Fenced off: Measuring growing restrictions on resource access for smallholders in the Argentine Chaco

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Abstract

The rapid expansion of commodity agriculture worldwide is threatening forest ecosystems and the livelihoods of millions of people who depend on them. Forest-dwelling smallholders in agricultural frontier regions are facing mounting pressures due to changes in land control, notably through the privatization and enclosure of natural resources. Impacts of agricultural expansion on smallholders have been mostly measured through deforestation, yet changes in land control and associated pressures on smallholder livelihoods occur well beyond the limits of deforested areas. We propose a novel approach to evaluate changes in access to land for smallholders stemming from gradual changes in land control along commodity frontiers. We apply this approach in the Argentine Gran Chaco, a region that has experienced amongst the highest global rates of deforestation for agriculture in recent years. Our findings suggest that access to natural resources for smallholders has been reduced far beyond what would be expected if only looking at deforestation, and that the degree to which access has decreased differs between livelihoods. As such, this study highlights the fact that forest smallholders are likely facing pressures to shift livelihood strategies well in advance of the actual conversion of forest in their immediate vicinity.

Keywords: Access, agricultural frontiers, deforestation, Gran Chaco, fences

1. Introduction

Agricultural systems have undergone profound social and economic transformations over the last century, in the transition towards globalized trade and through the increasing involvement of large-scale, often transnational companies in agricultural production (Cotula, 2013). This global restructuring manifests most markedly as processes of agricultural intensification and expansion (Barbier, 2012; Meyfroidt et al., 2018), and has led to large-scale land-use changes that affect both ecosystems and societies in areas suitable for modern agriculture. Of particular concern is the threat that the expansion of commodity agriculture poses to forested ecosystems and to the people whose livelihoods depend on forest resources (Hazell & Wood, 2008; Newton et al., 2020). Between 1980 and 2000, more than 83% of new agricultural land in the tropics came at the expense of forests (Gibbs et al., 2010). Despite widespread corporate commitment to curb deforestation (Donofrio et al., 2017), the rate of commodity-driven forest clearing has continued unabated into the new century: approximately one quarter of global forest loss between 2000 and 2015 can be attributed to deforestation for commodity production, making international demand for primary agricultural products the dominant driver of deforestation (Curtis et al., 2018). In Latin America, pasture and cropland expansion accounted for about half of forest loss between 1985 and 2018 (Zalles et al. 2021). The conversion of forests to agriculture has caused severe impacts on biodiversity (Macchi et al., 2020), carbon sequestration (Baumann et al., 2017; Villarino et al., 2017; Harris et al., 2021), and other ecosystem services (e.g., Barral et al., 2020).

Along with the ecological ramifications of deforestation, changes to the dynamics of resource control that accompany the expansion of large-scale commodity production have implications for the hundreds of millions of forest-dwelling smallholders (hereafter "smallholders") whose livelihoods depend on access to forest resources and services (Newton et al., 2020). The acquisition of land and the concentration of resources by agribusinesses, two processes linked to the development and expansion of large-scale commodity production, exacerbate existing pressures on forest smallholders (Borras & Franco, 2012). Notably, the prevalence of poverty and tenure insecurity in forested regions of low-income countries accentuates the reliance of smallholders on forest ecosystem services (Scoones, 2015) while simultaneously making them disproportionately vulnerable to dispossession and displacement (Agrawal, 2007). Where smallholders are not fully displaced, they may shift livelihood strategies in order to “hang in” (Dorward et al., 2009), potentially entering into poverty traps where poverty and the absence of property rights reinforce resource degradation (Hazell & Wood, 2008). As such, the appropriation of land and resources by agribusinesses may very well undermine smallholder livelihoods in ways that go beyond their direct displacement from deforested areas. Commodity frontiers, understood as “areas where the production of agricultural commodities (e.g., beef, soy, or palm oil) by large-scale farms expands over other land uses” (le Polain de Waroux et al., 2018), are thus not only environmental transition points, but also social arenas of resource competition characterized by actors with starkly asymmetrical competitive abilities.

Given the continued expansion of commodity frontiers (Laurance et al., 2014; Zalles et al., 2021), understanding their social outcomes is of critical importance. Yet the spatial representation of commodity frontier impacts remains focused on relatively simple measures such as the amount of deforestation in an area. While deforestation is directly related to habitat modification and can thus be used to assess the potential ecological impacts of commodity frontier expansion (Ochoa-Quintero et al., 2015), a binary measure of deforestation (i.e. forest cover vs. no forest cover) fails to account for the more complex social impacts that stem from gradual changes in resource control dynamics.

To effectively reduce the vulnerability of smallholders and support their adaptation, policies must address the full range of impacts of commodity frontier expansion on livelihoods, beyond the visible displacement of populations from deforested areas. Accordingly, in this article, we propose a novel spatial measure of access to land that can be used to more comprehensively examine the potential impacts of commodity frontier expansion on smallholder livelihoods across time and space. We start by outlining the conceptual foundations of the proposed approach and then apply it to examine the potential social impacts of a commodity frontier of the Argentine Gran Chaco in South America, a region whose high rates of deforestation are related to large-scale cattle rearing and the production of soybeans for export. We conclude with a discussion on the applicability of the approach and suggest directions for future research.

2. Background

2.1 Frontiers and access

Commodity frontier expansion is a multidimensional process characterized not only by the conversion of land to pasture and cropland but also by processes of land control – the "practices that fix or consolidate forms of access, claiming, and exclusion for some time" (Peluso & Lund, 2011). These processes take place beyond the visible extent of land-use change, in areas beyond the 'edge' of the deforestation frontier. In contemporary frontiers, the arrival of novel actors, the enclosure and privatization of resources, processes of territorialisation and legalization, and the use of force and violence, all act as agents of change in those processes (Peluso & Lund, 2011). Although changes in land control along commodity frontiers can occasionally result in increased returns for some smallholders (Sunderlin et al., 2008), they more frequently result in their partial or complete dispossession in favor of the accumulation and concentration of resources by more powerful actors (Amanor, 2012).

In spite of the multi-dimensionality of commodity frontiers, the evaluation of their impacts continues to rely on relatively unidimensional metrics. The land-use and land-cover changes that characterize frontier expansion have been, and continue to be, at the forefront of academic interest. Most studies have used deforestation as an indicator of the expansion trends and spatial extent of commodity frontiers (Arvor et al., 2013; le Polain de Waroux et al., 2018; Walker, 2003). Land-cover changes have also been used as indicators of environmental degradation, namely of biodiversity loss, habitat fragmentation, and reduction in carbon storage capacities (Baumann et al., 2017; Chaplin-Kramer et al., 2015; Piquer-Rodríguez et al., 2015) and, to a lesser extent, as indicators of displacement pressures on local populations (Paolasso et al., 2012). However, with the exception of a few studies that have mapped the location of large-scale land deals (e.g., Anseeuw et al., 2012; Messerli et al., 2014), the spatial and temporal distribution of land control dynamics occurring within commodity frontiers have received limited attention (but see Faingerch et al., 2021).

