

## Can zero deforestation agreements in the cattle sector protect Colombia's forests and páramos?

Clare C. Sullivan<sup>a,\*</sup>, Joseph App<sup>a</sup>, Lisa L. Rausch<sup>a</sup>, Steven Sotelo<sup>b</sup>, Daisy Tarrier<sup>c</sup>, Miguel Ángel Vianchá Pinzón<sup>d</sup>, Holly K. Gibbs<sup>a</sup>

<sup>a</sup> University of Wisconsin-Madison, 1710 University Avenue, Madison, WI 53726, USA

<sup>b</sup> International Center for Tropical Agriculture, Km 17, Recta Cali-Palmira CP 763537, Apartado Aéreo 6713, Cali, Colombia

<sup>c</sup> Envoy Vert Car 22 # 80-73, Bogota, Colombia

<sup>d</sup> Fundación Proyección Eco-Social, Cl. 4a #34c29, Villavicencio, Meta, Colombia

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### ABSTRACT

Zero Deforestation Agreements (ZDAs) for the beef and dairy sectors in Colombia could curb land cover change in the country's highly biodiverse tropical forests and páramos. Improved understanding of the structure of the cattle supply chain and the ZDAs' potential area of influence can help target companies with high-risk supply chains, inform implementation, and set realistic expectations for the ZDAs contribution to conservation goals for forest and páramos. We provide the first map of infrastructure for the beef and dairy sectors and link this to a dataset of cattle transactions to delineate "supply zones" or potential buying areas for each slaughterhouse and dairy. We use these supply zones to assess three spatially explicit scenarios of the potential reach of the ZDAs with expanded participation. At present, ZDA signatories' supply zones cover 10.4 Mha or 23% of Colombia's forests, with a large area of influence associated with beef sector signatories. Participation of all major companies could nearly double the ZDAs reach to include 41% of forests, and full participation could reach 49% of forests. The dairy ZDA also targets high alpine páramos, and 57% of unprotected páramos are within signatories' supply zones. Full participation could support the conservation of 96% of this unique ecosystem. We found that indirect animal movements make up 80% of the supply chain, so policy implementation will depend on monitoring and traceability systems that go beyond suppliers selling directly to slaughterhouses or dairies. More companies must participate and effectively implement the ZDAs to realize this conservation potential.

### 1. Introduction

Colombia's tropical forests cover 59 million hectares (Mha) (IDEAM, 2023), and are among the most biodiverse on the planet, as well as an important store of carbon (Phillips et al., 2016; Franco and Ruiz, 2014). In Colombia, deforestation remains a critical concern, with 1.9 Mha of forest lost between 2010 and 2023 (IDEAM, 2023). Pastures for cattle ranching are the dominant agricultural land use, covering 34 Mha (DANE, 2014) and the conversion of forests to pasture is a major driver of forest loss (Armenteras et al., 2006; Armenteras et al., 2013). Pasture expansion into forests threatens the country's biodiversity and contributes to global climate change, with 58 % of the country's emissions coming from the land sector (Gobierno de Colombia, 2020). One of the strategies identified in the country's Nationally Determined Contributions (NDC) to reduce cattle-driven deforestation and mitigate its

impacts on GHG emissions are Zero Deforestation Agreements (ZDAs) for the beef and dairy sectors.

ZDAs and other supply chain commitments are a promising form of forest governance that take supply chains as their starting point and mobilize supply chain actors like retailers, restaurants, dairies and slaughterhouses to require zero deforestation production by their suppliers (Lambin et al., 2018; Furumo and Lambin, 2020). They are grounded in a belief that markets and financial instruments are a flexible, efficient, and cost-effective means of achieving environmental goals. Similar commitments in the Brazilian Amazon have demonstrated potential to encourage changes in land management more quickly than government actions alone (Gibbs et al., 2015; Gibbs et al., 2016; Heilmayr et al., 2020; Levy et al., 2023). These private sector-led conservation initiatives can complement and fill gaps in public policy interventions (Lambin et al., 2018), as they may exceed legal

\* Corresponding author.

E-mail address: [ccsullivan3@wisc.edu](mailto:ccsullivan3@wisc.edu) (C.C. Sullivan).

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requirements (Rausch et al., 2019), strengthen monitoring and enforcement of national forest laws and target areas at high risk of conversion (Heilmayr and Lambin, 2016). To be effective, supply chain commitments must be supported by traceability and monitoring of all suppliers, not only direct suppliers, as well as include transparent data and third-party audits (Gibbs et al., 2015). Companies attempting to implement ZDAs face the often formidable problem of establishing traceability in their supply chains, i.e., maintaining information about a commodity and its origin (Gardner et al., 2019).

Colombia's ZDAs could play a key role in the country's overall strategy to combat deforestation and reduce emissions in the face of rising deforestation rates (Furumo and Lambin, 2020; Castro-Nunez et al., 2020). We map the cattle supply chain to provide insights into its structure, and the challenges and opportunities that this structure poses for implementing a traceability system. These insights can inform policy, set reasonable expectations and strengthen implementation of the ZDAs. We perform the first fine-scale analysis of the cattle supply chain in Colombia using a database with property-level cattle transactions and movements for the period 2018–2020. We combine these data with a novel map of cattle supply chain infrastructure (slaughterhouse and dairy collection and/or processing locations). We create “supply zones” around the infrastructure to identify the possible buying area, which is a proxy for the reach or influence of these companies and the policies and commitments that influence their buying choices. We then map the current reach of the ZDAs and define three spatially-explicit policy participation scenarios based on whether key actors in the beef and dairy sectors sign onto and implement the ZDAs in their supply chains. These scenarios characterize the ZDAs potential reach

and influence in terms of forest area, recent deforestation, pasture area and páramos.

## 2. Background

### 2.1. Beef and dairy sector

Colombia has the fourth largest cattle herd in Latin America, with 29.6 million (M) animals as of 2023 (ICA, 2023). Around 3.4 M animals are slaughtered annually (DANE 2023). Since Colombia's 2016 peace accord with the FARC, the cattle inventory has increased by 4.2 M animals (or 17 %) and the number of ranches increased by 32 % to 620,807 (ICA, 2023). Much of this growth is occurring in deforestation hotspots (Vianchá et al., 2020), many of which are in territory that was controlled by the FARC or other dissident groups (Murillo-Sandoval et al., 2023).

Extensive beef production is the main production system, utilized by 39 % of ranches in the cattle sector and common through the Orinoquia, Caribbean and Magdalena River valley, with an additional 20 % of production systems focused on fattening (MSG, 2018). About 6 % of ranches specialize in intensive dairy, and while they are located throughout the country, these systems are especially common in the mid to upper-elevation Andes (*ibid*, 2018). The remaining 35 % of Colombia's ranches are extensive dual-purpose systems, where a ranch's herd is managed on pastures for both beef and milk production, a practice that is common throughout the tropics (*ibid*, 2018). This system is most widespread throughout Colombia's warmer lower elevation areas in the Caribbean, valleys in the Andes and in the Amazon Basin, where it overlaps with deforestation hotspots.

