Agricultural expansion and the ecological marginalization of forest-dependent people

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Agricultural expansion into subtropical and tropical forests causes major environmental damage, but its wider social impacts often remain hidden. Forest-dependent smallholders are particularly strongly impacted, as they crucially rely on forest resources, are typically poor, and often lack institutional support. Our goal was to assess forest-smallholder dynamics in relation to expanding commodity agriculture. Using high-resolution satellite images across the entire South American Gran Chaco, a global deforestation hotspot, we digitize individual forest-smallholder homesteads (n = 23,954) and track their dynamics between 1985 and 2015. Using a Bayesian model, we estimate 28,125 homesteads in 1985 and show that forest smallholders occupy much larger forest areas (>45% of all Chaco forests) than commonly appreciated and increasingly come into conflict with expanding commodity agriculture (18% of homesteads disappeared; n = 5,053). Importantly, we demonstrate an increasing ecological marginalization of forest smallholders, including a substantial forest resource base loss in all Chaco countries and an increasing confinement to drier regions (Argentina and Bolivia) and less accessible regions (Bolivia). Our transferable and scalable methodology puts forest smallholders on the map and can help to uncover the land-use conflicts at play in many deforestation frontiers across the globe. Such knowledge is essential to inform policies aimed at sustainable land use and supply chains.

deforestation | subtropical and tropical dry forests and savannahs | commodity frontiers | small-scale agriculture | livelihoods

Smallholders produce about one-third of all crops globally, manage one-quarter of the global agricultural area, and are key to food security in low-income countries around the world (1, 2). Despite their importance, however, smallholders remain widely overlooked in policy making (3). This is particularly so for forest-dependent people (hereafter: forest smallholders), who live inside the forest matrix and depend on forests as their resource base for fuelwood, timber, nonwood forests products, or livestock herding (4). Forest smallholders are widespread, particularly in the tropics and subtropics (5). Yet despite recent advances in estimating their number and spatial distribution (4), we lack reliable information on how deforestation and agricultural expansion affects them across the world's major deforestation frontiers.

Putting forest-dependent people on the map is furthermore urgently needed in order to guide sustainable development programs to support them (4). Forest smallholders are particularly vulnerable, as they are typically poor and often lack formal land titles as well as institutional support (6). Today, agricultural expansion into tropical forests is often driven by large-scale farmers, producing commodities for global markets (7, 8). Such expanding commodity frontiers can trigger substantial and sometimes violent conflicts between forest smallholders and large-scale farmers (9), causing outmigration of forest smallholders to urban areas (10). Where forest smallholders persist, their resource base often vanishes or they are displaced to environmentally more marginal lands (11, 12), two processes referred to as ecological marginalization (13). While ecological marginalization has often been hypothesized, it has rarely been assessed empirically, and no study has quantified the ecological marginalization of forest-dependent people across any tropical deforestation frontier.

Despite the major challenges forest smallholders face where commodity agriculture expands (14), the geography of competition between forest smallholders and large-scale producers remains largely elusive. For instance, whereas major efforts have gone into mapping Indigenous communities (15), we lack similar datasets for forest smallholders more broadly. As a consequence, assessments of land available for further agricultural expansion

Significance

Millions of people globally rely on forest-based resources for their livelihoods, particularly in the tropics and subtropics. Deforestation is often hypothesized to diminish forest-dependent communities' resource base and to push them toward more-marginal environments, but such ecological marginalization has rarely been quantified. We developed an approach to identify homesteads of forest-dependent people and to track their resource base over 30 y across the entire South American Gran Chaco (1.1 million km^2). This highlighted that forest-dependent people are widespread across the Chaco forests, that their numbers have declined drastically since the 1980s, and that expanding commodity agriculture diminishes their resource base. Sustainability assessments must urgently consider forest-dependent people better, and our study provides a way forward to do so.

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The authors declare no competing interest.

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often do not fully account for the fact that many areas highlighted as available might in fact be inhabited by forest smallholders (16). Furthermore, it remains largely unclear to what extent commodity frontiers affect forest smallholders not just directly by displacing them but also by reducing forest cover and thus their resource base around their communities. These knowledge gaps hinder targeted actions toward avoiding or mitigating negative livelihood outcomes for forest smallholders.

Commodity frontiers have expanded particularly rapidly in South America in recent years, mostly driven by cattle and soy production (17). The expansion of commodity agriculture has been particularly rapid in the Gran Chaco (hereafter: Chaco), the world's largest tropical dry forest extending across Argentina, Bolivia, and Paraguay. This region harbors major carbon stocks (18), unique biodiversity (19), and is home to many Indigenous and non-Indigenous smallholder communities (20). The Chaco has recently become a global deforestation hotspot, which brings with it serious environmental impacts such as globally significant carbon emissions (18) and major biodiversity loss (21). Although there is increasing evidence that conflicts over land have become widespread (11, 22), information about the social costs of this expansion is scarce (7, 20, 23).