The notion of *access* to resources provides a useful point of departure to disentangle the complex effects of land control dynamics occurring in commodity frontiers. Several theories and frameworks place *access*, "the ability to benefit from things" (Ribot & Peluso, 2003), as a central factor for explaining differences in both livelihood pathways and land-use outcomes (Batterbury

& Bebbington, 1999). The 'Capitals and Capabilities' framework, building on Amartya Sen's Capabilities approach (Sen, 1989), posits that livelihood choices must be understood in terms of people's access to different forms of capital (financial, social, physical, natural, and human) because it is access to those capitals that gives them the capability to act (Bebbington, 1999). The 'Environmental Entitlements' framework echoes this approach in the importance that it places on access, with a greater emphasis on land-use outcomes. Leach, Mearns, and Scoones (1999) contend, in presenting the framework, that it is access to resources, rather than simply resource abundance, that explains key resource management and governance issues. This disaggregated 'entitlements' approach acknowledges that access to and control over resources are socially differentiated, as are people's ability to interact with and modify their environment (Leach et al., 1999). Lastly, Ribot and Peluso's Theory of Access proposes that how access to land and resources is gained, maintained, and controlled depends on access mechanisms, including rights-based mechanisms, technology, capital, markets, knowledge, authority, social identities, and social relations (Ribot & Peluso, 2003).

Ultimately, the livelihood implications for smallholders of commodity frontier expansion depend on whether they are able to maintain their access to land and resources as the frontier progresses into later stages of development, which are marked by processes of resource appropriation and consolidation (Barbier, 2012). Where smallholders are not able to compete for land and resources, they may lose access to them. Loss of access occurs not just through the destruction of these resources (when a forest is cleared, for example) but also through physical or institutional exclusion resulting from the reinforcement of claims by fencing, privatization, or violence (Li, 2014; Makki, 2014). In response, smallholders may need to shift their livelihood strategies, for example by engaging in contract farming, wage labor, and migration for off-farm work (Reardon et al., 2009). If pressure is exerted strongly on all livelihood options, they may be forced to leave the area. Along with the existence of resources (i.e., resource quantity, or amount of forest and land), then, an important question becomes: to what degree are smallholders able to maintain access to resources and the land they are on? By asking how and where access to land and resources is changing with the expansion of control by outside actors, it is possible to start disentangling the potential impacts of these changes on different livelihood activities and in different locations. In this study, we use a commodity frontier of the Argentine Gran Chaco as a case study to examine the changes in access that accompany frontier expansion.

2.2 Commodity frontiers and access loss in the Argentine Gran Chaco

The Gran Chaco ecoregion of South America, a dry woodland region covering more than one million km^2 across Bolivia, Paraguay, and Argentina (Olson et al., 2001), has experienced amongst the highest global rates of deforestation for agriculture in the last decades (Zalles et al., 2021). Deforestation in the Gran Chaco has been driven by an increase in export-oriented production of soybeans, principally destined to overseas markets such as China, Russia, and the European Union (Piquer-Rodríguez et al., 2018), as well as by domestic and international demand for beef (le Polain de Waroux et al., 2019). The shift towards intensive production of agricultural commodities by capitalized agribusinesses has resulted in the development of a number of commodity frontiers, the expansion of which have had profound impacts in the Argentine region of the Gran Chaco (Brown et al., 2006). Between 1985 and 2013, more than 142 000 km2 of the Chaco's forests was replaced by croplands (38.9%) or grazing lands (61.1%) (Baumann et al., 2017).

Along with high levels of deforestation, the expansion of commodity frontiers in the Gran Chaco has also been accompanied by important socioeconomic changes (Gorenstein & Ortiz, 2016). In contrast to smallholders with a longer history in the region, the social actors that have recently become established there (namely agribusiness but also speculators and other investors) are integrated into global markets and have access to important streams of technological and financial capital (Gasparri, 2016). The arrival of these new actors introduces fundamental asymmetries with smallholders — in relation to capital, access to knowledge and technology, and government lobbying capacity — which have resulted in an increasingly polarized distribution of land and natural resources (Rivas & Rivas, 2009). Associated with the concentration of resources are practices of claiming and exclusion, in particular privatization and enclosure, that create both physical and institutional barriers across a landscape where resource use by smallholders is oftentimes communal (Altrichter & Basurto, 2008). Resource claims made by large-scale commodity producers are reinforced by inequitable legal disputes and mechanisms of intimidation (such as violence, verbal threats, and the killing of animals) (Goldfarb & van der Haar, 2016). In combination, the mechanisms used by actors engaged in commodity production to consolidate control over resources have ultimately resulted in the dispossession of many smallholders (Estrada, 2010).

Dispossession often results in the displacement of smallholders who are evicted from their homes as forests get converted to pasture or cropland (Gorenstein & Ortiz, 2016). It may however take subtler forms, implying a gradual loss in the ability to control access to resources that are fundamental to smallholder livelihoods (Altrichter & Basurto, 2008). For example, the fencing of a plot of land by outsiders and the strengthening of their claim to that land through violence and intimidation may impede smallholders from accessing a water source, or from hunting game and collecting forest products. Consequently, along with displacement pressures, the emergence of barriers to resource access that are associated to the enclosure and privatization of land may pressure smallholders to adapt by shifting livelihood strategies (Cáceres, 2015).

In this paper, we propose a novel approach to evaluate the potential impacts of expanding commodity frontiers on smallholder livelihoods that builds on the notion of access to land and resources. This approach uses visible features of the landscape to analyze the spatial distribution of people's ability to benefit from resources, thereby addressing an important shortcoming of existing methods using land cover to assess the impacts of frontier expansion and providing an efficient way to diagnose changing pressures on smallholder livelihoods at medium scales. This can then serve to identify areas and livelihoods at risk and target more in-depth livelihood analyses.

3. Data and methods

Our approach uses the mapping of landscape elements that represent limits to resource use – hereafter 'access barriers' – as a way to approximate access to land and resources for the exercise of certain livelihood activities. These access barriers simultaneously represent physical and institutional limitations to access – i.e., they can act as proxies, for example, for the cost of accessing a space both because it is on private property and one might experience repercussions from infringement, and because a fence makes physical access more difficult. The approach is divided into four parts: i. mapping access barriers; ii. creating a typology of access barriers according to the degree to which they restrict access to space for the performance of different livelihood activities; iii. generating and mapping an index of access to land and resources for different livelihoods; and iv. assessing the potential impact of access changes linked to commodity frontier expansion on the spatial and temporal dynamics of smallholder livelihood activities.

3.1 Study area

The study area is delimited by the legislative boundaries of the Department of Pellegrini, in the north-west of the province of Santiago del Estero in Argentina (26.2ºS, 64.2ºW), and spans 7,330 km^2 (Figure 1). In 2019, the Department of Pellegrini was receiving substantive pressure from commodity frontiers advancing from the core agricultural areas of the province of Tucumán. The principal actors directly involved in the conversion of forested land to agriculture were capitalized medium- and large-scale farmers from the province of Tucumán and, to a lesser extent, from Buenos Aires and Córdoba (Estrada, 2010; le Polain de Waroux et al., 2018). The oldest land-cover changes (before 2000) were concentrated in the south-west region of the Department, whereas more recent changes (2010-2019) occurred in the center of the Department. In the south-east and north-east of the Department, a large proportion of the landscape remained forested. Pellegrini therefore presented a range of frontier conditions within a limited area.