## Beef Supply Chain

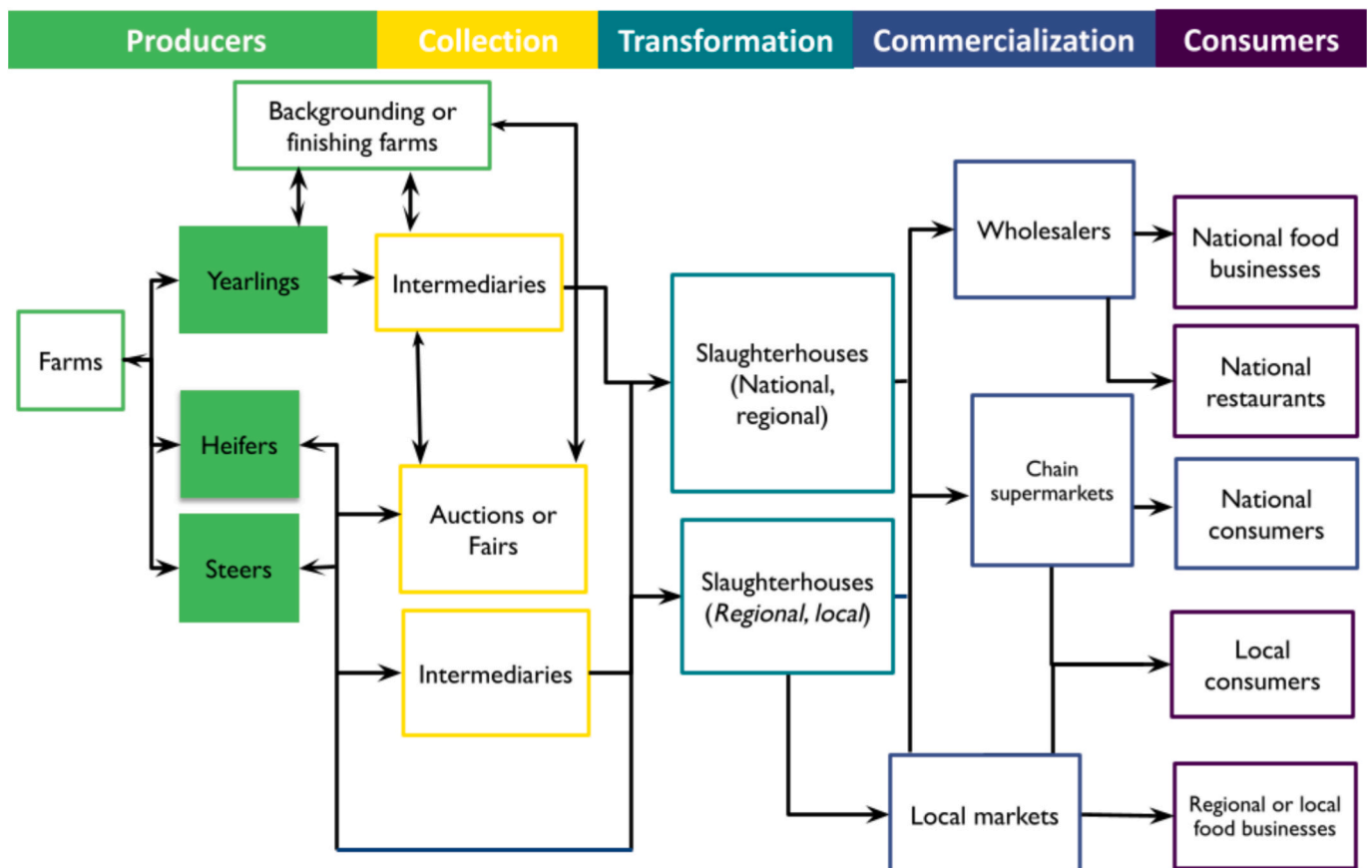


Fig. 1. Schematic of stages, actors and relationships in the beef supply chain in Colombia.

Understanding the structure of the cattle supply chain and the role of different actors such as smallholders, indirect suppliers, and high-volume ranches can help to evaluate environmental impacts, to identify influential actors, and to target and strengthen policy interventions (Alix-Garcia and Gibbs, 2017; Carvalho et al., 2021; zu Ermgassen et al., 2020). Cattle supply chains in Colombia, especially in the beef sector, can be complex and span several owners and properties across large distances (Castro-Nunez et al., 2021) (see Fig. 1 and Fig. S1 for schematics of supply chain stages, actors and relationships). Ranches may specialize in raising calves, rearing cattle for fattening prior to slaughter or may manage all phases as a full-cycle ranch. Cattle are sometimes transported hundreds of kilometers to be slaughtered (Klingler et al., 2018; Vianchá et al., 2020). In addition to ranchers, there are other actors or nodes in the beef supply chain, like intermediaries, who specialize in transport, and auctions, where cattle are bought and sold. Dairy supply chains are usually shorter and simpler, though they have multiple actors in the collection phase, like dairy aggregators and intermediaries, and the two sectors are linked (Vianchá et al., 2020). For example, older or less productive dairy cows may be culled and sold for slaughter, and male dairy calves are sold into the beef supply chain. Colombia's cattle and dairy sectors involve many companies and have tens of thousands of smallholders in their supply bases (DANE, 2014; MSG, 2018), characteristics that have proven difficult to manage effectively in other contexts.

Another important difference between the Colombian context and other prominent examples of supply chain commitments such as those in Brazil's soy and cattle sectors and South Asia's palm oil sector, is the current extent to which the market is domestic versus export-oriented. In most other contexts where companies are implementing supply chain commitments, a significant portion of the sector covered by the commitment is for export (e.g., Brazilian soy and Southeast Asian palm oil) or the country's exports make up a dominant share in the global market (e.g., Brazilian beef). In contrast, Colombia exports 3 % of its beef production (FAO, 2024) and 8 % of its dairy products (UPRA, 2020), and these export shares are most significant within the South American market. However, both sectors aim to increase their reach in global markets. Anticipation of this opportunity and the requirements of these markets could provide an incentive to increase participation in the ZDAs. Alternatively, this domestic focus could limit even signatory companies' motivations to effectively implement their commitments since pressure for this kind of action is often stronger from international markets (Lambin and Furumo, 2023).

## 2.2. Novel policies

Colombia's beef and dairy ZDAs are public-private initiatives developed by multi-stakeholder groups led by the national government. They were first signed in May 2019 by a mix of government, nongovernmental organizations (NGOs) and companies, and actors continue to sign on to this day. The dairy ZDA is the first commitment of its kind, and the beef agreement is only the second (following Brazil) despite pasture expansion being the primary global driver of tropical deforestation (Goldman et al., 2024; Pendrill et al., 2019). The aspiration is that these two policies will eventually be adopted sector-wide and support the country's forest conservation goals, leading to deforestation-free beef and dairy production and complementing other forest conservation efforts, such as forest policies and protected areas (PAs) (MSG, 2018; Furumo and Lambin, 2020). The dairy ZDA prohibits land cover change in Colombia's páramos, a tropical alpine ecosystem. Páramos are critically important for conservation due to their high incidence of endemic species, especially plants and birds, soil carbon density and the role they play in hydrological cycling (Hofstede et al., 2003; Sarmiento et al., 2013; Rangel-Churio and Pinto-Zárate, 2012).

Beef and dairy companies sign on to the ZDAs, which like many supply chain commitments are voluntary (Byerlee and Rueda 2015), and pledge to eliminate deforestation and páramo conversion (in the dairy

ZDA) from their supply chains. To realize this pledge, signatories agree to avoid purchasing from suppliers with land conversion in the relevant land covers since the signing date (i.e. May 2019) and to require suppliers who cleared forests or páramos (in the dairy ZDA) between 2011 and the signing date to have action plans to conserve and restore deforested areas (Secretaría Técnica, 2019a; Secretaría Técnica, 2019b). Monitoring and compliance with this aspect of the ZDAs is not clearly specified and given the scale of recent deforestation, these efforts would not be insignificant. The ZDAs call for monitoring on all properties on which an animal lived; this poses a challenge as the country does not yet have a national traceability system that enables monitoring the full cattle supply chain. Companies are motivated to sign the ZDAs due to a desire to differentiate their products in the domestic market based on deforestation-free and sustainable sourcing practices, to position themselves for access to new markets and to alleviate pressure from the ZDAs' participating government agencies and NGOs (Furumo and Lambin, 2020).

Participation by companies in the ZDAs is increasing but still limited, and both operationalizing the policy within companies' supplier base and implementing monitoring and traceability by signatory companies is nascent. At present, the data needed to identify and map producers' properties and to track their products is not readily available. Colombia has a robust national forest monitoring system and recent momentum to create a national animal traceability system, but cattle movements are currently registered by groups of animals and only for sanitation purposes. As a result, signatory companies beginning to implement the policies are in various stages of adapting available data and building their own datasets by mapping their suppliers, socializing the policy amongst them, and conducting analyses of forest cover and deforestation, sometimes using monitoring and traceability tools and often working with NGO support. These datasets and their results are not publicly available.

See Table S1 for a list of signatories. There are 49 signatories to the dairy ZDA, including 21 companies, 15 of which collect and process milk, plus three restaurant chains and six rancher or industry associations. There are 50 signatories to the beef agreement, including 11 rancher or industry associations and 16 companies, which occupy different positions in the supply chain, such as individual farms, restaurants, slaughterhouses and grocery chains. In Brazil, slaughterhouses have served as the most important leverage point in the supply chain. Slaughterhouses in Colombia also play an important role linking ranches and buyers, and often already maintain internal data systems. However the majority have less influence over the suppliers of the cattle they process because they do not buy animals directly –instead, functioning as service providers contracted by clients to slaughter animals (Vianchá et al., 2020).

The dairy agreement covered at least 28 % of the dairy sector in 2023, significantly up from 9 % in 2019, based on market share calculated from the annual revenue of 83 top dairy companies (La Nota, 2023a) (Fig. S2A). There are a number of smaller dairy companies participating whose annual revenue is too small to feature in this estimate. Signatory companies to the dairy ZDA have at least 7,600 direct suppliers and more than 15,000 indirect suppliers, and collect 784 million liters of milk annually (Table S2). There are 99,000 specialized dairy producers and 250,000 dual-purpose dairy producers in the country yielding more than 7.3 billion liters of milk annually (Carulla and Ortega, 2016; Nivia Osuna et al., 2018). Despite having hundreds of thousands of producers and thousands of small processors, the dairy sector in Colombia is more consolidated than the beef sector, with a relatively small group of large companies that control much of the market. The beef ZDA includes 4 % of the market share of companies directly involved in beef processing and sales. However the ZDA has been signed by two grocery chains that together make up 32 % of the grocery market. There are also several smaller beef retailers and restaurants that are not captured in either of these estimates (La Nota, 2023b)(Fig. S2B). Of the signatories to the agreement, rancher

associations have at least 3,200 producers in their membership, beef retailers reported over 200 high-volume direct suppliers and individual slaughterhouses had an average of 1,289 direct suppliers over the three-year period of our animal movement dataset (Table S2). The whole beef sector in Colombia produced 707,000 tons of beef in 2023 from 55,000 direct suppliers associated with 150,000 indirect suppliers (Fedegan, 2023; ICA, 2023).