Our overarching goal was to assess forest-smallholder dynamics in relation to expanding commodity agriculture in the Chaco for the period 1985 to 2015, during which commodity frontiers expanded dramatically in the region. Specifically, we ask the following: 1) how did the expansion of commodity agriculture in the Chaco shape the numbers and geographic patterns of forest smallholders? and 2) did the expansion of commodity agriculture result in increasing ecological marginalization of forest smallholders? We addressed these questions by digitizing forest-smallholder homesteads using high-resolution satellite images across the entire 1.1 million-km^2 Chaco (Fig. 1). We then reconstructed dynamics of forest-smallholder homesteads back to 1985 and quantified trends in ecological marginalization by assessing resource base loss and environmental marginality (proxied by agroclimatic conditions and accessibility) around homesteads.

Results

Distribution of Forest Smallholders in the Chaco. To assess how deforestation and commodity agriculture expansion related to forest-smallholder dynamics in the Chaco since 1985, we first digitized forest-smallholder homesteads across the Chaco on screen from high-resolution imagery based on distinctive homestead

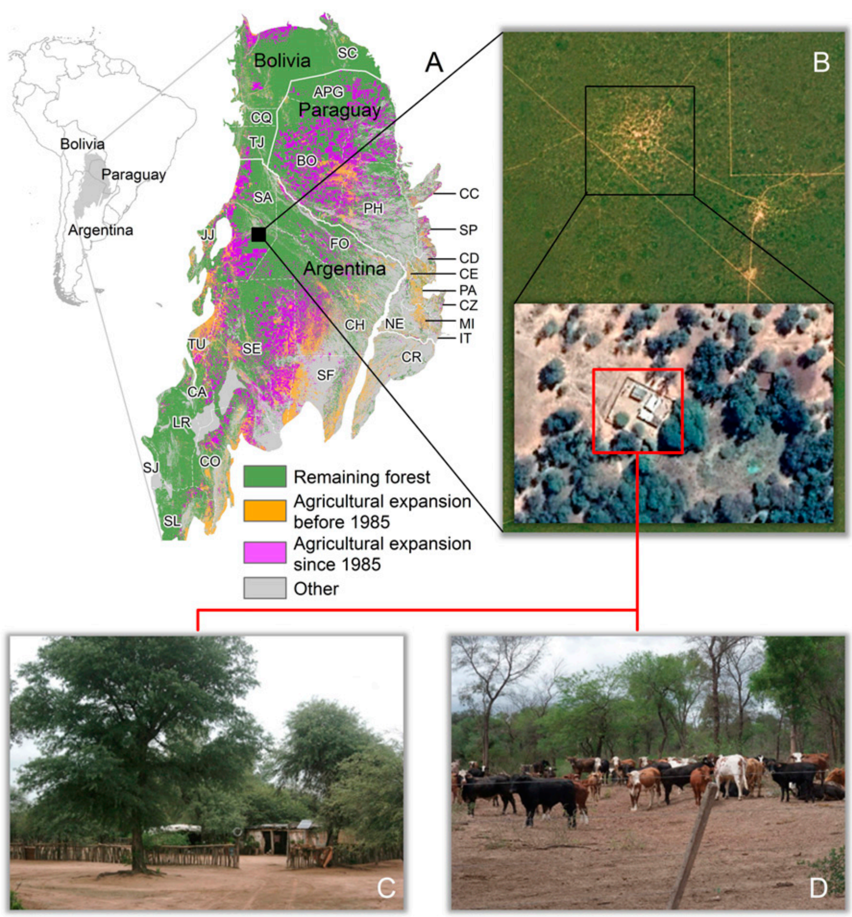

Fig. 1. Study region and key characteristics of forest-smallholder homesteads for digitization. Chaco region in South America and spatial patterns of agricultural expansion since 1985 (purple), agricultural expansion before 1985 (orange), and remaining forest (green, year 2015). "Other" represents natural grasslands, savannahs, wetlands, water bodies, and settlements (*A*). We used three key characteristics of forest-smallholder homesteads for digitization: 1) distinctive landscape patterns of Chacoan forest-smallholder homesteads (i.e., degradation of natural vegetation and soils, gradually decreasing with increasing distance from the center of the homestead) (*B*), (2) presence of at least one house (*B* and *C*), and (3) presence of a stable, corral, and/or water hole or well confirming livestock presence and thus a relatively permanent occupation (*C* and *D*). Photos: authors. Administrative units (provinces, departments, and states): APG, Alto Paraguay; BO, Boquerón; CA, Catamarca; CC, Concepción; CD, Cordillera; CE, Central; CH, Chaco; CO, Córdoba; CQ, Chuquisaca; CR, Corrientes; CZ, Caazapá; FO, Formosa; IT, Itapúa; JJ, Jujuy; LR, La Rioja; MI, Misiones; NE, Ñeembucú; PA, Paraguarí; PH, Presidente Hayes; SA, Salta; SC, Santa Cruz; SE, Santiago del Estero; SF, Santa Fe; SJ, San Juan; SL, San Luis; SP, San Pedro; TJ, Tarija; TU, Tucumán.

features easily recognizable in these images (e.g., bare soil footprint around homesteads, presence of a house and watering place; *Materials and Methods* and Fig. 1). This yielded a time series of forest-smallholder homesteads for 5-y intervals from 1985 to 2015 at a scale of 1 × 1 km^2. This database revealed that forest-smallholder homesteads are very widespread across the Chaco but also that their numbers markedly decreased during our study period. Our digitization further showed that the share of Chaco forest under forest-smallholder influence was about 45% in 1985, if assuming a 5-km impact radius around homesteads in which forest-smallholder activities (e.g., firewood collection, livestock grazing, and hunting) take place. Despite considerable deforestation due to advancing commodity agriculture, the share of Chaco forest influenced by forest smallholders remained largely stable until 2015, while both the number of forest smallholders and the share of forest that they influenced declined (*SI Appendix*, Table S1).