Large-scale commodity producers in Pellegrini expand over areas occupied by small-scale family producers often referred to as *campesinos*, or peasants. Campesinos across the region tend to practice a mix of livestock rearing, hunting, small-scale agriculture, and forest-product harvesting (including wood for fuel, charcoal, and construction, and non-timber forest products such as honey and medicinal plants) (Altrichter, 2006). We focus on charcoal, cattle, goat, and pig production as the four livelihood activities of interest for our analysis of the potential impacts of commodity frontier expansion.

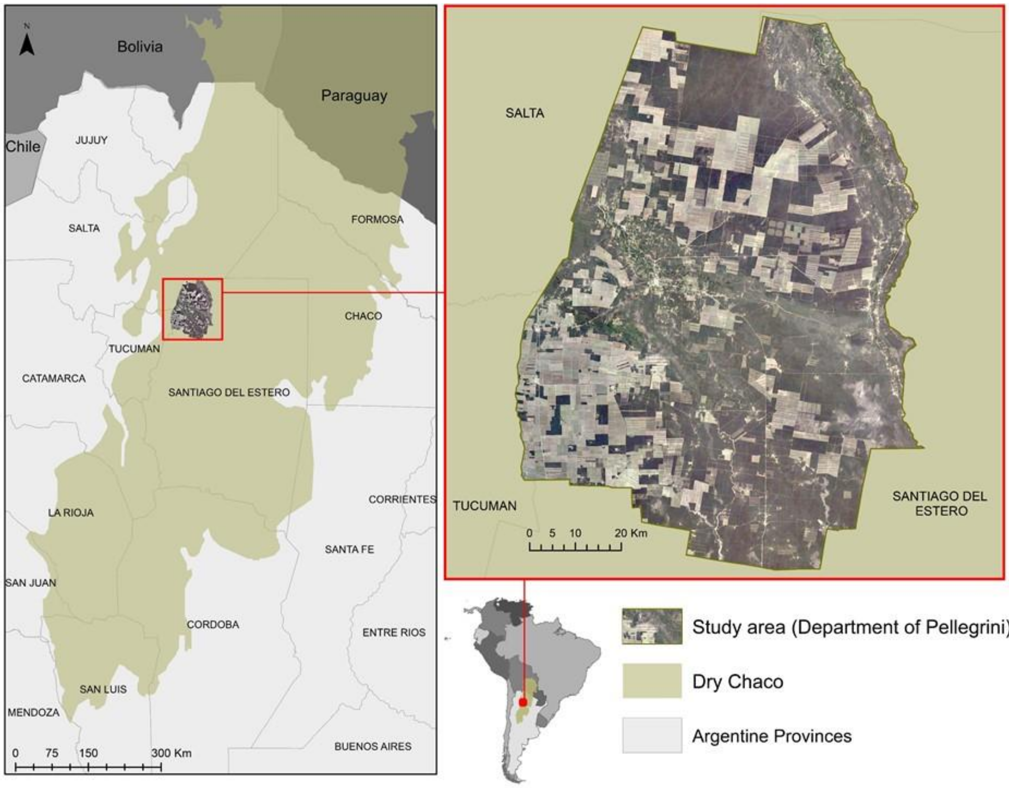

Figure 1. Study area. Landsat imagery for 2019 is displayed for the Department of Pellegrini.

3.2 Mapping access

3.2.1 Mapping, typology, and weighting of access barriers

We employed a methodology similar to that used by Seward *et al.* (2012) to map access barriers using satellite imagery. We considered all visible linear deforestation features within the study area to be potential access barriers and mapped them using the path tool in Google Earth Pro (2018), which provides access to yearly pre-processed Landsat mosaics at 30 m resolution. We mapped features for years 2000, 2010, and 2018 in an additive process, starting from existing features, adding those that appeared in the two subsequent periods and removing those that disappeared, which yielded three individual layers (Figure 2, step 1).

In order to assess how access to livelihood opportunities varied across the study area, we first identified the barriers relevant to campesino access by creating a typology of access barriers. The typology was informed by means of unstructured, conversational interviews with over thirty key-informants conducted between May and August 2019 by the first author (Figure 2, step 2).

Once the relevant access barriers (e.g., roads, fences) were identified and typified, we proceeded to visually classify the previously digitized line segments according to barrier type using visual interpretation in combination with a vector dataset of provincial and national roads from the Federal Ministry of Agriculture, Livestock, and Fisheries of Argentina (Figure 2, step 3). We then created a weighting scheme whereby each barrier type was assigned a relative *permeability* for the production of charcoal and for cattle, goat, and pig rearing, respectively (Figure 2, step 4). We refer to permeability as campesinos' (or their livestock's) ability to pass through or overcome a barrier to perform a given livelihood activity, acknowledging that permeability may differ between livelihoods for any barrier type. The weights were standardized between 0 (completely permeable) and 1 (completely impermeable). Altogether, we generated four livelihood-specific barrier maps, each differing in the weighting assigned to the different barrier types, for each time point analyzed, yielding 12 spatial layers.

3.2.2 Generating livelihood-specific access indices

Based on the maps of weighted access barriers, we developed a livelihood-specific Access Condition Index (ACI) representing the distribution of access conditions throughout the study area for different livelihood strategies in 2000, 2010, and 2018. We implemented the ACI using a custom spatial analysis workflow developed in the Python programming language with the ESRI Arcpy library (provided with ArcMap 10.6). To calculate the ACI, we first converted the permeability-weighted barrier layers from vector to raster format for each livelihood and year.

Second, for each 30 x 30 m raster cell, we computed a value representing the cost of crossing existing barriers to access resources in surrounding cells. To do this, we applied a cost-distance function to determine a fictive 'cumulative barrier friction' value between each cell and all other cells within a livelihood-specific buffer around it for use as an intermediary step in the index calculation (Figure 2, step 6). We set the radius values for the livelihood-specific buffers according to the typical maximum distances that each activity is conducted at, based on information gathered from interviews and literature (Figure 2, steps 5 and 6). The cost distance function accounts for the cost of sequentially encountering barriers as a person or animal moves through space: with a permeability value of 0 (fully permeable) attributed to all non-barrier cells, the cost distance from the buffer's center to a point in the buffer becomes a function of the number and permeability of (pixel-wide) barriers crossed. As a result, a higher output value was generated where more barriers and/or less permeable barriers are crossed.

Third, the 'cumulative barrier friction' values for each livelihood were weighted according to the ability to benefit from certain land covers. The cost-distance values for charcoal production were weighted by the availability of forest resources (deforested: 0, forested: 1). Because animals can graze on grass- or croplands as well as in forests, the cost-distance values for pig, goat, and cattle production were weighted as 1 for all landcovers.

Last, the final ACI value was computed for each cell in the study area by assigning it the land-cover weighted average of the cumulative barrier friction values across all cells in its surrounding buffer. For a given livelihood *ll* at a given time *t* (here 2000, 2010 or 2018) and location (pixel) *p*, the ACI can thus be expressed as follows:

$$ACI_{ll,t,p} = 100 \times \frac{\sum_{i}^{N_{ll}} \left(W_{ll,t,i} \times \left(\frac{1}{1 + F_{ll,t,i}}\right)\right)}{N_{ll}} \quad (Equation\ 1),$$

Where N_{ll} is the number of pixels *i* within a livelihood-specific radius of activity around *p*, $W_{ll,t,i}$ is the resource weight (between 0 and 1) assigned to each pixel *i* according to the livelihood-specific suitability of the land cover within that pixel at time *t* (determined in the previous step), and $F_{ll,t,i}$ is the cumulative barrier friction value calculated based on the number and distribution of weighted barriers between the focal pixel *p* and *i*.