### 3. Material and methods

#### 3.1. Animal movements and geocoding

Cattle movements between owners and their properties, or to fairs and slaughterhouses must be recorded in a form called a *guía sanitaria de movilización interna de animales* or “*guías*” utilized by the national livestock agency, the *Instituto Agropecuario Colombiano* (ICA) for sanitary purposes. The *guía* registers animal movements, the majority of these are sales, though in theory, any movement, even between a producer’s own properties should be reported. Animals are tracked as a group not as individuals. We obtained three complete years (2018–2020) of anonymized *guía* data via a *derecho de petición* or a solicitation for public information to ICA. We geocoded these movement records consisting of 4.6 M transactions. Each transaction can be geocoded to sub-national administrative units, municipalities or *veredas*, using place names from text fields in the *guías* that identify their origin and destination. Unique cattle producers (individuals or businesses) and unique production locations can be distinguished in the data, but our data did not include enough identifying information to link transactions to individual property maps as done in previous work in Brazil (Skidmore et al., 2021, West et al., 2022). Nonetheless, these matched records create a wall-to-wall spatially explicit map of the cattle supply chain from the subnational administrative units where cattle are sourced to slaughterhouses.

We classified transactions by movement types and found that animals are moved by producers between three types of locations: properties, animal concentrations, and slaughterhouses, resulting in six types of transactions in the data. Each transaction associated with a property, hereafter “producers,” has two identifiers, which enable us to distinguish individuals or businesses and unique production locations but not to link to a physical property boundary. Animal concentrations, hereafter, “fairs,” refer to a movement that took place in a venue, permanent or temporary, that brings together a large number of animals for commercial or recreation purposes. Fairs must be registered with ICA and can take many forms and serve many purposes. Most movements of this type are associated with livestock auctions and fairs. This does not include feedlots, which fall under the producer category. Slaughterhouses are livestock processing facilities, and are registered with ICA as well as the national sanitation agency, see below for more details on their identification (INVIMA, 2020). Transactions that originate with producers and end with slaughterhouses were classed as direct transactions. All other transactions are classed as indirect given that they pose the same risks for supply chain governance, in that, as a point of aggregation, animals of origins can be mixed and the land use for all associated properties becomes relevant to the whole group.

#### 3.2. Supply chain infrastructure

We obtained lists of infrastructure for both sectors (INVIMA, 2020, ICBF, 2018) and geolocated them using Google Earth, confirming the location with visual identification in available high-resolution satellite images in Google Earth or Google Street View (2022). If the facility could not be located, but was confirmed to be in operation, a point was placed in the center of the town.

For the beef sector, we geolocated slaughterhouses based on lists from the national sanitation agency, identifying 175 registered facilities that were active in 2020 (INVIMA, 2020). We used information about the certification status from these lists to class the 175 slaughterhouses

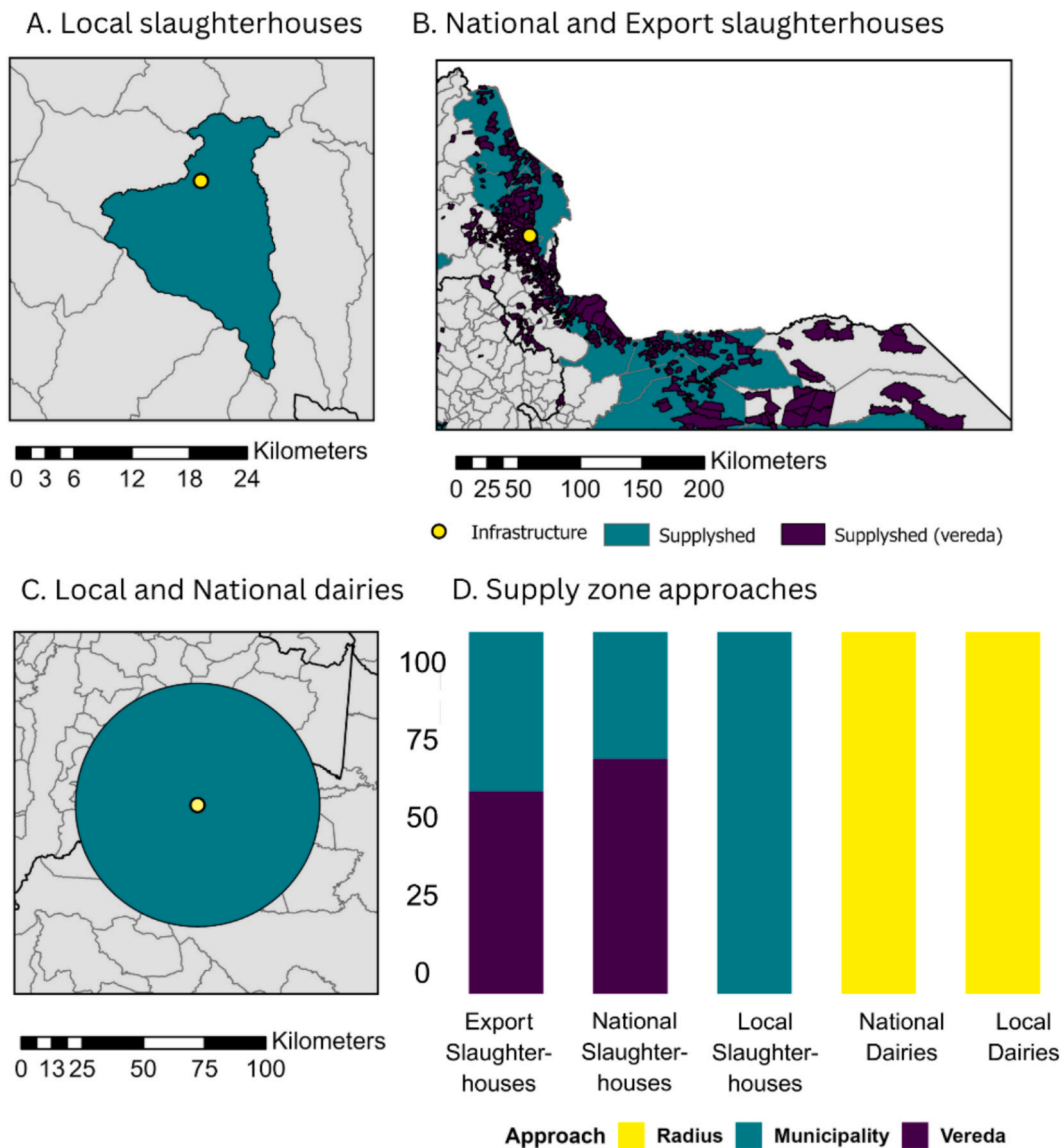
into three types: Export, National, and Local (INVIMA, 2020). Export slaughterhouses refer to those that meet the highest sanitation standards as demanded by global markets and are certified to export beef products. National slaughterhouses meet a national sanitation standard (Decree 1500) and their products can be distributed nationwide. Local slaughterhouses are exempted from the requirements of Decree 1500 but can only process cattle from the municipality in which they are located (Díaz and Burkart, 2019).

We searched for dairy collection and processing facilities based on censuses of food production establishments conducted in each department by the national sanitation agency in 2018; these lists contained 1223 dairy processing facilities (ICBF, 2018). Dairy facilities do not have a sanitary classification comparable to the beef sector, so we used the company’s market share to determine whether they were likely to serve national or local markets. Large companies found among the top 83 dairy companies by revenue were classed as “National” (La Nota, 2023a; La Nota, 2023b), all other companies were classed as “Local.”