Using a random sample of areas in which we mapped every individual forest-smallholder homestead in a Bayesian model allowed us to estimate total homestead numbers with 95% credible intervals from the original forest-smallholder presence data (*Materials and Methods*). The Chaco harbored 25,906 forest-smallholder homesteads in 2015 (refer to *SI Appendix*, Table S2 for credible intervals) as opposed to 28,125 in 1985, a net loss of 2,219 homesteads or almost 8%. Argentina harbored the most forest-smallholder homesteads (24,558 in 1985 and 22,407 in 2015), followed by Paraguay (2,162 in 1985 and 1,878 in 2015), and Bolivia (1,399 in 1985 and 1,623 in 2015). We found the strongest relative decrease in forest-smallholder homesteads in Paraguay (−13%) followed by Argentina (−9%), while homestead numbers increased by 16% in Bolivia.

Dynamics of Forest Smallholders in the Chaco. Building on our 30-y time series of forest-smallholder homestead locations, we assessed the geographic patterns of forest-smallholder dynamics by identifying three trajectories of change (*Materials and Methods*): 1) "persisting" homesteads (i.e., present from 1985 to 2015), 2) "disappearing" homesteads (i.e., present in 1985 but not in 2015), and 3) "emerging" homesteads (i.e., present in 2015 but not in 1985). This provided further insights into the net changes highlighted in the section *Distribution of Forest Smallholders in the Chaco*. From all forest-smallholder homesteads we identified for 1985, a total of 23,017 (refer to *SI Appendix*, Table S2 for credible intervals) homesteads "persisted" (~82%) until 2015, while 5,053 homesteads "disappeared" (~18%) during that time (*SI Appendix*, Fig. S1). From all forest-smallholder homesteads we identified for 2015, a total of 2,838 "emerged" since 1985 (~11%). In Argentina, homesteads disappeared particularly drastically in the late 1990s and in the 2000s, with the peak disappearance rate between 2005 and 2010. Emerging forest-smallholder homesteads appeared predominantly in the 1990s in Argentina and Bolivia and the early 2000s in Paraguay. The number of emerging homesteads decreased substantially across the entire Chaco after 2005, with less than 200 new forest-smallholder homesteads after 2010. Homesteads predominantly disappeared in the northern Argentinean Dry Chaco, especially in the provinces of Santiago del Estero, Chaco, and Formosa (Fig. 2 and *SI Appendix*, Table S3). These were also the provinces where most new forest-smallholder homesteads—albeit in much smaller numbers—emerged, together with Tarija (Bolivia) and Presidente Hayes (Paraguay).

Ecological Marginalization of Forest Smallholders. For our analyses, we assumed ecological marginalization to be the case if at least one of two conditions was fulfilled (*Materials and Methods*): 1) forest resource base loss occurred in the surrounding of homesteads (up to 5-km distance) and/or 2) forest-smallholder homesteads were increasingly located in environmentally more marginal locations.

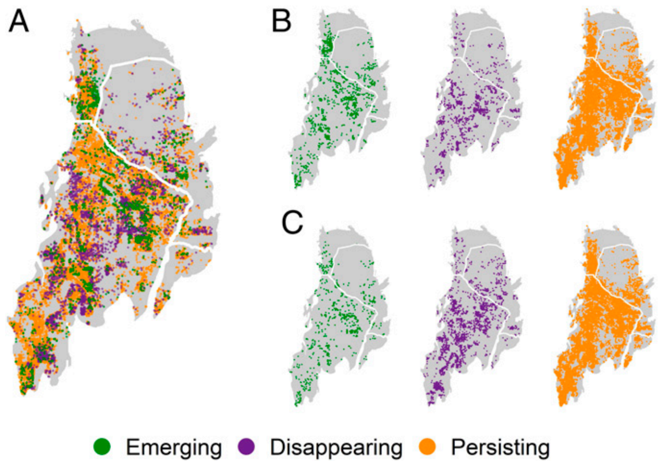

Fig. 2. Geographic patterns of forest-smallholder dynamics across the Gran Chaco. Forest-smallholder dynamics in the Chaco between 1985 and 2015 (*A*), between 1985 and 2000 (*B*), and between 2000 and 2015 (*C*). Clear clusters of emerging (green) and disappearing (purple) forest-smallholder homesteads are highlighted that differ in major ways from the overall geographic distribution of persisting forest-smallholder homesteads (yellow).