The analysis resulted in a series of livelihood-specific maps, where the ACI values represent the relative degree of access to perform a certain livelihood activity from a given location. The ACI values ranged from 0, representing maximum access restriction within the buffer, and 100, representing no access restriction (i.e., 100% accessibility).

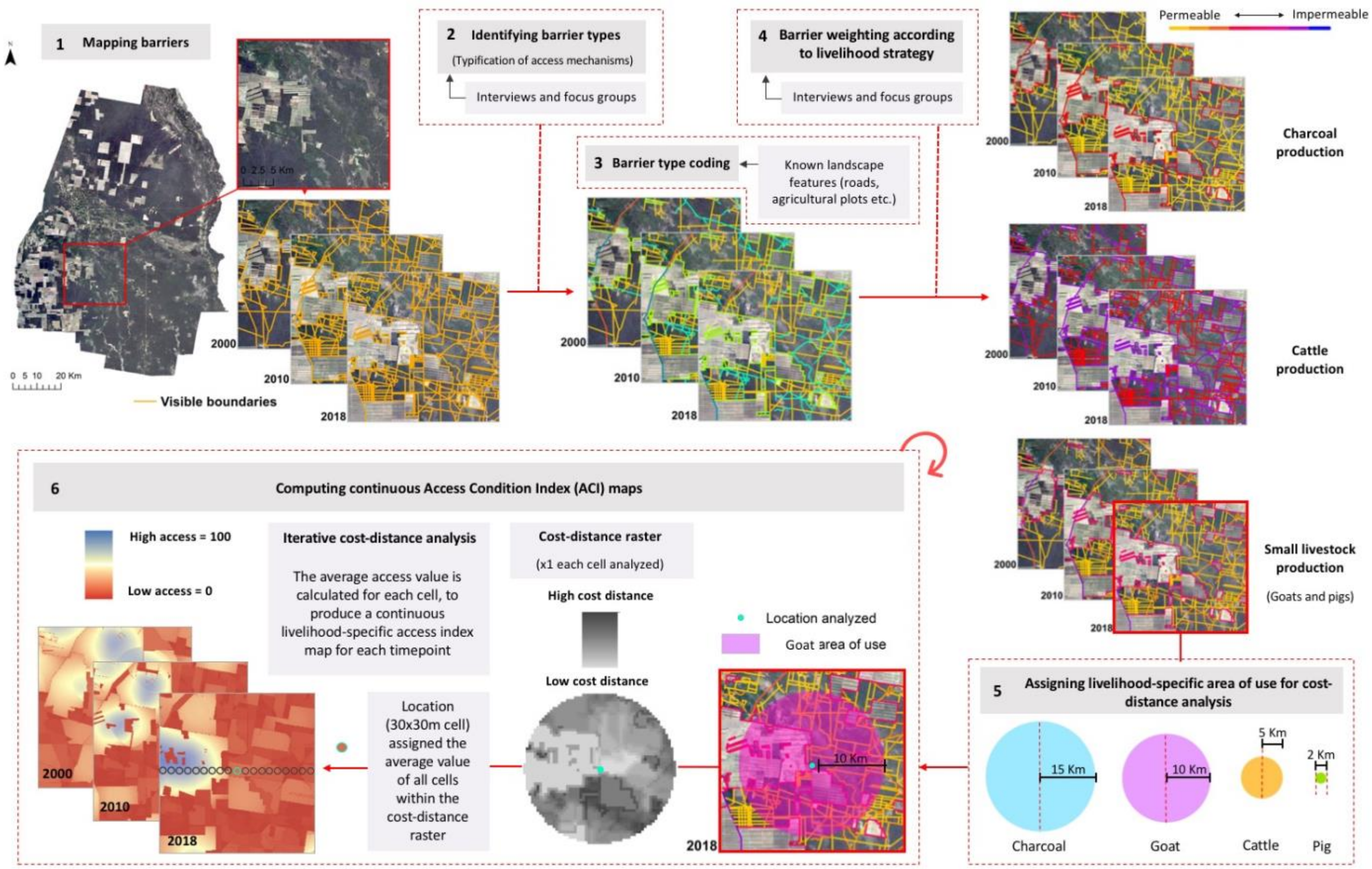

Figure 2. Schematic workflow for calculating the Access Condition Index (ACI).

3.3 Potential impact of access restrictions on livelihoods in the study area

To evaluate the potential impact of access restrictions on campesino livelihoods, we used community locations from the 2018 national agricultural census of Argentina (CAN 2018 – in progress at the time of this study), which we completed and corrected where necessary. We extracted the ACI values for each campesino community and year by assigning the average ACI value across a developed area polygon around the community. This was done to better approximate conditions experienced across the entire community rather than at an arbitrary, centralized location. We therefore used the census point locations for all 84 communities within the Department limits as a reference to visually map developed areas (deforested areas with apparent residential land uses) associated with each community and year using Landsat imagery. The ACI values for all communities were then examined to identify communities that may have experienced pressures to shift livelihood strategies or that potentially risked displacement, if pressures were exerted on all livelihood options. In order to visually convey spatial differences in ACI values between communities and across years, we manually delimited five sub-regions within the study area based on visual interpretation of community spatial grouping patterns, and assigned each community to the sub-region it was located within. The sub-regions are as follows: Centre-South (CS); Central Belt (CB); Eastern Flank (EF); North-West (NW); and South-West (SW).

3.4 Comparing approaches

Lastly, we computed a more conventional index of frontier impacts based on forest extent and forest loss data developed by Hansen *et al.* (2013) and contrasted it with the livelihood-specific ACI. The forest index is specific to each livelihood's area of use (i.e., the radius of the buffer used in generating the ACI) but not specific in the degree to which deforestation represented a restriction to access for the different livelihoods analyzed here. The Forest Index (FI) can thus be expressed, using the same structure as the ACI (*Equation 1*), as follows:

$$FI_{ll,t,p} = 100 \times \frac{\sum_i^{N_{ll}}(W_{t,i})}{N_{ll}} \quad (Equation\ 2),$$

FI thus considers availability of forest resources within a given livelihood buffer for each location analyzed, but differed from ACI in that it does not take into consideration barriers to accessing those resources (i.e. equivalent to $F_{ll,t,i} = 0$ in *Equation 1*). Moreover, $W_{t,i}$ is only dependent on time and location (not livelihood) as it was set to 0 for deforested pixels and 1 for forested pixels for all livelihoods.

4. Results

4.1 Typology of access barriers

Interviews indicated that fences represent an important barrier to land and resources for campesinos in the study area. The most common form is the wire fence (*alambrado*), which is made of several rungs of metal wire held taut by wooden posts spaced 2-3 meters apart. In general, the number of rungs reflects the purpose of the fence. Fences with fewer than four wire rungs serve to contain cattle and/or as physical markers of land claims. Fences with more than four wire rungs (averaging six) serve to contain smaller livestock, such as pigs, goats, and sheep. Among campesinos, the wire fence has largely replaced the traditional stick enclosure (*cerco-rama*). Where campesinos wish to enclose land, the high cost of wire and the labour required to erect fences are the main factors limiting the extent to which they are able to do so. In contrast, capitalized agribusinesses and investors do not face such limitations, and thus fence more liberally. Plots that have been converted to agriculture by agribusiness as well as forested land that has been claimed by capitalized actors are consequently almost always delimited by wire fencing. Fences can thus represent both a physical barrier and an institutional one.