#### 3.3. Supply zones

We created supply zones around each beef and dairy sector infrastructure point (for examples see Fig. 2). These zones are an estimate of the possible buying area, and in turn, the reach or influence of companies over producers. For National and Export slaughterhouses, we matched 1.2 M transactions to a mapped slaughterhouse to create individual supply zones. We used the finest scale administrative unit possible with our dataset: the origin *vereda* (when possible to match at this scale) or the origin municipality. Supply zones are the direct sourcing region for the slaughterhouse, but likely contain indirect suppliers who are often co-located in the same area as direct suppliers (Brandão et al., 2023). Less accurate geocoding, where transactions are linked to the municipality, overestimates the spatial extent of the supply areas compared to those delineated to a *vereda*. Given that some linking to the municipal scale is unavoidable with our dataset, these zones may represent an optimistic upper-bound estimate of policy coverage. For Local slaughterhouses, we used the municipality boundary as the supply zone, due to the sourcing and sales limitations mentioned above (FEDEGAN, 2023; Vianchá et al., 2020). For the dairy sector, although dairy ranches buy, sell, and move animals, we define supply zones as the sourcing area where milk could be collected frequently and generate a 50 km radial buffer around each dairy infrastructure facility. This catchment size was informed by the allowable distance for most of their suppliers reported in interviews with dairy companies (see Table S3 for a sensitivity analysis). While we do not expect that suppliers are located in a circle around infrastructure as their relationship with buyers is influenced by many factors, such as road infrastructure (Brandão et al., 2023), this method of defining supply zones for forest-risk commodities has been used to assess Brazil’s cattle agreements (Alix-Garcia and Gibbs, 2017; Barreto et al., 2017) and land cover impacts of oil palm in Cameroon (Ordway et al., 2019) and Indonesia (Heilmayr et al., 2020).

We used the supply zone dataset to map the ZDAs’ current reach and construct spatially-explicit scenarios that explore how these policies could be scaled up based on their adoption and implementation by different types of companies. Although supply locations were treated equally, future analyses could weight these zones by the volume of animals transacted to identify high-exposure areas and improved policy targeting. Because some ZDA signatories are outside of the processing stage of the supply chain, we took two approaches. For signatories like dairies or slaughterhouses, we used our infrastructure and/or animal movement data to locate them and map their supply zones. For signatories that are not involved in the processing stage of the supply chain, such as farms, restaurants, retailers or supermarkets, we relied on publicly shared supply chain data or information from our interviews. Associations were mapped only if they also are involved in processing. In the dairy sector, we mapped the supply zones of 20 of the 21 companies that signed the ZDA, but were unable to map one signatory, a restaurant



**Fig. 2.** Approaches used to map supply zones of beef and dairy infrastructure by type, A) Municipal boundary for Local slaughterhouses, B) Combination of vereda and municipal boundaries for National and Export slaughterhouses, C) Radial buffer for Local and National dairies, and D) Proportion mapped by each approach (median value for Export and National slaughterhouses).

group. In the beef sector, we were able to map the buying areas or partial buying areas for nine of the 16 company signatories, including the largest signatories from both the processing and retail stage. Many of these actors are only beginning to operationalize the ZDAs. See [Table S2](#) for more information on the ZDA signatories and the methods used to map each).

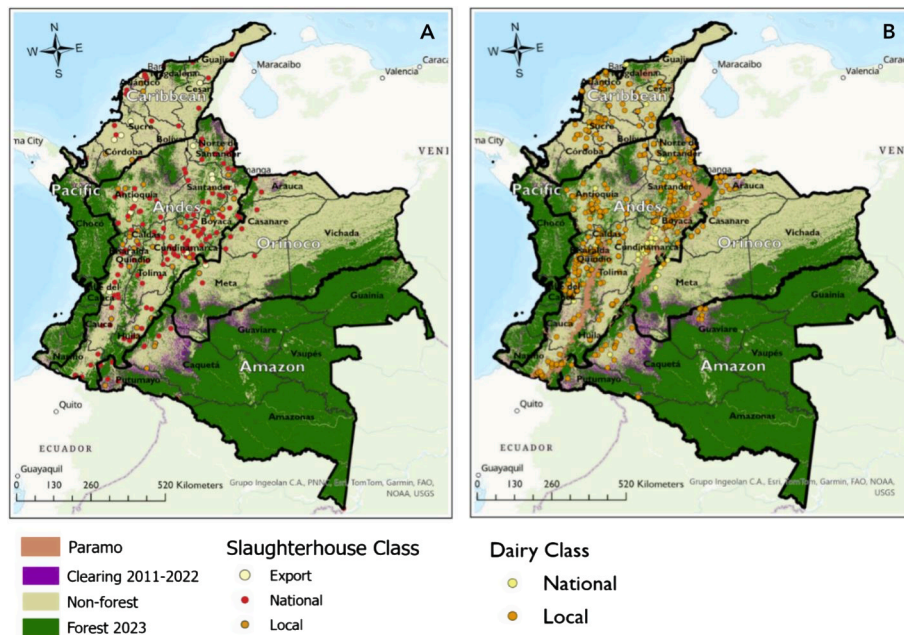
We assessed land cover in each supply zone. We used forest cover and forest cover change maps produced by IDEAM biannually for 2010–2012 and annually for 2013–2023 (IDEAM, 2024) and pasture maps for 2024 (IDEAM, 2024). For the dairy sector, we calculated the area of páramos (Morales-Rivas et al., 2019).

To better understand the structure and context of the ZDAs and inform our analysis, stakeholder interviews were conducted with dairies, slaughterhouse managers, ranchers, policy-makers, and companies in six departments during several visits to Colombia between June 2018–October 2023. Additional information about methods can be found in the Supplemental Information (SI).

## 4. Results

### 4.1. Mapping cattle supply infrastructure, actors, and cattle movements

We produced the first map of slaughterhouses and dairy production infrastructure for the beef and dairy sector (Fig. 3A–B). We geolocated all 175 registered slaughterhouses active in 2020, spatially referencing 19 Export slaughterhouses, 127 National slaughterhouses, and 29 local slaughterhouses (Table S3). Slaughterhouses, especially Export and National slaughterhouses, are concentrated in the Andes and Caribbean, with most Export slaughterhouses located near urban centers in these regions. We geolocated 727 dairy collection and processing infrastructure points, these included 133 National dairies and 594 Local dairies; the other 496 facilities in the census could neither be located nor confirmed to be operating (Table S3). This mapping included infrastructure for 61 of the top 83 dairy companies, totaling 91 % of the dairy sector by market share (La Nota, 2023a). National dairies were predominantly located in the Andes and Caribbean, while Local dairies were widespread throughout the country in urban and rural areas. The highest density of both types is in the Caribbean, Bogota’s savannah,



**Fig. 3.** A-B. Maps of cattle supply chain infrastructure by type in Colombia for A) the beef sector, and B) the dairy sector, showing deforestation (2010–2023), forest cover (2023), páramos (B only) and major ecoregions. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

Antioquia, and the coffee-producing region. The Amazon and Pacific regions, which have large tracts of forest and are less populous, have less supply chain infrastructure.

#### 4.2. Indirect sourcing poses risks for effective monitoring and traceability in the cattle sector

The indirect component of the cattle supply chain is predominant (Table S5). In our dataset, out of the 4.6 M *güía* transactions related to the movement of 50.2 M animals—with 16.7 M animals moved on average per year (Fig. 4B; Fig. S4-5); the majority (82 %) of animals were moved indirectly (Fig. 4B; Fig. S4-5). This makes it difficult for companies to know where an animal came from. The proportion of animals moved by indirect transactions was comparable (between 84–85 %) in the five major cattle producing departments (Antioquia, Córdoba, Meta, Casanare, and Caquetá) (Fig. 4B; Fig. S4-5), which together represent 48 % of all animal movements; however, it varies widely at the municipal scale (Fig. 4A). The proportion of indirect movements is lowest throughout the Andes, and increases with distance to major urban markets, in more geographically isolated population centers such as Leticia, Amazonas, and Inírida, Guanía. These municipalities have a low volume of movements and access to major markets, even indirectly, is more limited, resulting in a higher proportion of direct sales into small slaughterhouses. Indirect transactions are also more infrequent throughout Norte de Santander, along Colombia's border with Venezuela, which has restrictive sanitation requirements.

Many of the animals moved indirectly were moved through fairs, with 17.0 M animals moved in this manner over the three-year period. Fairs bring dispersed rural producers together to buy and sell animals for herd management or aggregation before slaughter. We identified 2,986 animal fairs. However, the bulk of these movements, or 60 %, occurred in just 47 high-volume fairs, each of which moved more than 100,000 animals.