To assess the first condition, we overlaid our forest-smallholder homestead time series with high-resolution maps of forest cover and agricultural change for the Chaco between 1985 and 2015. We found less forest and more agricultural land in the wider surrounding of disappearing homesteads compared to persisting and emerging homesteads, particularly beyond 1-km distance from homesteads (Fig. 3 *A* and *C* and *SI Appendix*, Fig. S2). Despite a generally decreasing forest resource base for all trajectories, disappearing homesteads had the highest losses, more than double those of emerging and persisting homesteads (Fig. 3*B*). Agriculture in the wider surrounding of homesteads also increased the most for disappearing homesteads (Fig. 3*D*). Moreover, we found a considerable share of persisting forest-smallholder homesteads were impacted by ecological marginalization, as about 18% of them (~4,150) experienced a loss of at least 25% of the forest resource base in the 5 km surrounding their homesteads, and about 5% of them (~1,150) experienced a loss of at least 50% (*SI Appendix*, Fig. S3). The forest area lost around homesteads increased substantially with increasing distance from the homestead.

We further mapped hotspots of disappearing forest-smallholder homesteads at the scale of 10-km diameter hexagons ($n = 15{,}863$) and overlaid these hotspots with data on deforestation frontiers (nine classes; low, medium, and high forest cover and deforestation rates, respectively; *Materials and Methods*). Overall, we found the largest number of forest-smallholder homesteads in areas with low deforestation rates and high forest cover (*SI Appendix*, Fig. S4). Active deforestation frontiers with high forest cover had a particularly high share of disappearing forest-smallholder homesteads. From all hotspots of disappearing forest-smallholder homesteads, more than one-half ($n = 245$) occurred outside areas classified as active deforestation frontiers; however, a considerable number of such hotspots ($n = 181$) spatially co-occurred with active deforestation frontiers (Fig. 4*A*). Finally, overlaying deforestation frontiers with forest-smallholder homesteads highlighted the substantial impact of frontier expansion on these smallholders (Fig. 4*B*). About 55% of forest-smallholder homesteads present in active deforestation frontiers lost at least 50% of their forest resource base (~35% lost up to 75% and ~20% lost up to 100%). Resource base loss in deforestation frontiers was particularly severe in the Argentinean provinces of Salta, Cordoba, and Santiago del Estero.

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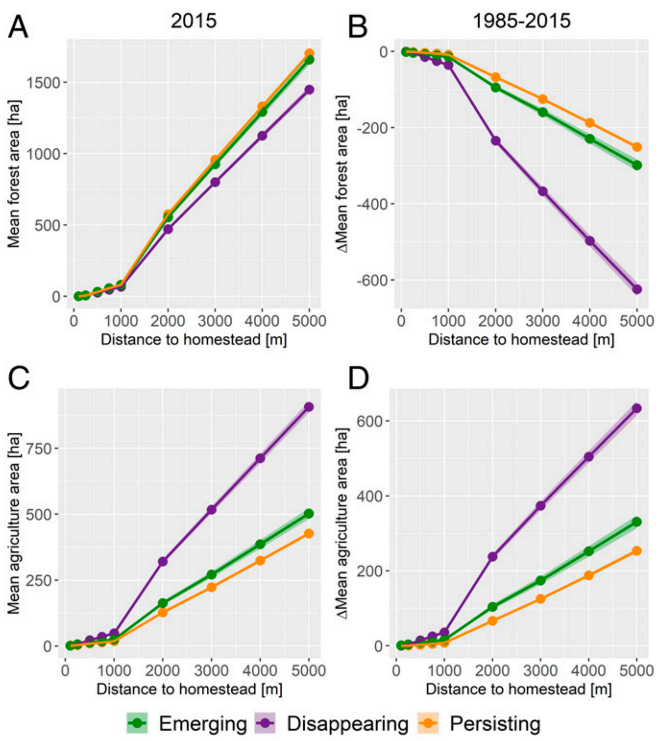

Fig. 3. Forest and agriculture around forest-smallholder homesteads. Average forest area in 2015 (*A*) and changes in forest area between 1985 and 2015 (*B*) with increasing distance from forest-smallholder homesteads. Average area of agricultural land in 2015 (*C*) and changes in agricultural area between 1985 and 2015 (*D*) with increasing distance from forest-smallholder homesteads. Estimates were calculated for concentric ring buffers separately. Shaded areas represent 95% CIs.

To assess the second ecological marginalization condition (i.e., homesteads found in increasingly marginal locations), we overlaid our database of forest-smallholder homestead dynamics with indicators of agroclimatic conditions (i.e., aridity index) and accessibility (i.e., travel time to major cities). This revealed marked yet country-specific ecological marginalization trends (Fig. 5). In Argentina, persisting forest-smallholder homesteads tended to be found in more-arid regions compared to other homesteads (Fig. 5*A*). In Bolivia, persisting homesteads also often occurred in dry conditions, but emerging homesteads appeared in even-more–arid areas. In Paraguay, forest-smallholder homesteads generally occurred in more-humid conditions than in Argentina and Bolivia, and while disappearing and emerging homesteads were located in drier regions compared to persisting homesteads, homesteads disappeared particularly in the driest regions of the Paraguayan Chaco. In terms of accessibility, forest-smallholder homesteads in Argentina were generally located in more-accessible regions compared to Bolivia and Paraguay (Fig. 5*B*). While forest-smallholder trajectories did not differ much among trajectories in terms of accessibility, homesteads emerged predominantly in less-accessible regions in Bolivia and Paraguay, consistent with our marginalization hypothesis. Finally, mapping the most-marginalized forest-smallholder homesteads according to our criteria highlighted that most of these homesteads fulfilled one but not multiple marginalization conditions (*SI Appendix*, Fig. S5).