Roads were identified as another important barrier for campesinos and their livestock for several reasons. According to Article 25 of the National Transit Law of Argentina (24.449), enforced at the provincial level through the penal code of Santiago del Estero (6.906, art. 155), the owners of property bordering on public roads must have fences that prevent animals from entering the road area, lest they be sanctioned. Moreover, public roads, which include small municipal roads, are fenced by the federal government along both sides. Roads themselves hinder livestock movement by making crossings dangerous: campesinos reported losing livestock due to collisions with vehicles. Finally, campesinos also reported that incidents of livestock robbery were more common near roads due to non-local transit. This combination of physical characteristics and social dynamics consequently make roads a composite type of barrier from the point of view of campesino access in the study area.

A third type of access barrier for campesinos are *deslindes*, demarcations in the form of deforested strips of land. In general, these demarcations serve to define the limits of claimed land, but they can also physically function as access passageways for properties. Access passageways are also seen as resource claims however, as they signify an active form of occupancy (Law 26.737). The extent to which these *deslindes* constituted barriers to access depended, according to informants, on livelihood activities. Livestock tends to cross back and forth freely through demarcations, but campesinos' access to harvest forest product (e.g., timber for charcoal) depends on the legitimacy and authority associated to the claim made through any given demarcation. Demarcations hence oftentimes represent institutional rather than physical barriers to access for campesinos.

4.2 Coding of access barriers

Because the insufficient resolution of the satellite imagery and a lack of available field validation data across the department did not allow us to distinguish between fences and demarcations, we classified any barrier located within the forest matrix (as opposed to roads or the edges of farmland, which are systematically fenced) as a single category representing either a fence or a demarcation. We hereafter refer to these barriers as "internal barriers". Roads were coded according to whether they were provincial, national, or municipal in order to capture differences in the volume of transit (and thus risk to livestock), as well as in the probability of theft. Farmland was identified visually from Landsat images for each timestamp in Google Earth. The municipal road dataset was outdated so we used it minimally for coding, and classified any internal barrier that was not a straight line as a municipal road. The municipal data were thus only used to identify municipal roads that bordered straight-line farmland boundaries.

4.3 Weighting of access barriers

The permeability value assigned to each barrier type was set to reflect a combination of the barriers' own characteristics and of the characteristics of the livelihood activity under consideration. For example, most fences have only three wires and are therefore relatively permeable for small livestock, but relatively impermeable for cattle. The permeability value of access barriers was also set according to whether these were internal (i.e., flanked on both sides by forest) or bordered farmland. Using fences again as the example, internal fences were weighted as more permeable for goats and pigs than fences bordering agricultural plots because of the heightened risks associated with animals crossing into open farmland (e.g., of animals being killed or claimed by farm owners as their own, both of which were reportedly frequent occurrences).

Because we considered overlapping barrier types (e.g., a road intersecting a farmland boundary) as having a cumulative effect, the classification process resulted in the following ranking, with gradually decreasing permeability: internal (i.e., within the forest matrix) fences/demarcations; internal municipal roads; internal provincial roads; internal national roads; fence on farmland boundary; municipal roads on farmland boundary; provincial roads on farmland boundary; and national roads on farmland boundary (Figure 3). To account for the combined fence/demarcation barrier type, we assumed that half of the internal fence/demarcation barriers were demarcations and that the other half were fences. Given that the former do not impede movement but that the latter represent a complete restriction for cattle movement, internal fences/demarcations received an intermediate permeability ranking (0.5) for cattle production activities. Because boundaries with farmland and roads were assumed to be completely fenced, all other barrier types were assigned permeability scores of 1 (complete access restriction) for cattle. The same rationale was used in weighting barriers for small livestock and charcoal production.

The final barrier permeability weighting scheme is provided in Table 1. A detailed description of the rationale behind barrier permeabilities and weightings, as well as additional details on the radii assigned to the different livelihood buffers, are available in the Supplementary Information (Appendixes A – C). The code necessary to reproduce this study is available through a GitHub repository link provided in Appendix E.

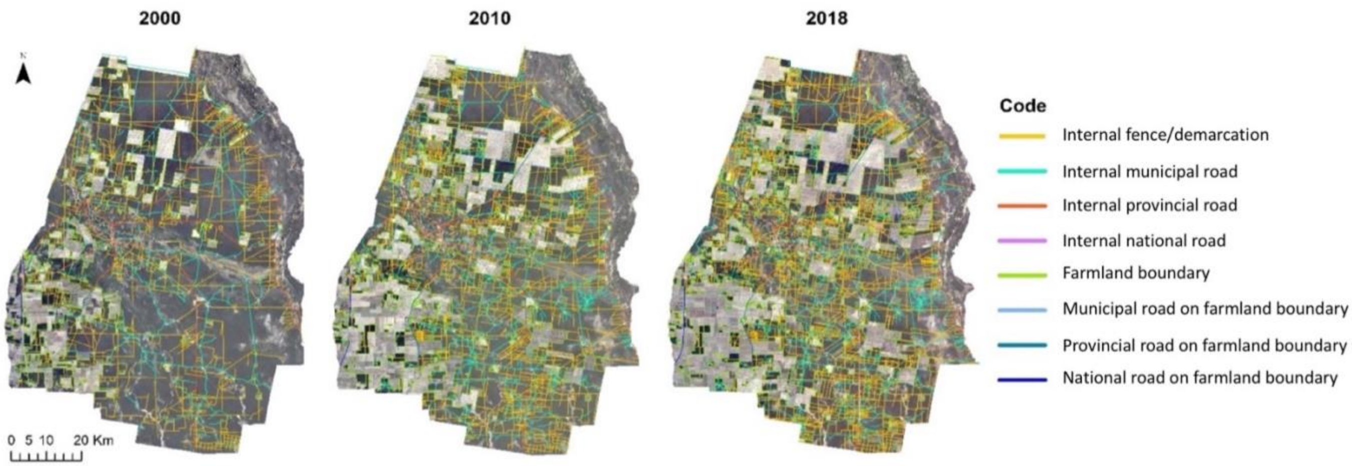

Figure 3. Distribution of barrier types in the Department of Pellegrini for 2000, 2010, and 2018, classified based on the barrier typology developed in this study.

