastoral (SPS) se ha considerado un sistema de gestión sostenible que contribuye a la reducción de los gases de efecto invernadero (GEI), entre otros beneficios, en comparación con los pastos abiertos. Sin embargo, pocas investigaciones se han realizado sobre el carbono almacenado en el suelo y en la biomasa arbórea de los pastos tradicionales con árboles dispersos (PWT) en comparación con los pastos en monocultivo (PM). El presente estudio se realizó en la Región Amazónica Ecuatoriana (RAE), a lo largo de un gradiente elevacional de 400 a 2000 msnm, dentro de la zona de amortiguamiento y transición de la Reserva de la Biosfera Sumaco (RBS), utilizando 71 parcelas circulares temporales de 2826 m2, donde 26 parcelas fueron establecidas en PWT y 45 parcelas en PM. Los principales resultados en PWT muestran diferencias significativas ($p \leq 0,01$) entre la biomasa de carbono por encima del suelo (AGCárboles) de 41,1 (tierras bajas), 26,5 (colinas medias) y 16,7 (alta montaña) Mg ha-1 respectivamente, con una media de 31,0 Mg ha-1 en toda el área de estudio. La reserva total de carbono a lo largo del gradiente altitudinal en cinco componentes: (AGCárboles), carbono subterráneo (BGCárboles), carbono en pastos (AGClitter+pasto) y carbono en componentes del suelo (0-10 y 10-30 cm) para PWT osciló entre 112,80 (tierras bajas) y 91,34 (alta montaña) Mg ha-1 ; mientras que para los sistemas PM la evaluación de tres componentes (AGClitter+pasto) y el carbono en componentes del suelo (0-10 y 10-30 cm) osciló entre 52,5 (tierras bajas) y 77,8 (zona media) Mg ha-1. Finalmente, el trabajo muestra las principales especies arbóreas dominantes en los sistemas de pastoreo que contribuyen al almacenamiento de carbono a lo largo del gradiente elevacional y concluye con recomendaciones para la toma de decisiones encaminadas a mejorar los sistemas ganaderos mediante un enfoque silvopastoral para mitigar los efectos del cambio climático.

f. Respecto a las reservas de carbono en el bosque Andino-Amazónico

El propósito de este estudio fue examinar cómo la diversidad, riqueza y características estructurales de los árboles, así como la biomasa por encima del suelo, varían a lo largo de un gradiente de elevación a pequeña escala de 601 a 1000 m sobre el nivel del mar (msnm) en un bosque amazónico andino perennifolio y sus implicaciones en términos de almacenamiento de carbono. Se estudiaron árboles con un diámetro a la altura del pecho superior a 10 cm en 20 parcelas permanentes de 0,1 ha, cinco en cada sitio de elevación. Se determinó la riqueza de especies, la densidad, el área basal, la biomasa aérea y se calculó el valor de importancia de la biomasa (VIB). Los 1378 árboles estudiados pertenecían principalmente a las familias Moraceae (17 especies) Fabaceae (16) y Meliaceae (10). La riqueza de especies aumentó significativamente ($p<0,007$) a lo largo del gradiente de elevación a pequeña escala y fue mayor en el rango de 901-1000 m.s.n.m. La biomasa aérea varió entre 246,8 y 320,9 Mega gramos por hectárea (Mg ha-1) y no difirió a lo largo del gradiente ($p>0,579$). La contribución desproporcionada de unas pocas especies, algunas de las cuales son las menos abundantes pero con una elevada BAG en nuestros estudios (por ejemplo, Sterculia sp., Nectandra sp., Ficus sp., e Inga sp.) a las reservas de carbono es importante tenerla en cuenta en futuras investigaciones sobre el secuestro de carbono. Dado que la producción de biomasa sobre el suelo se concentró en unas pocas especies, algunas poco comunes, la toma de decisiones en programas de reforestación y cómo deben seleccionarse las especies puede tener implicaciones a la hora de medir y promover el almacenamiento de carbono.

g. *En relación con los medios de subsistencia y el coste de oportunidad de las zonas de pastoreo*