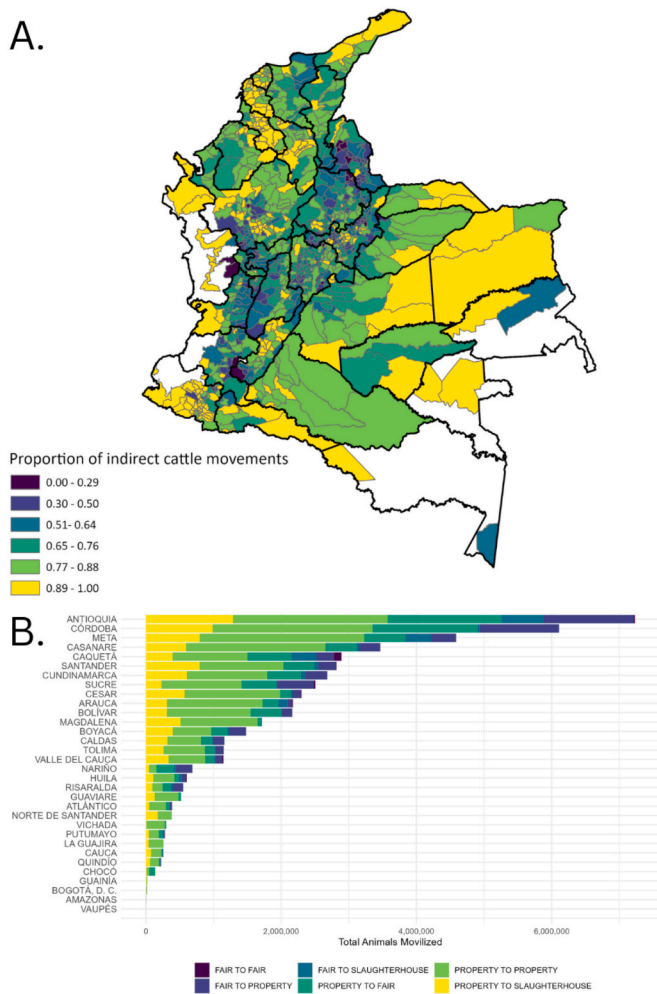
Colombia's cattle supplier base features a large number of producers, who play different roles in the supply chain, and many of whom operate from multiple properties. During the three-year period of the data, there were 262,031 producers who moved or received animals from 449,585 properties. Of these, there were 111,320 direct producers, or 42 %,

meaning that these producers moved animals to a slaughterhouse at some point during the three-year period. This group was associated with the movements of 33.9 M animals or 68 % of all animals moved (Table 1). Direct producers averaged 12 transactions per year associated with 126 animals moved. Their contact with slaughterhouses could place them within reach of a ZDA's monitoring and traceability system, which are likely to be implemented by or at slaughterhouses since they are important points of aggregation. The movement of animals to slaughterhouses represented less than half (38 %) of the movements by a direct producer on average (Table 1). There were an additional 150,711 producers, who only moved cattle indirectly over the same period (Table 1). These producers moved 8.0 M animals or 19 % of all animals moved. They averaged 3 transactions per year associated with 29 animals. While the production stage of the supply chain overall is a complex network of transactions, an individual producer is typically linked to just a few other producers. On average, a producer moved animals to 4 different other producers, though direct producers had twice as many connections as indirect producers. Only 5 % of a producer's animal movements were internal within their own properties.

#### 4.3. Scope of monitoring and traceability in slaughterhouse supply zones

Export and National slaughterhouses process almost all of the animals slaughtered. Nationally, 10.7 M animals were slaughtered from 2018 to 2020, with an average of 3.8 M animals slaughtered annually. We mapped 175 of these authorized facilities, where 92 % of animals were slaughtered. Just over half of animals (52 %) were slaughtered in National slaughterhouses, with most (46 %) of the remaining animals slaughtered in Export slaughterhouses, while 2 % of animals were slaughtered in Local slaughterhouses. Local slaughterhouses did not process a large volume of animals, but they served municipalities with lower population density, and less connection to markets where slaughter might otherwise happen clandestinely. Median slaughterhouse volume per year in Export slaughterhouses was just under 100,000 animals, and was 12,500 in National slaughterhouses during our study period (Fig. 5A).

The supply zones of both Export and National slaughterhouses spanned large areas and distances, with numerous direct suppliers. The reach of Export slaughterhouses was significantly higher therefore the



**Fig. 4.** A-B. A) Proportion of indirect cattle movements in each municipality, and B) cattle movements originating in each department by transaction type in Colombia during 2018–2020.

scope of monitoring would be as well. Export slaughterhouses had over 1,500 direct suppliers in a given year, while National slaughterhouses had 500 direct suppliers (Fig. 5B). Supply zones of Export and National slaughterhouses were made up of supplying properties from hundreds of veredas (Fig. 5C); for instance, the median number of supplying veredas was around 200 for National slaughterhouses, and was three times that for Export slaughterhouses. Except for a few outliers, where many animals are sourced from fairs, the median proportion of animals that arrived from fairs did not differ between slaughterhouse types and was less than 12 % (Fig. 5D).

#### 4.4. Indications of informality

There were 578 entities registered as receiving animal movements for slaughter in the data; although, only 175 facilities were authorized to operate over this period. The entities received 150,451 transactions totaling 643,936 animals (8 %). For the last decade, the national government has advanced policies to modernize slaughterhouse infrastructure, resulting in the official closure of many slaughterhouses that did not meet the new regulations; even so, some of these may continue to operate informally at a small scale (Romero et al., 2017; Ministry of Social Protection, 2007).

The national livestock census, which is derived from vaccination visits, found that the total number of cattle ranches over this period ranged from 600,578 in 2018 to a high of 655,661 in 2019 (ICA, 2023).

Our dataset represents the full record of cattle movements recorded during the time period; any producer not represented in the data either did not move cattle during the three-year period or did so informally. Because of the high incidence of informality in the sector, it is likely that at least a portion of the 25–32 % of cattle properties that do not appear in the *guías* operated informally to some extent.

#### 4.5. Importance of different types of companies for forests, deforestation, pastures and páramos

Individual supply zones in the beef sector are much larger than the dairy sector and in total cover more than twice the area of forests (Table 2; Fig. 6A-B). The combined reach of all Export and National slaughterhouses is comparable in both area and forest area, although there are only 19 Export slaughterhouses and 127 National slaughterhouses. Each type of processor has about a third of Colombia's unprotected forest area within their supply zones and over 70 % of recent deforestation. Much of the supply zones overlapped. National slaughterhouses sourced from more areas within the Andes, especially the southern Andes, and Export slaughterhouses supply zones extended further into the Orinoquia (Fig. 6A). Local slaughterhouses had constrained sourcing areas which were largely contained within the supply zones of other slaughterhouse types.

In contrast, in the dairy sector, the numerous Local dairies supply zones have high potential to extend the ZDA's forest conservation efforts. They encompass 9.7 Mha of forest, and 776,000 ha or 45 % of recent deforestation. The supply zones of Local dairies could extend the reach of the ZDAs to additional forest areas and deforestation hotspots. National dairies have 4.5 Mha of forest coverage within their supply zones, and are geographically concentrated in the mid-elevation Andes and Bogotá's montane savannah (Fig. 6B). The presence of many participating companies in the same areas could reinforce the ZDAs, even if it does not translate into broad coverage of forest area.

The dairy sector is also important for the conservation of Colombia's páramos outside of protected areas, where full participation of the sector would reach almost the entire ecosystem (96 %). National dairies have 1.4 Mha of unprotected páramos within their area of influence. The majority of the páramo area within Local dairies supply zones overlaps with this area, but the participation of Local dairies adds 276,000 ha. Recruiting Local dairies with supply zones that encompass páramos into the ZDAs may be important to prevent leakage, which can occur when production restrictions or standards are introduced causing some producers to shift to markets with laxer standards.

#### 4.6. Scaling up ZDA policies: Current reach and policy participation scenarios

We mapped the ZDAs' current reach and constructed three spatially-explicit scenarios for expanded participation in the policies that explore how these policies could be scaled up based on their adoption and implementation by different types of companies (Table 3). Since signatories are just beginning to map their supply chains and implement the policies, even the current reach of ZDA signatories does not yet ensure zero-deforestation sourcing in their supply zones. All supply zone maps are based on the direct sourcing region for each mapped slaughterhouse and dairy; however, full implementation of the ZDAs for both sectors requires tracing animal movements to indirect suppliers, and can include companies from different positions in the supply chain.