Discussion

Globally, the livelihoods of large numbers of people living in forests and critically dependent on these forests are threatened by deforestation. Yet the scarcity of information on where forest-dependent people live and how expanding commodity agriculture impacts on them is a major barrier to address and mitigate these threats. We carried out a comprehensive assessment of forest smallholders across an entire subtropical/tropical deforestation frontier to trace the dynamics of >25,000 individual forest-smallholder homesteads over an area of 1.1 million km^2. Forest smallholders are widespread across the Chaco forests and influence about one-half of the remaining forest. Yet, their homesteads disappeared in large numbers where commodity agriculture expanded. We also find evidence for an increasing ecological marginalization of forest smallholders due to the declining forest resource base in the surrounding of their homesteads, with increasing resource base loss as the distance to the homesteads increases. Furthermore, forest smallholders often persisted in the most arid and inaccessible regions of the Chaco. Together, this revealed widespread, yet largely hidden, land-use conflicts between forest smallholders and other land-use actors—a pattern likely representative of deforestation frontiers around the world. As agricultural commodity frontiers expand into even the most remote forests, adequate consideration of forest smallholders in land-use planning and policy discussions aimed at increasing sustainability in these frontier regions is urgently needed.

Forest Smallholders Inhabit Large Parts of the Chaco. While forest smallholders are known to be widespread, with estimates of about 800 million forest-dependent people living in tropical rainforests globally (4, 24), their spatial footprint has remained elusive (25). Here, we reveal the spatial patterns and density of forest smallholders at broad spatial scales, indicating where remaining Chaco forests likely contribute to sustaining their livelihoods (5, 26). Importantly, our mapping revealed surprisingly large areas of Chaco forests influenced by forest smallholders, with several regions characterized by forest smallholders being present in almost all forests. Given that forest smallholders, in the Chaco and elsewhere, typically comprise under-represented minorities

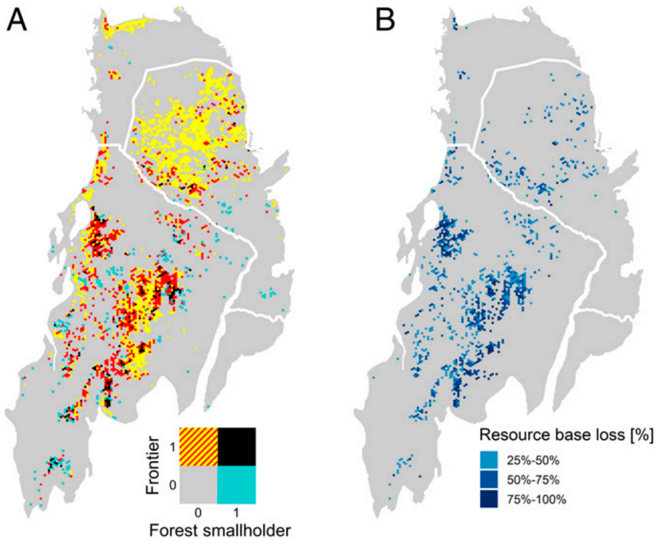

Fig. 4. Spatial co-occurrence of forest-smallholder dynamics, deforestation frontiers, and resource base loss. Deforestation frontiers and hotspots where forest-smallholder homesteads disappeared, aggregated for hexagons of 10-km diameter (*A*). Black hexagons represent active deforestation frontiers and hotspots where forest-smallholder homesteads disappear. Red and yellow hexagons represent active deforestation frontiers, without hotspots where forest-smallholder homesteads disappear (red/yellow: forest-smallholder homesteads present/absent). Turquoise hexagons represent areas of hotspots where forest-smallholder homesteads disappear outside active deforestation frontiers. Resource base loss in deforestation frontiers with forest-smallholder presence between 1985 and 2015 (*B*). No frontier hexagon had a resource base loss <25%.

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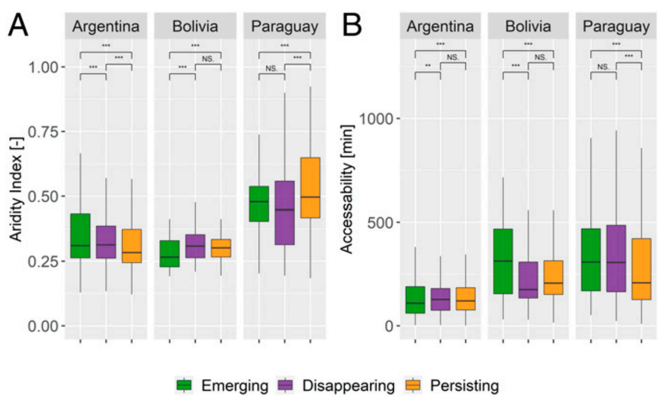

Fig. 5. Ecological marginalization of forest smallholders based on agroclimatic and accessibility conditions. Distributions of aridity index [-] (*A*) and accessibility as travel time to major cities of >50,000 inhabitants [min] (*B*) for the three forest-smallholder trajectories per country. A lower aridity index indicates more arid conditions, and short travel times indicate better accessibility. Significance of differences between groups was assessed with two-sample Wilcoxon tests (*** = 0.001, ** = 0.01, * = 0.05, NS, not significant).

suffering from power imbalances, low tenure security, and weak political representation (14), understanding where they dwell is key to assess and mitigate the impacts of deforestation on them (4, 5). Likewise, mapping forest smallholders is also important to understanding their often-strong impacts on the local environment [e.g., through hunting or logging (27, 28)]. Both are important to devise policies to achieve cobenefits between local livelihoods and conservation (29).