El cambio de uso de la tierra por pastos se considera la principal causa de deforestación en la Región Amazónica Ecuatoriana (RAE). Para detener e invertir este proceso es necesario comprender, entre otros factores, los medios de subsistencia locales, los ingresos procedentes de las zonas de pastoreo y las opciones adecuadas para fomentar la producción sostenible, vinculando el enfoque de reparto de tierras con el de ahorro de tierras. El presente estudio utiliza datos recogidos de 167 hogares a lo largo de tres gradientes elevacionales dentro de la zona de amortiguación y transición de la Reserva de la Biosfera Sumaco (RBS) en la RAE. Los resultados de un análisis comparativo de las principales variables de capital (humano, social, natural, financiero y físico), y el coste de oportunidad de la evaluación de la superficie de pastoreo proporcionan conclusiones clave: a) el concepto de conservación y uso compartido de la tierra debe considerarse como estrategias locales complementarias, incluidos los medios de subsistencia de los hogares y el coste de oportunidad de la superficie de pastoreo; b) fomentar los mercados con derechos de restauración diferenciados, basados en los hogares dedicados a zonas de pastoreo de bajo coste de oportunidad y menor impacto en los medios de subsistencia de los capitales como elementos clave de las iniciativas económicas y de conservación; c) se debaten las implicaciones políticas sectoriales, incluida la intensificación moderada y las mejoras tecnológicas para reforzar el enfoque de conservación y uso compartido de los pastos.

SUMMARY

8. SUMMARY

The summary of the entire work has been organized considering the essential parts of each of the sections. For this reason, we have respected the order of the publications maintained throughout the manuscript.

a. Bibliometric analysis summary:

Silvopastoral systems are in permanent change and in a state of crisis and at risk of disappearing given the changes in science and strategic priorities. In this work a bibliometric analysis with the purpose of identifying the changes associated to the different silvopastoral systems (mixed of crop, forest, livestock, and other uses) was performed. The tool Bibliometrix in R has been applied to analyze 5,708 documents published between 1983 and 2022, by including the terms “silvopastoral” and “silvopasture” among others. The results show a longitudinal and exponential increase in silvopasture studies over the last 20 years. The growth was adjusted to a function S, with an R^2 of 96.06%. The interest of researchers regarding the knowledge of silvopasture has evolved; initially it focuses on the characterization of silvopasture and recently, it is focused on the search for strategies to improve the sustainable use of the silvopasture; including ecosystem restoration and implementation of good practices. In America: The United States, Brazil, Mexico, Colombia, Argentina); In Asia: China and India; In Europe: Spain, Germany and the United Kingdom stand out as the countries with the largest scientific production in the study of silvopasture. In the case of Ecuador, leaders in silvopasture are included in citations, which facilitates the construction of a group of experts who contribute to the development of public policies. The most cited publications took place in journals of the Springer group, Elsevier and MPDI (Sustainability, Forest, Agronomy and Agriculture journals), mostly in Open Access systems. In the future, the disruptive contribution of Open Access systems to the global dissemination of scientific knowledge should be evaluated.

b. Concerning productive characterization along altitudinal gradient:

The increase in livestock production in the Ecuadorian Amazon Region has caused an increase in deforestation and the advance of the agricultural frontier. The aim of the current study was to conduct a socioeconomic and productive characterization in Andean-Amazonian livestock systems in Ecuador. The study area was part of the Sumaco Biosphere Reserve (SBR) and three other zones: low (400 to 700 masl), middle (701 to 1600 masl),

and high (701 to 1600 masl). Data were collected from 167 ranching households. There are significant differences ($p \leq 0.001$) in the results. It was identified that 56.1% of the producers in the middle zone are indigenous (Kichwa). The largest ($p \leq 0.01$) average household size (6.7 household members) and the highest level of household heads without schooling (16%) were found in the same area. Heads of households over 54 years of age were reported throughout the gradient. The largest farms were also found in the middle zone, with an average of 62.3 ha, of which an average of 32.9 ha is native forest, 2.1 ha is agricultural land, and 27.2 ha is cattle pasture. The household economy is driven by a greater investment in livestock in the upper area, and therefore their annual gross income has a high impact on their economy. With these results, this study presents recommendations to achieve the Sustainable Development Goals.