Table 1. Barrier permeability weighting according to barrier type and livelihood

Livelihood	No barrier	Internal fence/ demarcation	Internal municipal road	Internal provincial road	Internal national road	Farmland boundary	Municipal road on farmland boundary	Provincial road on farmland boundary	National road on farmland boundary
Charcoal	0	0.1	0.1	0.1	0.1	0.5	0.5	0.5	0.5
Cattle	0	0.5	1	1	1	1	1	1	1
Goats	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Pigs	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8

4.4 Potential impacts of access restrictions on communities in the study area

There were noticeable differences in access conditions between regions, between communities within regions, between years, and between livelihoods. Figure 4 shows that continuous areas of high access for cattle, notably in the south-East of the study area, became increasingly fragmented by varying degrees of access restrictions between the three time points. Contrary to the general patterns of increasing access restrictions across the study area, the ACI increased (i.e. decreased access) in areas where forest was converted to agriculture (i.e. in the south-West). This is due to land parcel agglomeration by agribusiness, where internal fences are removed once a plot is deforested and cultivated. Because communities do not occur within agricultural plots, the ACI values for those areas do not reflect campesinos' actual lived conditions. While the index was mapped continuously for illustrative purposes, the ACI values that are of interest for the assessment of smallholder impacts are those within areas that are inhabited by smallholders, and that thus represent the degree of access to perform a given livelihood activity from their place of residence outwards over the area of use.

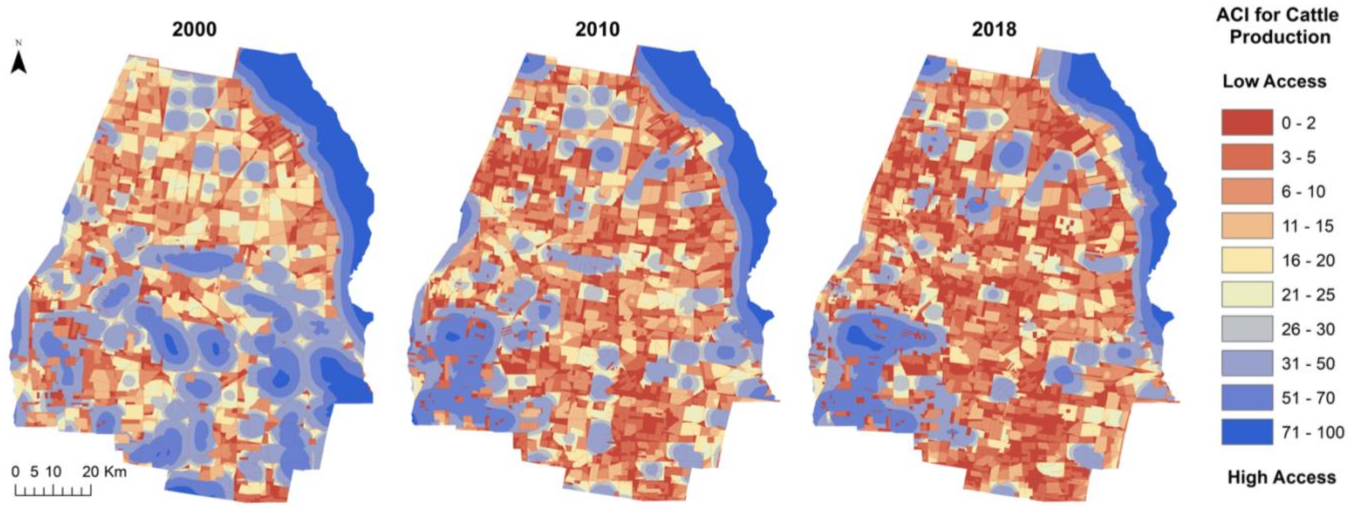

Figure 4. Access Condition Index values for cattle production. The higher the ACI value at a location, the greater the degree of access to resources from that location to perform a given livelihood activity.

Figure 5 shows ACI values averaged across developed areas of known campesino communities. Across years, access to land and resources was greatest for communities in what we call the Eastern flank (average cumulative ACI across livelihood categories = 32.5) and the Central belt (22.3), and most restricted in the North-West (16.3). Cumulative access also varied between communities within regions, in particular in the Eastern flank (Figure 5, panel a). Across all four livelihoods, the access index decreased by 22% on average between 2000 and 2010 (Wilcoxon signed rank test, $p < 0.01$), and by 14% between 2010 and 2018 (Wilcoxon signed rank test, $p < 0.01$). In other words, access to land and resources needed to conduct core livelihood activities became more restricted from 2000 to 2018 for forest-dwelling campesino communities in the study area (Figure 5, panels b and d).

Changes in the access index were not uniform across the four livelihoods considered. Across all years, access to land for pig rearing was greatest relative to the other livelihoods analyzed, while access to land for charcoal production was the most restricted. Moreover, the relative access between livelihoods varied both between communities and between regions. The level of access to space for charcoal production was maintained between 2000 and 2018 in the Eastern flank (albeit slightly reduced), while it became almost completely restricted across all other regions. Access to space for goat production also became severely restricted between 2000 and 2018 for all communities in the North-West, most in the Center-South, and for some in the South-West (Figure 5, panels a.1-a.3).

Finally, it should be noted that the community ACI values were already low in 2000. The cumulative ACI mean across all communities for 2000 was 113 out of a maximum total cumulative ACI mean of 400 (Figure 5, panel c). In other words, in 2000, communities had on average only 28% of their total potential access in a fully forested, unfenced landscape. The mean cumulative ACI dropped to 88 (+- Sd) in 2010, and 76 (+- Sd) in 2018, or 22% and 19% of the total potential access, respectively. The ACI values for all communities in the study area are provided in Table 1. of Appendix D.