Our study highlights the power of remote sensing to put forest smallholders on the map. Our transferable methodology requires a modest workload compared to ground assessments, is based on publicly available high-resolution imagery, and delivered a robust forest-smallholder map including uncertainty estimates. Even more promisingly, recent advances in deep learning and artificial intelligence now allow for automatic object identification of settlements (30), houses (31), or trees (32). This suggests our most labor-intensive step, the manual, on-screen digitization of individual forest-smallholder homesteads, can soon be automated, and our methodology thus might be scaled up further to large or even global extents.

Where Commodity Agriculture Expands, Forest Smallholders Disappear. One in five forest-smallholder homesteads disappeared in the Chaco during a period of drastic deforestation (18). It is important to highlight that deforestation in the Chaco during our study period has almost exclusively been associated with the expansion of large-scale, commodity agriculture (7, 18, 33, 34). These forest losses resulted in a resource base loss for forest smallholders living in areas where deforestation frontiers expanded (Fig. 3). While forest smallholders can exert considerable pressure on the forests surrounding their homesteads, their activities rarely lead to the full conversion of forest (*SI Appendix*, Fig. S6). Forest loss driven by forest smallholders is limited to the immediate surrounding of their homesteads (35–37) and is small compared to the deforestation driven by the expansion of commodity agriculture in their wider surroundings. Qualitatively assessing the drivers of forest loss for a random sample of persisting homesteads with considerable forest resource base loss in their 5-km surrounding (n = 100) confirmed this, as only 5% of these forest resource losses were attributable to forest-smallholder activities (*SI Appendix*, Fig. S7). Furthermore, our study period covers almost the entire history of commodity agriculture expansion in the region. Most forest-smallholder homesteads were already present in the landscape at the start of this expansion, as their settlement had happened many decades earlier but had not resulted in widespread deforestation.

Homesteads disappeared particularly strongly in the 2000s, which coincides with the period of highest deforestation rates in the region, especially in Argentina and Paraguay (38, 39), as well as price increases for agricultural commodities. To protect remaining native forests, a zoning plan (the so-called Forest Law) was passed at the federal level in Argentina in 2007. Large areas of forests harboring forest smallholders were zoned for sustainable use (*SI Appendix*, Fig. S8), meaning that conversion to cropping or intensified ranching was prohibited. Forest smallholders are hence seen as, in principle, compatible with maintaining forest cover and with sustainable forest use, in contrast to commodity agriculture. This could explain the declining numbers of disappearing forest-smallholder homesteads after 2010, particularly when considering that the Forest Law was implemented with a time delay (40).

Where forests are converted to commodity agriculture, it leads to major losses of forest-related ecosystem services (41). In addition, forest smallholders often lose access to forests, as they rarely hold land titles (14). Large-scale producers typically fence their properties, thereby excluding forest-smallholder livestock from the forests surrounding their homesteads (42). Consequently, disappearing forest-smallholder homesteads do not just occur within active deforestation frontiers (Fig. 4) but also in areas of emerging frontiers where land is being partitioned for later development, explaining the displacement of forest smallholders (43). It is possible that some disappearing homesteads were displaced to other areas and were mapped there as emerging homesteads. There is indication that such displacement is happening in parts of the Chaco (11, 43, 44), but our data cannot resolve this as we could not track household members. Such displacement processes are common for deforestation frontiers, as agricultural expansion is estimated to impact the livelihoods of numerous forest-dependent and forest-proximate people globally (4, 25), often through displacement (12, 24). Securing land titles for such forest smallholders would help safeguarding their livelihoods and often also the forests they depend on.

The strong decrease in forest-smallholder homesteads we find suggests growing conflicts between forest smallholders and large-scale producers, which have been driving the recent wave of deforestation (17, 18). This is corroborated by frequent reports about strong tensions, conflicts, and unrest in the region, as local communities lose forest-related ecosystem services [e.g., fuelwood, forage, hunting, and subsistence farming (45)]. For instance, in northern Argentina alone, 220 land conflicts were reported between 1980 and 2011, with the majority (~80%) occurring after 2000 and affecting more than 2.7 million ha of Chaco forests and almost 130,000 people (46). In this region, we found that a large number of forest-smallholder homesteads (more than 3,700) has disappeared over our study period. Importantly, conflicts can also arise between forest smallholders and land-use actors other than large-scale producers, such as other types of smallholders (e.g., clearing forest to practice small-scale ranching and farming). For example, areas in the Bolivian Chaco have seen an increase in smallholder numbers driven by the immigration of campesinos from other regions of Bolivia, as encouraged by the government, with impacts on preexisting forest-dependent communities (47). Importantly, our estimate of disappearing homesteads is conservative, as additional forest-dependent people live outside the forest-smallholder homesteads we mapped. These include Indigenous communities living in larger settlements in all three Chaco countries, such as Qom, Guaraní, or Wichí communities.