The supply zones of current ZDA signatories contain 23 % (10.4 Mha) of forests and cover 574,000 ha of recent deforestation (33 % of deforestation between 2010–2023) (Table 3; Fig. 7A-H). Although a larger share of companies in the dairy sector are signatories, the bulk of this area (8.0 Mha of forests and 507,833 ha of deforestation) comes from the extensive supply zones of a group of slaughterhouses that have signed the ZDAs. Although this area is large, the number of signatory companies sourcing from these same areas is limited and many non-

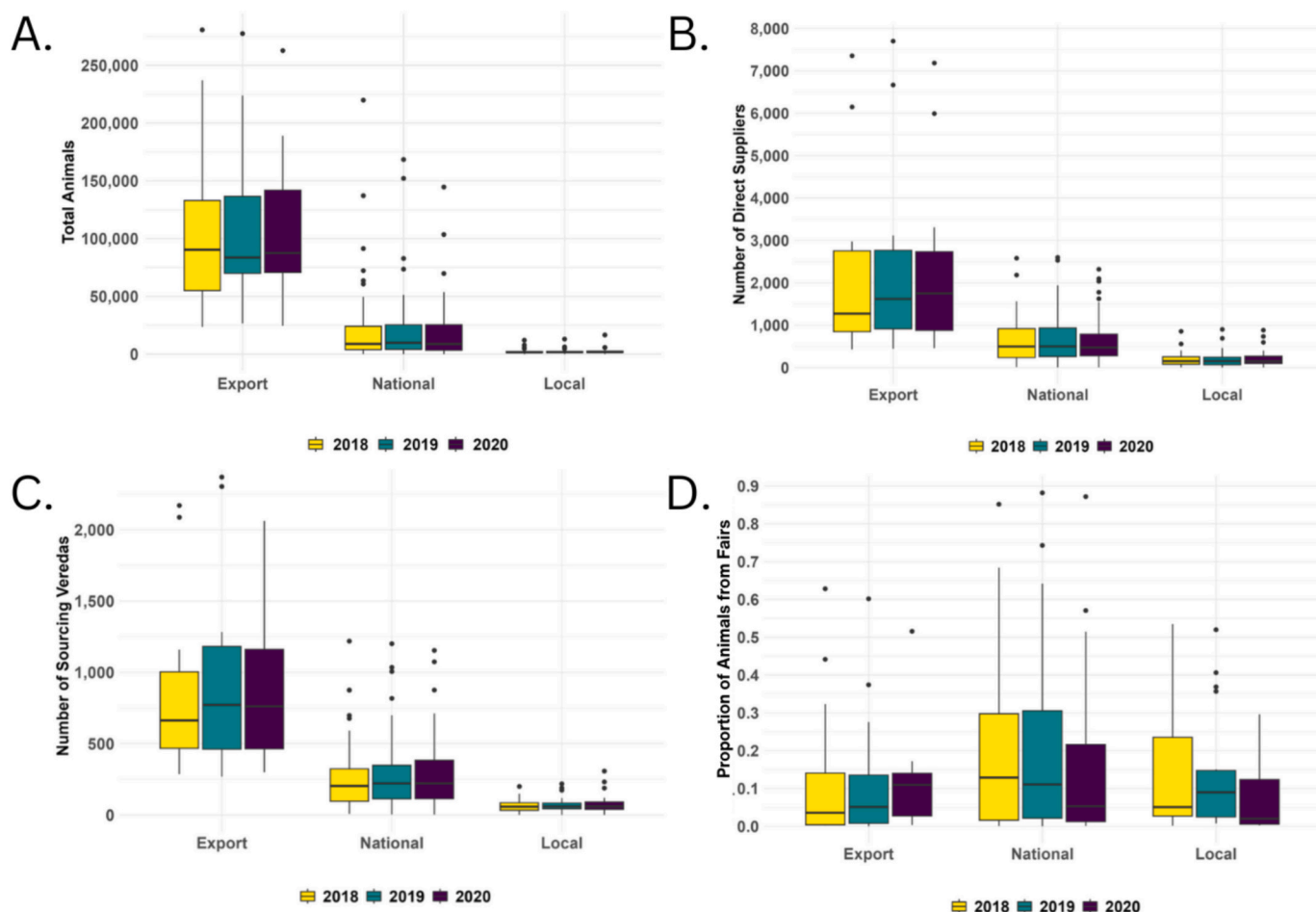


Fig. 5. A-D. Boxplots characterizing slaughterhouse supply zones by type (Export, National and Local) per year (2018–2020), A) Number of animals slaughtered, B) Number of direct suppliers, C) Number of different veredas from which cattle are sourced, and D) Proportion of animals moved via fairs.

Table 1

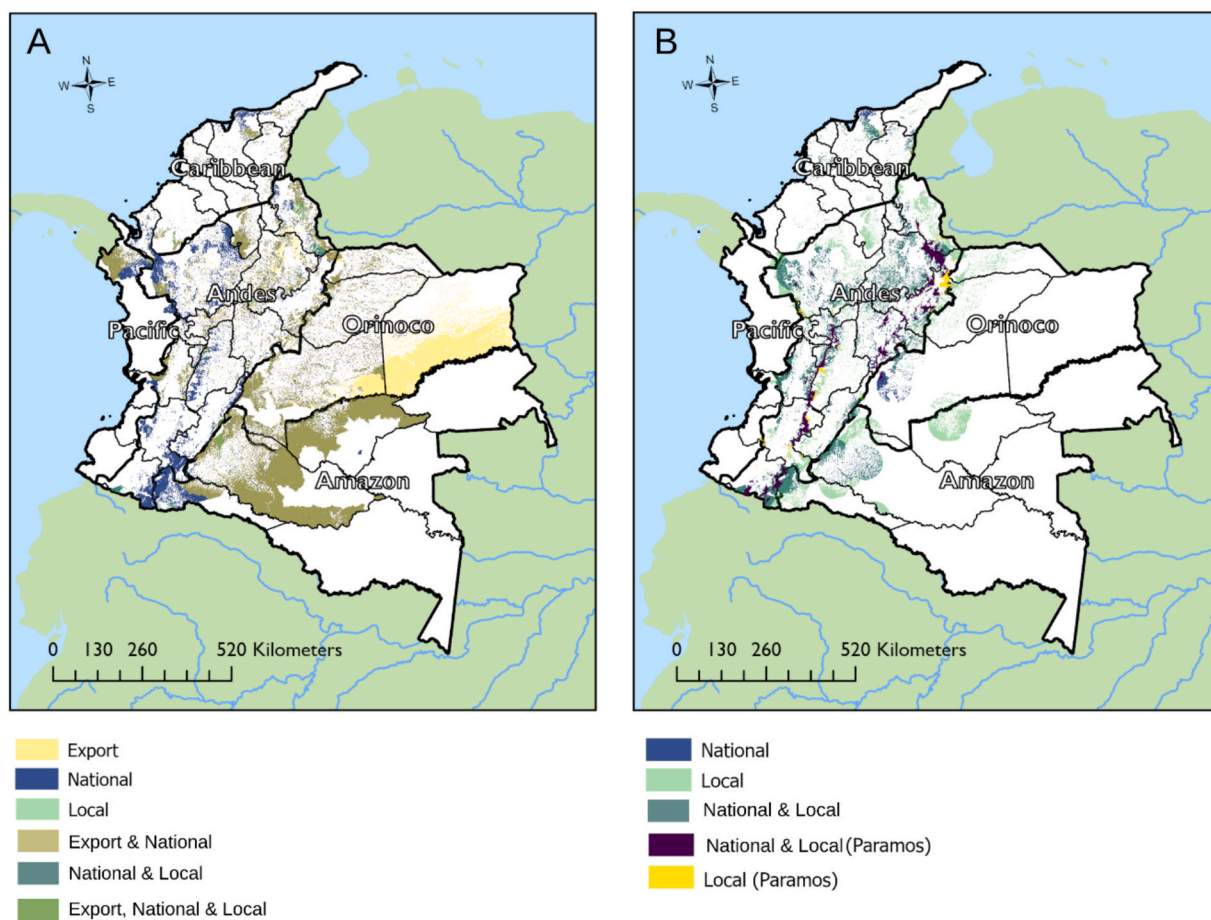
Average producer behavior across all producers, direct producers (those who moved cattle at least once to a slaughterhouse) and indirect producers (those who did not move cattle to a slaughterhouse) during 2018–2020.

	Count of producers	Volume (head of cattle)	Number of annual transactions		Volume (head of cattle) of animals moved annually		Proportion of animals moved directly		Number of properties they move animals to	
	(Total)	(Total)	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)
All producers	262,031	41,958,848	7.24	20.81	77.65	361.02	0.16	0.29	4.21	7.87
Direct producers	111,320	33,970,451	11.33	28.48	125.97	498.53	0.38	0.33	6.21	11.11
Indirect producers	150,711	7,988,397	2.99	6.20	29.48	90.41	–	–	2.73	3.46

Table 2

Coverage of forests (2023), recent deforestation (2010–2023), pasture (2024), and páramos (dairy sector only) within supply zones of different types of companies in the beef and dairy sector.