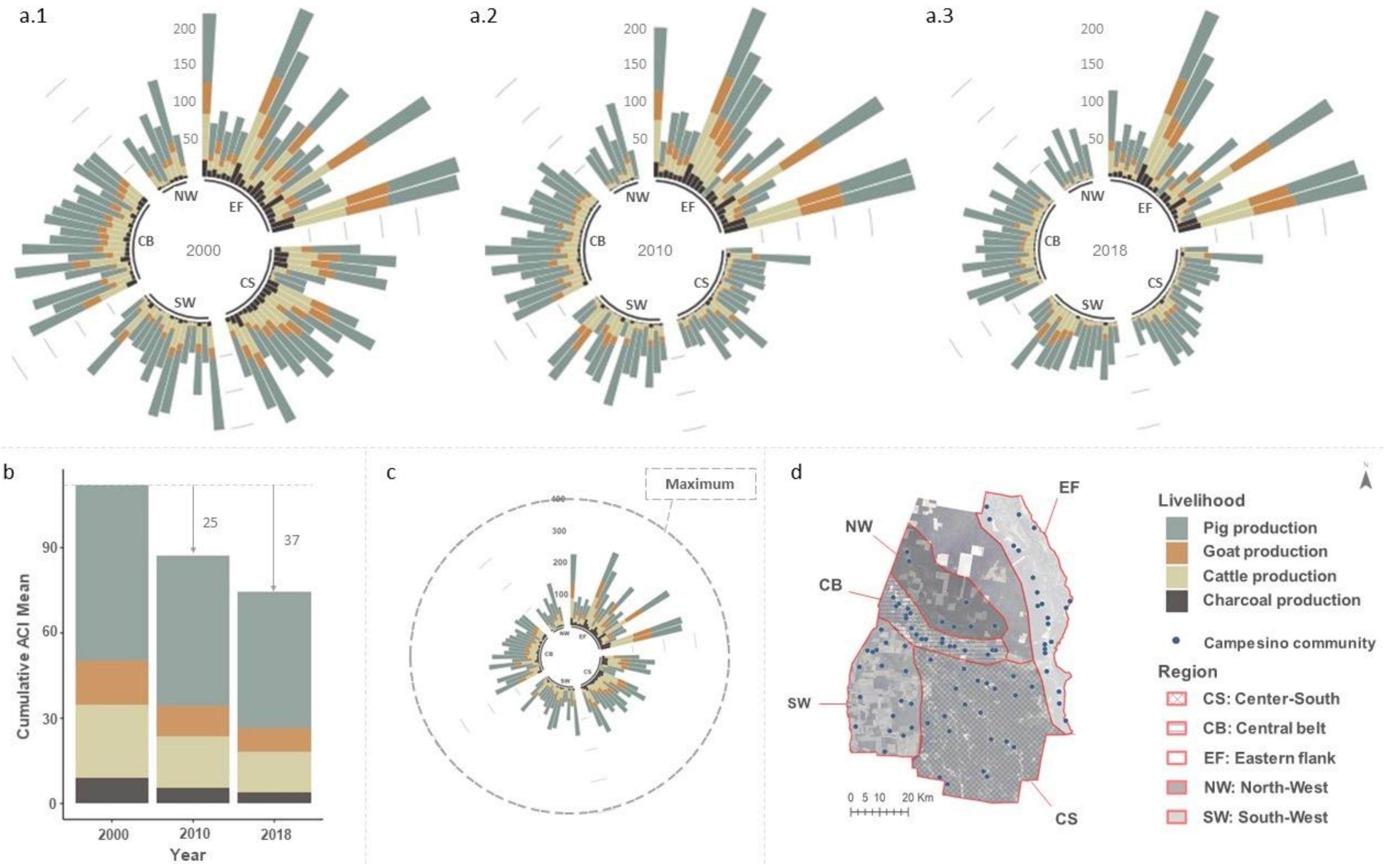

Figure 5. Results of the access analysis. Panels a.1, a.2, and a.3, show access conditions in 2000, 2010, and 2018, where each stacked bar represents the ACIs (by livelihood) for a community and communities are grouped radially by geographic region. Panel b shows the mean cumulative ACI for all communities at each time point. Panel c shows the maximum cumulative community ACI (outer ring = 400), compared to the actual community ACI values in 2000. Panel d shows the point locations of the campesino communities and the extent of the regions, the delimitation of which was conducted for visualization purpose by the authors based on the spatial grouping patterns of communities.

4.4 Comparing approaches for analyzing commodity frontier impacts

The median FI was greater than the median ACI for each of the four livelihoods considered in the analysis (Figure 6, panel a). The FI was significantly correlated to the ACI for all livelihoods save for pig production (Spearman's rank correlation (SRC): p-value = 0.91), and most strongly correlated to charcoal production (SRC: rho = 0.56, p-value <0.001) (Figure 6, panel b). Notwithstanding, the FI did not vary significantly between cattle, goat, and charcoal production livelihoods (Kruskal-Wallis, p-value = 0.61).

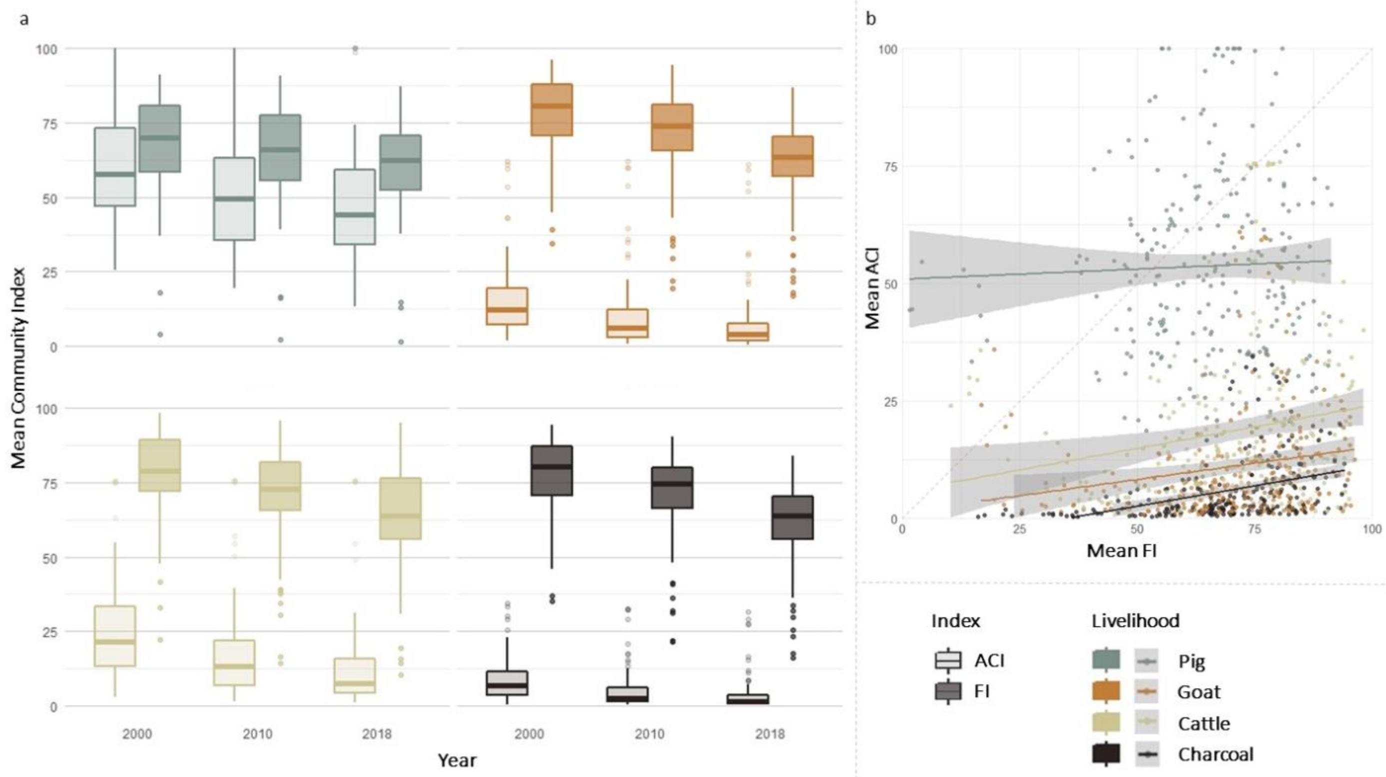

Figure 6. Comparison of approaches. Panel a shows box plots for access condition index (ACI, light boxes) and deforestation index (FI, dark boxes) per period (2000, 2010, and 2018). Panel b shows a comparison of the FI and ACI for each livelihood across all periods.

5. Discussion

5.1 A novel index of access

The livelihood-specific access condition index (ACI) developed here provides a way to quantify the degree to which access to land and resources for different livelihood activities is restricted through space and changes over time. Based on the density, spatial arrangement, and permeability of access barriers around a location, the ACI provides a proxy of access to the space and resources that are necessary for performing a given livelihood activity, and allows the identification of areas of higher potential pressure on livelihoods. Overall, our analysis shows that access for campesino smallholders in the study area decreased between 2000 and 2018 for all four livelihoods across the study area. Access conditions also varied noticeably among livelihoods. This variation points to the importance of a livelihood-specific framework in evaluating access dynamics. Compared to the ACI, the FI estimated higher degrees of access to land and resources across activities. The large differences in magnitude and spatial distribution between the ACI and the FI demonstrate how approaches that rely on deforestation as an indicator of access conditions may be underestimating the extent and intensity of the social impacts of commodity frontier expansion. Our results therefore also highlight the importance of representing spatial processes of claiming and exclusion taking place within frontier areas when approaching the social impacts of commodity frontier expansion.