Expanding commodity frontiers are, however, not the sole driver behind the disappearance of forest-smallholder homesteads. First, forest smallholders could themselves be responsible for forest loss in their surrounding and thus marginalization would at least partly be self-induced. Forest-smallholder activities, especially livestock grazing, can induce forest degradation

(35–37) and could cause or amplify resource base loss, ultimately resulting in the abandonment of homesteads. Second, rural outmigration and urbanization are widespread throughout South America (10), often driven by better economic opportunities, infrastructure, healthcare, and educational institutions in cities, along with a lack of investment in infrastructure and housing in rural areas. The Chaco is no exception to this (48), and this could in part explain the numbers of declining homesteads we find. Finally, forest smallholders can theoretically adapt to changing conditions as commodity agriculture expands. For example, some forest smallholders in the Argentinean Chaco have switched from forest grazing to intensified pastures (42), to systems that integrate woodland and livestock management, or to rotational systems of different forest uses (49, 50). Such systems can make forest smallholders less forest dependent but typically require an initial investment that many forest smallholders cannot afford (49) and are therefore currently very rare.

Increasing Ecological Marginalization of Remaining Forest Smallholders. We find a general decline in forest resources in the surroundings of forest-smallholder homesteads in all Chaco countries but particularly in Argentina. This suggests a massive erosion of their resource base in the form of ecosystem services as the Chaco's forests vanish (Figs. 2 and 4), likely with major livelihood impacts (51). Again, our estimates are likely conservative because our approach cannot measure additional resource loss due to access restrictions arising [e.g., from new fences (11)], and we do not measure the effect of forest degradation as livestock grazing, selective logging, or firewood collection get concentrated in increasingly smaller forest areas. Analyzing forest-smallholder homesteads in the context of climate and accessibility indicators corroborates our finding of increasing ecological marginalization, yet to a lesser degree compared to forest resource base loss and with substantial regional variation. Persisting homesteads are typically found in semiarid conditions ($0.20 < \text{aridity index} < 0.50$; Fig. 5) that are only marginally suitable for commodity cropping due to low rainfall. Likewise, where forest smallholders have expanded (i.e., mainly Bolivia), they expanded predominantly into the most marginal agroclimatic conditions, consistent with theoretical assumptions (52). Patterns of agroclimatic marginalization were less clear for the Argentinian and Paraguayan Chaco, possibly in part because of the Forest Law and the more consolidated frontiers in Argentina, as well as the overall low number of forest smallholders in Paraguay. Moreover, agroclimatic conditions differed markedly between countries, with conditions generally more favorable (i.e., less arid) in the Paraguayan Chaco, making it difficult to compare across countries.

Ecological marginalization can result in poverty traps for forest-dependent communities (53), and our results thus signal potentially strong social impacts of the current boom of commodity agriculture in the Chaco (11, 44). Ecological marginalization of forest smallholders has often been hypothesized but rarely quantified—and never mapped across active deforestation frontiers. Furthermore, our results show that for forest-dependent people, capturing changes in their resource base is essential for understanding ecological marginalization, as broad-scale climate and accessibility indicators provide only a partial picture of the pressures that forest smallholders are facing and thus of their marginalization.

Putting Forest Smallholders on the Map. Forest-dependent people such as forest smallholders in the Chaco are often "under the radar" of planning and policy discussions due to missing data on where they live and how deforestation impacts them. We demonstrate for the Chaco that forest smallholders are widespread and numerous and that the spatial footprint of their resource use is considerable. This translates into strong imperatives to better represent forest-dependent people in policy discussions and to consider the potential impacts of environmental change on these people. Concretely, mapping forest-dependent people—and identifying the forests they depend on—can inform land-use planning to better protect peoples' livelihoods and traditional land systems or to help resolve conflicts about tenure [e.g., such mapping could be used to inform the implementation and revision of Argentina's Forest Law (5, 26)]. As forest-dependent people often experience nonsubstitutable dependence on forest-derived livelihood benefits and can also be subject to ecological marginalization (as found in this study), there is a clear need to develop spatially explicit conservation and sustainable development measures and policies to target priority areas and communities (4). In particular, the transfer of tenure and forest governance to forest-dependent people can provide a great opportunity to improve their livelihoods (54).

For conservation planning and action, knowing the locations of forest smallholders is similarly important to leverage potential cobenefits between conservation and development goals (4). The Chaco exemplifies a region increasingly transformed by globalization, and there is a growing desire to identify and trace the environmental impacts embodied in the agricultural commodity trade, such as carbon or biodiversity loss (55, 56). Identifying where expanding commodity agriculture impacts forest smallholders provides a basis for assessing livelihood impacts and marginalization through expanding production of traded commodities (57). This can pave the way for supply chain mechanisms to lessen these impacts (58). All of this requires better information on the spatial footprint and numbers of forest smallholders in dynamic regions, and we provide here a viable methodology to achieve that goal. Putting forest-dependent people on the map can help to avoid unwanted livelihood outcomes of commodity frontiers and to help steer these systems toward more-sustainable and just futures.