c. Regarding to livelihood capitals and perception of climate change:

The Sustainable Development Goals (SDG) of 2015 identify poverty, growth, and inequality as three key areas of intervention towards the UN 2030 Agenda for human well-being and sustainability. Herein, the predominant objectives are: (a) To determine the poverty groups by quintiles through the cattle income in households of small milk producers; (b) To characterize rural livelihoods by using capital theory; and (c) To assess the perception of climate change (CC) and the willingness to accept adaptation as well as mitigation measures. The current study was performed in communities that are located in the Ecuadorian Andes, where some 178 surveys were conducted with indigenous Kichwa and mestizo heads of households. From the total net income determined, five groups were organized. The Lorenz curve was applied as a general indicator of the relative inequality, as well as the Gini coefficient (G). On the basis of the theory of capital, the human, social, natural, physical, and financial characteristics were determined, and seven variables were considered to evaluate the perception and willingness to accept mitigation and adaptation actions of the given quintiles. The result of the Gini coefficient was 0.52, which indicates that the poorest 20% of the population only receives 3.40% of the income, while the richest 20% of the quintile obtain about 54% of the total income. It is evident that most producers know little about CC, but that they are willing to receive strengthening programs. Therefore, it is essential to establish strategic guidelines from public policy in order to reduce inequality and to improve the social welfare of producers, with a transversal axis in the strengthening of the capacities on the impact, mitigation, and adaptation to CC, as well as the provision of several tools, such as access to climate information.

d. Related to best management practices (BMPS) and REDD+ approach:

Deforestation is a severe threat to diversity in the Ecuadorian Amazon Region (EAR). To mitigate deforestation, it is necessary to know the relevant stakeholders' roles and interactions and deepen our knowledge of the local livelihoods, objectives, potentials, limitations, and "rights of being" among farms, as well as the best management practices (BMPs). In this study, our aim was to identify and assess livestock BMPs along an elevational gradient to foster sustainable production and reduce emissions from deforestation and forest degradation (REDD+). This approach could be environmentally and economically beneficial. Data were collected from 167 households along three elevational gradients, as well as from 15 interviews held among a multidisciplinary panel of key stakeholders and researchers in the EAR. The results showed that most of the Kichwa population lives in the medium zone, which features a larger agricultural and forest surface. Conversely, in the lower and upper areas, livestock predominates, where the upper area is specialized in milk production and the lower area in dual-purpose cattle (meat and dairy). The stakeholder assessment provided several key results: (a) social, structural, and technical factors have complementary effects on BMP adoption; (b) the sixteen assessed BMPs facilitated the implementation of existing financial incentive programs and enabled public–private partnerships to develop REDD+ projects. The policy implications of implementing these approaches are also discussed.

e. Related to carbon stock in silvopastoral systems:

Silvopastoral system (SPS) has been considered as a sustainable management system contribute to greenhouse gas (GHG) reduction, among other benefits compared with open pasture. However, little research has been conducted on the soil and tree biomass carbon stored in traditional pasture with dispersed trees (PWT) compared with pasture in monoculture (PM). The present study was conducted in the Ecuadorian Amazon Region (EAR), along an elevational gradient from 400 to 2000 masl., within the buffer and transition zone of the Sumaco Biosphere Reserve (SBR), using 71 temporary circular plots of 2826 m^2, where 26 plots were stablished in PWT and 45 plots in PM. The main results in PWT show significant differences ($p \leq 0.01$) between aboveground carbon biomass (AGC_{trees}) from 41.1 (lowlands), 26.5 (Middle hills) and 16.7 (high mountains) Mg ha^{-1} respectively, with an average of 31.0 Mg ha^{-1} in the whole study area. The total carbon pool along the altitudinal gradient in five components: (AGC_{trees}), belowground carbon

(BGC_{trees}), pasture carbon ($AGC_{litter+pasture}$) and carbon in soil components (0–10 and 10–30 cm) for PWT ranged from 112.80 (lowlands) to 91.34 (high mountains) Mg ha^{-1} ; while for the PM systems assessing three components ($AGC_{litter+pasture}$) and carbon in soil components (0–10 and 10–30 cm) ranged from 52.5 (lowlands) to 77.8 (middle zone) Mg ha^{-1}. Finally, the paper shows the main dominant tree species in pasture systems that contribute to carbon storage along elevational gradient and concludes with recommendations for decision-making aimed at improving cattle ranching systems through a silvopastoral approach to mitigate the effects of climate change.