Type of supply zone	Count	Area ha	Forest (2023)		Deforestation (2010–2023)		Pasture (2024)		Páramos	
			ha	%	ha	%	ha	%	ha	%
Export slaughterhouses	19	57,408,280	16,017,102	35.1	1,234,824	71.7	17,713,938	67.90	–	–
National slaughterhouses	127	61,333,588	15,212,525	33.4	1,335,490	77.5	21,821,888	83.64	–	–
Local slaughterhouses	29	2,812,085	929,164	2.0	58,331	3.4	828,184	3.17	–	–
Entire beef sector	175	72,710,269	20,239,277	44.4	1,485,124	86.2	22,881,983	87.71	–	–
National dairies	133	27,475,220	4,547,986	10.0	265,034	15.4	13,421,371	51.44	1,369,622	82.5
Local dairies	594	45,359,014	9,679,828	21.2	776,107	45.1	20,305,947	77.83	1,543,145	93.0
Entire dairy sector	727	46,830,788	9,953,619	21.8	791,148	45.9	20,841,968	79.89	1,599,181	96.4



**Fig. 6.** A-B. Coverage of forests (2023), and páramos (dairy sector only) within beef and dairy supply zones of different types of companies: A) Export, National and Local slaughterhouses, and B) National dairies, and Local dairies. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

**Table 3**

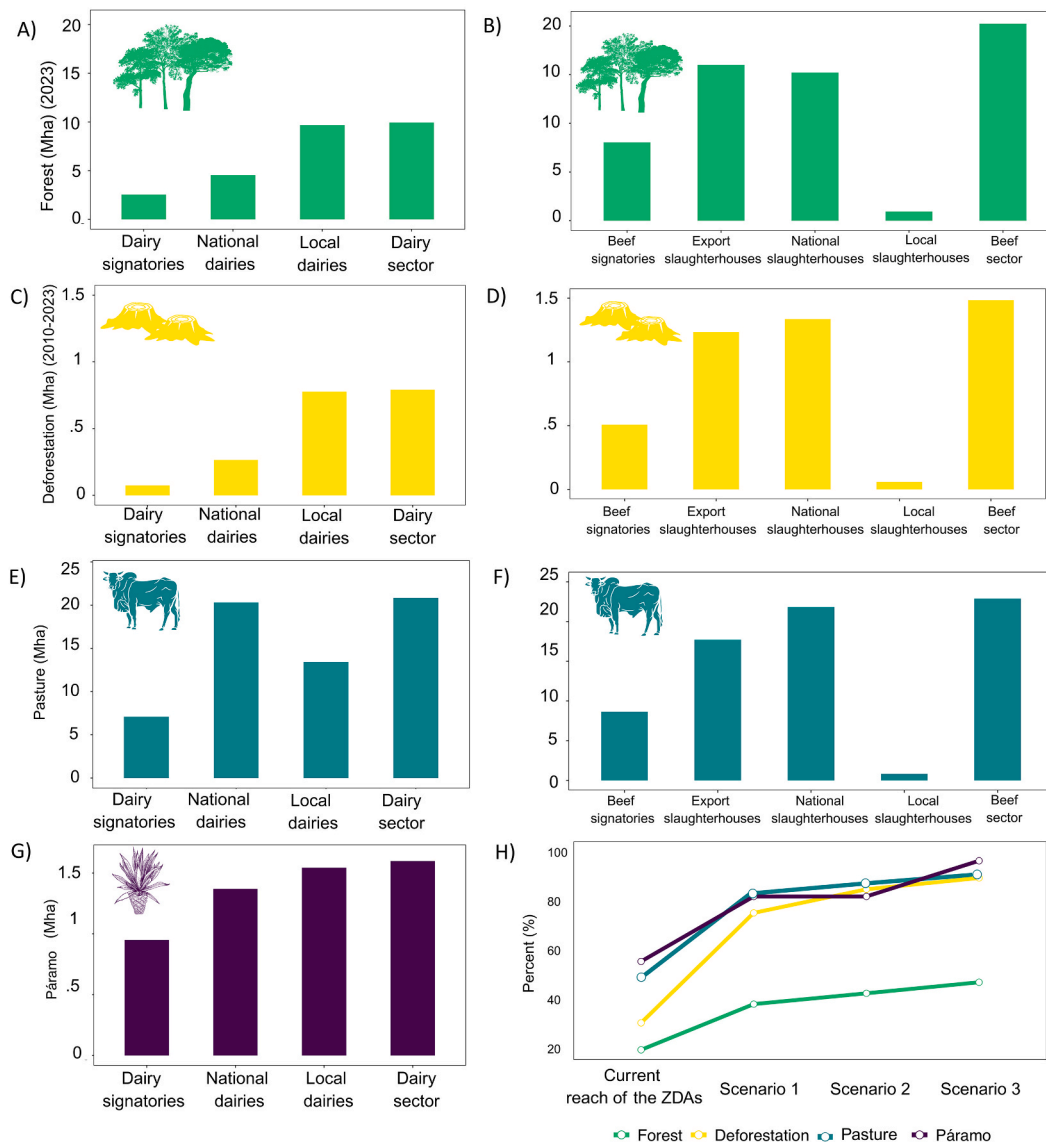
Current zero deforestation agreement (ZDA) coverage and three spatially-explicit policy participation scenarios, in terms of area in hectares and proportion of forest cover (2023), recent deforestation (2010–2023), pasture (2024), and páramos.

Current reach and scenarios		Count	Area	Forest (2023)		Deforestation (2010–2023)		Pasture		Páramos	
				ha	%	ha	%	ha	%	ha	%
<i>Current reach of the ZDAs*</i>	Supply zones of current companies that have signed the beef and dairy ZDAs	24	40,207,789	10,375,736	22.8	573,533	33.3	13,725,027	52.6	949,030	57.2
<i>Beef signatories</i>		6**	27,805,286	8,051,178	17.7	507,833	29.5	8,639,754	33.1	–	–
<i>Dairy signatories</i>		18***	14,943,855	2,542,819	5.6	74,763	4.3	7,103,655	27.2	949,030	57.2
<i>Scenario 1: Participation by the largest companies</i>	Current signatories plus supply zones of Export-oriented beef and National-oriented dairy infrastructure	160	68,136,080	18,521,899	40.6	1,310,843	76.1	21,797,215	83.6	1,369,622	82.5
<i>Scenario 2: Participation by medium sized companies</i>	Current signatories plus supply zones of Export-oriented and National-oriented beef and National-oriented dairy infrastructure	287	74,648,892	20,424,080	44.8	1,468,649	85.3	23,900,434	91.6	1,369,622	82.5
<i>Scenario 3: Full participation of beef and dairy sector</i>	Supply zones of all mapped beef and dairy infrastructure	1043	79,192,201	22,381,833	49.1	1,544,695	89.7	24,876,252	95.4	1,599,181	96.4

\*Given that signatory companies are in the early stages of mapping their supply chains and implementing the policies, the current reach of ZDA signatories does not guarantee zero deforestation sourcing in their supply chains.

\*\*There are 7556 mapped direct suppliers and four processing plants associated with these signatories.

\*\*\*There are 37 processing facilities associated with these signatories.



**Fig. 7.** A–H. Potential coverage in supply zones of zero deforestation agreement (ZDA) signatories and different types of companies in the dairy sector (left) and the beef sector (right) of A–B) forest (2023); C –D) recent deforestation (2010–2023); E –F) pasture (2024); G) páramos; and H) proportion of forest cover (2023), recent deforestation (2010–2023), pasture (2024), and páramos for current ZDA signatories and three spatially-explicit policy participation scenarios.

signatory companies also source from these areas, which can create risks of leakage (Fig. S6). Current signatories of the dairy ZDA have 950,000 ha or 57 % of unprotected páramos within their supply zones (Table 2; Fig. 7G). The ZDAs' reach is predominantly in the Cordillera Central and central Cordillera Oriental, with few companies participating with supply zones around large páramo complexes like Almorzadero and Santurbán-Berlin-Chili-Barragán.

Adoption by the largest companies in both sectors (Scenario 1) adds the participation of Export slaughterhouses and National dairies. These companies are most likely to be motivated to adopt the policies and be capable of implementing the traceability and monitoring requirements for zero-deforestation sourcing. Together, their supply zones covered 18.5 Mha of forest or 41 %, 1.3 Mha or 76 % of recent deforestation, and 1.4 Mha or 83 % of unprotected páramos (Table 3; Fig. 7H). These processors are located near major population centers, and in the dairy sector, they are concentrated in areas that have lost much of their forest cover. In the case of the beef processors, supply zones of this type of slaughterhouses are large and include cattle production landscapes that are quite distant from the actual processing infrastructure. This scenario represents a realistic increase in adoption of the ZDAs and would

increase the forest area within the policies' reach by 56 % over the area of current ZDA signatories' supply zones.

Adoption by medium-size companies (Scenario 2) adds the supply zones of National slaughterhouses. The majority of slaughterhouse infrastructure falls into this category and this expands the coverage to potentially include 20.4 Mha (45 %) of forest. This scenario includes a larger increase in coverage of recent deforestation and includes 1.5 Mha or 85 % of deforestation occurring outside of PAs (Table 3).

Full coverage of the formal beef and dairy sector (Scenario 3) is the most optimistic scenario and reflects the ZDA's goal of full participation (Table 3; Fig. 7H). This could cover 49 % of Colombia's forests outside of PAs, 90 % of recent deforestation and 96 % of páramos. Many of the supply zones of the companies added in this scenario overlapped with supply zones of those included in Scenarios 1–2 (Fig. 6A–B; Fig. S6). While participation by smaller companies adds just 4 % more area of potential forest coverage and 4 % more deforestation, it adds 14 % more páramo coverage. It could also have the benefit of reinforcing the coverage of the policies and reducing opportunities for leakage. Informal actors in the sector, which our analysis shows may be prevalent, could undermine this coverage. Additionally, while expansion of

pasture is the primary driver of deforestation, it is not the only driver in the supply zones, other important drivers are land grabbing (often linked to cattle), illicit crop production, illegal mining, and infrastructure expansion (González et al., 2018; FCDS 2024).