Our approach provides a readily applicable way to better represent these processes, notably in regions where tenure data is lacking, and allows for a nuanced assessment of access restrictions that is informed by both changes in tenure conditions (e.g., privatization) and the physical enclosure of resources. Moreover, our approach complements tenure-based mapping approaches (e.g., Faingerch et al. 2020) by allowing the mapping of access conditions in a way that does not depend on participatory mapping techniques, which rely on participants recognizing and orienting within a cartographic representation of space, and that is spatially exhaustive and scalable to larger extents. Five points should be noted about the calculation of the ACIs for future applications. Firstly, we relied on the high mapping accuracy (94%) of Seward *et al.* (2012), who employed a very similar methodology, albeit with a higher resolution (1 m), as an indirect confirmation of the mapping accuracy. Where possible, ground-truthing barrier presence through field surveys would improve the index's accuracy. Secondly, the resource weighting used here was kept purposely simple, but future applications of the approach may include more complex resource weightings by, for example, using full land cover classifications (rather than a binary forest-non-forest classification) to account for the differential value of land covers for specific livelihood activities. Thirdly, the manual vectorization of all visible line segments does limit, to a certain degree, the spatial extent at which the methodology can be applied. However, given the simplicity of the process and public availability of input data, we are confident that the approach can be readily applied at the provincial level (on the order of 10^5 km^2), and can thus serve to inform policy for large administrative units. Fourthly, it is possible that non-physical barriers to access are missed through this approach. However, fieldwork conducted by the first author, as well as other studies that have examined control dynamics in the region (e.g., Cáceres 2015, Cáceres et al. 2010, Altrichter & Basurto 2008), suggest that the most prevalent mechanisms used by actors in the Gran Chaco to control access to resources are the enclosure or demarcation of claimed land and resources. Consequently, the risk of substantially underestimating access restrictions in the region is low. Finally, the calculation of ACIs over a large area is computationally intensive. However, this issue can easily be solved by calculating the ACI only over locations of interest, such as settlements, which considerably reduces computing time.

5.2 Potential smallholder impacts

The calculation of changes in access for smallholder communities point to some potential impacts of frontier expansion, and thereby demonstrate the usefulness of this methodology for approaching the multiple dimensions of smallholder dispossession. First, trends in ACI let us identify threats to certain livelihoods in spatial and temporal terms. Our findings indicate that the viability of charcoal production, one of the few income-generating activities of the rural poor in Argentina (Fasano, 2010) is likely becoming precarious across the study area. This result aligns with those of Rueda *et al.* (2015), who found lower charcoal production in the Department of Pellegrini between 2003 and 2011 compared to departments to the East where the commodity frontier was younger. Our results also suggest that relative differences in the degree of access restriction between activities may be generating pressures for smallholders to shift livelihood strategies. For example, considering the relatively low access restrictions for pig production, there may have been pressure to transition from charcoal production to that activity. Similar to findings presented by Cáceres *et al.* (2010, 2011), ACI trends also suggest that campesinos are likely under pressure to shift from goat to cattle production, and that the overall feasibility of livestock production has greatly decreased. Moreover, in areas where communal or open access grazing is no longer an option due to high levels of fencing, campesinos may be resorting to rearing pigs in small enclosures instead. Finally, where a greater number of livelihood activities are severely restricted, campesinos may have experienced displacement pressures, particularly in the North-West, where the majority of communities lost access to land almost entirely for charcoal, cattle, and goat production, and saw a notable decrease in access for pig production. These displacement pressures could be contributing to the rural-to-urban migration that is producing the growth of regional cities (Sacchi & Gasparri, 2016). By identifying heterogeneous restrictions to different livelihood activities, the approach can be followed up with survey-based fieldwork targeted to hotspots of potential smallholder livelihood impact. Ongoing work by the authors uses household livelihood surveys to examine these hypothesized impacts in greater detail.

6. Conclusion

The expansion of commodity frontiers in the Argentine Gran Chaco has been characterized by the large-scale appropriation and accumulation of land and forest resources by outside agents. Frequently, resource accumulation has taken the form of deforestation to make way for pasture or cropland, a process which has resulted in the displacement of many campesino communities (Cáceres, 2015). Nevertheless, processes of resource appropriation and exclusion are not restricted to deforested areas. Within the forest matrix, enclosure and privatization are being used by capitalized, often politically powerful actors as means to assert control over land and resources. These process of changes to land control, and their potential impacts on smallholder livelihoods, have not been accounted for in research that quantifies the spatial dynamics of commodity frontier expansion. To fill this gap, we presented a novel approach for the spatial analysis of commodity frontier impacts that builds on the idea that the ability to access land and resources is an indicator of the social impacts of commodity frontier expansion.

By evaluating the degree to which livelihood activities have been restricted by the emergence of barriers limiting access to land, we were able to identify campesino communities that have likely experienced pressures to shift their means of production due to high restrictions on access to land for particular livelihood activities. We also identified communities where people may have experienced pressure to move away entirely, as they experienced severe access restrictions for multiple livelihood activities simultaneously. Ultimately, the access barriers that are emerging at the advancing edge of commodity frontiers are negatively impacting smallholder livelihoods in the Argentine Gran Chaco. The approach proposed here serves to highlight that these impacts are also being felt heterogeneously in regions that have not yet experienced widespread deforestation for commodity production. Our findings thus point to the importance of effective policy aimed at reducing campesino vulnerability beyond hotspots of deforestation.

In addition to its suitability for the investigation of the social impacts of commodity frontier expansion in the Gran Chaco, the proposed approach provides methodological advancements for the study of commodity frontiers more generally. We demonstrated that the magnitude of commodity frontier impacts on smallholder livelihoods can be severely underestimated when using deforestation as the sole indicator of commodity frontier dynamics. The discrepancies in impact estimation between the two approaches point to two shortcomings of the more traditional approach. Firstly, while a deforestation-based measure may capture impacts incurred by smallholders within late-stage frontier situations, it fails to capture the impacts of the early-stage processes of claiming and exclusion that precede large-scale land cover changes. Secondly, a binary deforestation-based approach does not account for variations in impact according to livelihood strategy. The approach introduced in this study addresses these shortcomings by analyzing changes in land control, rather than land cover, and by disaggregating the potential impacts of these changes by livelihood. In doing so, it provides a way to more accurately characterize the potential social impacts of commodity frontiers and identify specific areas or livelihoods experiencing greater pressure. Because it requires a relatively limited amount of field data, the method can be seen as an efficient diagnosis and appraisal tool to be used in tandem with other, more field-intensive approaches to the estimation of social impacts of agricultural expansion and deforestation.

Given the continued expansion of commodity frontiers into forested regions, now and into the future, it is of critical importance that their impacts for forest smallholder livelihoods be assessed not just from a point of view of resource abundance, but rather through the lens of access to land and resources. Doing so will allow accurate targeting of policies aimed at reducing smallholder vulnerability in contexts where the expansion of commodity production occurs into regions with high levels of rural poverty and tenure insecurity.

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