f. Related to carbon stock in Andean-Amazon forest:

The purpose of this study was to examine how tree diversity, richness, and structural characteristics as well as above-ground biomass varies along a small-scale elevation gradient from 601 to 1000 m above sea level (m.a.s.l.) in an Evergreen Andean Amazon forest and their implications in terms of carbon storage. Trees with diameter at breast height greater than 10 cm were surveyed in 20 permanent 0.1 ha plots, five at each elevation site. We determined species richness, density, basal area, aerial biomass and calculated a biomass importance value (BIV). The 1378 trees surveyed were mainly contained in the families Moraceae (17 species) Fabaceae (16) and Meliaceae (10). Species richness significantly increased ($p<0.007$) along the small-scale elevation gradient and was greatest in the range of 901–1000 m.a.s.l. Aerial biomass varied between 246.8 and 320.9 Mega grams per hectare (Mg ha^{-1}) and did not differ along the gradient ($p>0.579$). At the highest tree density, the highest BIV of Iriartea deltoidea was found at 601–900 m.a.s.l. The disproportionate contribution of a few species, some being the least abundant but with high AGB in our surveys (e.g., *Sterculia* sp., *Nectandra* sp., *Ficus* sp., and *Inga* sp.) to carbon stocks is important to consider in future research on carbon sequestration. As the production of above-ground biomass was concentrated in a few species, some uncommon, decision making in reforestation programs and how species should be selected may have implications when measuring and promoting carbon storage.

g. Related to livelihoods and opportunity cost of grazing areas:

Land use change to pastures is considered the main cause of deforestation in the Ecuadorian Amazon Region (RAE). To halt and reverse this process it is necessary to understand among other factors, the local livelihoods, income from grazing area and appropriate options to foster sustainable production linking the land-sparing and land-sharing approach. The present study uses data collected from households along three elevational gradients within the buffer and transition zone of the Sumaco Biosphere Reserve (SBR) in the EAR. The results of a comparative analysis of the main capital variables (human, social, natural, financial, and physical), and the opportunity cost of grazing area assessment provides key findings: a) the concept of land-sparing and land sharing should be considered as complementary local strategies, including household livelihoods and the opportunity cost of grazing area; b) encourage markets with differentiated restoration rights, based on households engaged in low grazing areas opportunity costs and less impact on capitals livelihood as a key elements of economic and conservation initiatives; c) sectoral policy implications including moderate intensification and technological improvements to strengthen the pastureland-sparing and sharing approach are discussed.

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ANEXOS

ANEXOS

Ganadería de leche en la zona alta de la Reserva de Biosfera Sumaco (RBS), Amazonía Ecuatoriana:

Figura 23. Sistema de pastos con árboles en ganadería bovina de leche en la zona alta de la Reserva de Biosfera Sumaco, Amazonía Ecuatoriana.

Figura 24. Investigadores monitoreando los sistemas de pastoreos con árboles en ganadería bovina de leche en la zona alta de la Reserva de Biosfera Sumaco, Amazonía Ecuatoriana.


Figura 25. Sistema de pastos con árboles en ganadería bovina de doble propósito (leche y carne) en la zona media de la Reserva de Biosfera Sumaco, Amazonía Ecuatoriana.


Figura 26. Productor ganadero explicado las buenas prácticas implementadas en el sistema de ganadería bovina en la zona media de la Reserva de Biosfera Sumaco, Amazonía Ecuatoriana.

Figura 27. Sistema de pastos con árboles en ganadería bovina de doble propósito (carne y leche) en la zona baja de la Reserva de Biosfera Sumaco, Amazonía Ecuatoriana.

Figura 28. Paisaje productivo de pastos con árboles en ganadería bovina de doble propósito (carne y leche) en la zona baja de la Reserva de Biosfera Sumaco, Amazonía Ecuatoriana.