The pasture analysis can be found in the SI.

## 5. Discussion

### 5.1. Current and potential reach of zero deforestation agreements

The supply zones of current ZDA signatories include key deforestation hotspots, a sizable extent of Colombia's forests, and about half of Colombia's páramos. Although there are several high-profile signatories, the signatories from the beef and dairy sector represent only 60 % of the ZDAs' potential reach (Scenario 3-full participation) in terms of forest area, 37 % in terms of recent deforestation and 54 % in terms of páramos. Increased participation by key actors could greatly enhance the conservation potential of the ZDAs.

In the beef sector, reaching the majority of forests could be achieved by implementing ZDAs in the supply zones of 19 Export and 127 National slaughterhouses. These slaughterhouses act as aggregators and often slaughter animals that have traveled great distances. Because their supply zones span large areas, there is potential to influence adjacent areas as well as distant forests. The zones of influence of Local slaughterhouses have just a fraction both of the cattle supply chain and of Colombia's forests within their supply zones and largely overlap with Export and National slaughterhouses. These slaughterhouses are important to more isolated communities but have not met more stringent requirements such as the national sanitation standard, Decree 1500 (Vianchá et al., 2020), and might struggle to meet the ZDAs' traceability and monitoring requirements.

In the dairy sector, the story is somewhat different. Many National dairies already participate in the ZDAs and their supply zones tend to overlap those of signatory slaughterhouses, which could reinforce deforestation-free production in these areas. However, within the dairy sector, the majority of recent deforestation and forest cover are within the supply zones of Local dairies. There has been some promising uptake among Local dairies since the ZDAs launched in 2019, notably the signing of the ZDA by several smaller dairies and an association of 1,600 dairy ranchers in Caquetá. Local dairies like these do not have the same resources for implementing monitoring in their supply chains as National dairies and may require support. For páramos, having the participation of both Local and National dairies is critical for reaching conservation goals. Increased participation by Local dairies adds some páramo extents and their overlapping supply zones would reinforce the ZDAs in regions where larger actors already participate.

We identified considerable overlap among supply zones of these companies, which could serve to reinforce the policy. However, without increased participation, this type of overlap poses risks in terms of leakage because non-compliant producers have many options to avoid market exclusion (Brandão et al., 2023; Alix-Garcia and Gibbs, 2017, Levy et al., 2023). The actual overlap of companies' influence may be more limited than our supply zones indicate, as most companies only interact with a subset of the cattle properties within a supply zone. Refining estimates of a company's reach to just its current supplying properties would require finer scale data (spatial boundaries of properties).

Monitoring and traceability are essential for ZDAs to move from a pledge to an effective policy, but these requirements can prove challenging. Monitoring even direct suppliers requires having robust data systems in place that permit linking animal movements to accurate property boundaries. Traceability is also needed to identify the indirect origins of products, but this is especially difficult due to the mobility of cattle, which contributes to complex supply chains with many actors and sales (Klingler et al., 2018). Indirect sourcing is often not clearly addressed in ZDAs and can limit their effectiveness (zu Ermgassen et al.,

2022). The lack of adequate monitoring of supply chains, and especially of indirect suppliers, has reduced the effectiveness of similar agreements in the Brazilian Amazon (Gibbs et al., 2016; Alix-Garcia and Gibbs, 2017; Pereira et al., 2020). Our results portend similar challenges in Colombia's cattle supply chain, especially in the beef sector, as the majority of animal movements are between producers, with a large number of producers funneling animals to a smaller subset of producers that collect and aggregate animals (Carvalho et al., 2021; Tarrier et al. 2024). Only these last actors directly and regularly engage with the higher-up actors, like slaughterhouses and their clients, that are often targeted by ZDAs. Animal fairs or auctions also feature prominently in the cattle supply chain in Colombia, with 33 % of animals in our dataset either originating from them or being moved to them. In contrast, in Brazil only 6 % of transactions are associated with them (zu Ermgassen et al., 2020). It is promising that these movements appear in our dataset, and some fairs have well-developed data systems to manage auctions and host the sanitation agency to issue guías.

Signatories to the ZDAs are beginning to implement monitoring of their direct suppliers, but there remains a need to communicate the requirements of the ZDAs to these producers. Engagement with the indirect portions of their supply chain, which can span well outside of their immediate region will pose a greater challenge. Our results show that this accounts for the majority of transactions across Colombia, particularly in more remote regions, but also in the main cattle production centers of the Andes and Caribbean. The prevalence of informal activities is another challenge as these actors will be the most difficult to incorporate into traceability systems. The geographic pattern of indirect movements coincides with areas where there is less state presence, higher informality and more insecurity due to the presence of illicit activities and non-state actors (Murillo-Sandoval et al., 2023; FCDS 2024). Reaching this segment of the supply chain will require greater transparency of the guías data than is currently available and/or the implementation of a complementary traceability system, plus robust monitoring and clear rules for evaluating compliance of producers and addressing non-compliance. Animal-level tagging and traceability covering the full herd or significant portion such as is in place in Uruguay and Australia is a model of what is possible, but even a basic system could help advance the ZDAs.

A basic monitoring system could be most readily implemented in the Export and National slaughterhouses. While direct suppliers are relatively dispersed, the scale of monitoring required for National slaughterhouses is in the hundreds of suppliers, and around a thousand for most Export slaughterhouses, with only the very largest having several thousand suppliers. For instance, for an average National slaughterhouse to begin to implement monitoring and traceability requirements of the ZDA, it would need to start by monitoring 500 direct suppliers over a comparable period of time (three years) as our analysis, a feasible goal. Moreover, while most cattle movements were indirect, almost half of suppliers (42 %) moved cattle directly at least once. Again, over a comparable period of time, almost half of producers moving cattle and engaging in the formal market would come into direct contact with a slaughterhouse, and could be more easily incorporated into a ZDA monitoring and traceability system. Moreover, these suppliers moved 68 % of the cattle in the supply chain. Pairing monitoring with effective incentives for suppliers to remain in or regain compliance with ZDA requirements will also be essential.

There is concern that these types of policies could have unintended consequences on smallholders, potentially negatively impacting their participation in markets, income and well-being (DeFries et al., 2017; Furumo et al., 2020; Zhunusova et al., 2022). Similar cattle supply chain policies in Brazil have exemptions that exclude smallholders from requirements for monitoring and compliance (GTFI, 2025). These exemptions can be made without limiting the policy's effectiveness because larger properties are often more critical to include in supply chain-led forest conservation efforts, for instance, in Mato Grosso, Brazil, nearly 80 % of the forests that remain on private properties are on

very large properties (Richards and VanWey, 2016). Colombia's ZDAs do not exclude or have distinct protocols for smaller properties, of which there are many in Colombia. Indirect producers, which we define based on their position in the supply chain, may not be the equivalent to smallholders, but they move a fraction of the animals annually that direct producers move. These smaller producers, while numerous, are associated with only 18 % of overall animal movements. This unequal distribution of activity could provide an entry point for gradually implementing traceability systems while maximizing their impact (TARRIER et al., 2024).

## 6. Conclusion

Our results show that Colombia's ZDAs can play an important part in the conservation of Colombia's forests and páramos and already have significant coverage of forests and recent deforestation indicating that critical actors in the supply chain and the regions with the highest deforestation risk are within reach of these supply chain policies. The scenarios are even more optimistic for páramos. However, much depends on the extent to which the beef and dairy sectors adopt these new policies and how effectively they are implemented within the supply chains of individual companies. Our findings on the challenges and opportunities for advancing traceability in the context of the Colombian cattle supply chain can inform the implementation of the ZDAs sector-wide, and stakeholders are actively searching for solutions. For example, a non-anonymized version of the animal transaction data that we used for this analysis could be connected to property boundaries, which could form the basis of a robust monitoring and traceability system (Vianchá et al., 2020; TARRIER et al. 2024). Efforts to establish a national traceability system at the legislative level have stalled but hold promise. For these efforts to be successful, zero-deforestation cattle production and traceability systems must include the participation of critical actors in both the beef and dairy supply chain and be adapted to the Colombian context.

## CRedit authorship contribution statement

**Clare C. Sullivan:** Writing – review & editing, Writing – original draft, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Joseph App:** Conceptualization. **Lisa L. Rausch:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Steven Sotelo:** Writing – review & editing, Data curation, Conceptualization. **Daisy TARRIER:** Writing – review & editing, Data curation, Conceptualization. **Miguel Ángel Vianchá Pinzón:** Writing – review & editing, Investigation, Conceptualization. **Holly K. Gibbs:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Two authors report financial support was provided by a non-governmental organization, the National Wildlife Federation. The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

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