Materials and Methods

Forest Smallholders in the Chaco. Forest smallholders, here encompassing both Indigenous and non-Indigenous people, occupy a large part of the Chaco, using and shaping its forests (36). Their homesteads typically consist of a group of houses and farm buildings, often accompanied by small subsistence crop fields or vegetable gardens. The spatial footprint of such homesteads is usually stable (*SI Appendix*, Fig. S6) but increases (typically in regions not affected by the expansion of commodity agriculture) and decreases (in regions where commodity agriculture expanded) have been documented (35). Forest-smallholder homesteads are typically inhabited by a single family, but the number of family members per homestead can vary. The influence of forest smallholders, however, extends substantially into the forest surrounding their homesteads. Most importantly, forest smallholders commonly keep a range of livestock (mainly cattle, goats, sheep, swine, and poultry) and depend on the presence of natural or artificial water sources (rivers and ponds but also wells or rainwater tanks) to overcome water scarcity in the dry season. Livestock usually roam freely in the forests surrounding the homestead, relying on a combination of local grasses and tree foliage for food. This leads to piospheric patterns of grazing impact and soil compaction around water points and homesteads (36) (radial patterns with greater intensity at the focal point and lower intensity radiating outwards). Aside from forage, forest smallholders furthermore depend on the surrounding forest in several other ways. These include the collection of firewood for home use and charcoal production (59, 60), the production of fence posts and occasionally timber (20, 61), subsistence hunting (29, 62–64), and the collection of nonwood forest products (e.g., plants used in the production of fabrics such as chaguar, wild honey, or fruits such as algarroba used in the production of traditional foods) (20). Some forest-smallholder activities, particularly livestock herding, hunting, and timber harvesting, can have substantial local impacts on forest structure and biodiversity (28, 36).

Forest smallholders in the Chaco are also among the poorest members of society. In Argentina, about one-third of rural residents of the Chaco provinces were unable to cover at least one basic need in 2010, such as decent housing, appropriate food, or education (65). Forest smallholders also frequently lack titles to the land they occupy. While mechanisms to regularize land tenure for long-term residents of a piece of land exist, they are complex and costly, leaving forest smallholders disadvantaged when they compete for land with outside investors (14, 66, 67). Displacement is a frequent outcome of these conflicts (43, 68). In sum, forest smallholders are a widespread actor group whose livelihoods impact the Chaco forests in many ways but who are also themselves at risk from deforestation. Despite this, our understanding of where forest-smallholder farms are located, what their spatial footprint of influence on the Chaco forests is, and how recent deforestation has impacted them remains unclear.

Mapping Forest Smallholders across the Chaco. We used high-resolution images available in Google Earth and the Landsat archive to map forest-smallholder dynamics across the entire Chaco between 1985 and 2015. We performed three main steps: 1) digitization, 2) consistency check and harmonization, and 3) assessment of temporal dynamics. Although our map does not differentiate between forest smallholders recognized as Indigenous people and those known as criollos (i.e., local mestizos), we recognize the importance of that distinction to the actors themselves (29, 64).

In step one, we digitized all forest-smallholder homesteads in 2015 using Centre National d'Etudes Spatiales (CNES)/Airbus high-resolution imagery in Google Earth, with a consistent initial viewing height of 30 km. We subdivided the study area into 551 sampling rectangles, each 60×40 km^2, and randomly assigned them to six interpreters. We defined the size of the sampling rectangles pragmatically to ensure that one rectangle could be entirely displayed on a digitization screen at the initial viewing height. When digitizing, we searched for three key characteristics of forest-smallholder homesteads (Fig. 1): 1) the distinctive landscape pattern of a Chaco forest-smallholder homestead (i.e., degradation of natural vegetation and soils which gradually decreases with increasing distance from the center of the homestead), 2) the presence of at least one house, and 3) the presence of a stable, corral, and/or water hole or well (i.e., confirming livestock presence and thus a relatively permanent occupation). We backtracked all identified homesteads to check if they had existed in 1985 using Landsat satellite imagery available in Google Earth. In case forest-smallholder homesteads were not present in 1985, we determined the year in which they appeared. Finally, we digitized additional forest-smallholder homesteads that were present in 1985 but not anymore in 2015 and determined when they had disappeared. Google Earth provides satellite imagery on an annual basis, allowing a detailed timing of the year of emergence or disappearance. As the spatial resolution of satellite imagery available via Google Earth improved over time (from 30-m resolution in the 1980s, 1990s, and 2000s to <1-m after 2010), we mainly relied on key characteristic 1 (distinctive landscape pattern) and, if possible, on characteristics 2 (presence of houses) and 3 (infrastructure, e.g., watering place) for identifying forest-smallholder homesteads in 1985 (*SI Appendix*, Fig. S6). Our digitization resulted in an initial set of ~30,000 forest-smallholder homesteads.

In step two, we performed a consistency check and harmonization of the initial database. Forest-smallholder homesteads are often clustered (36), and we expected some omission errors (i.e., not all individual homesteads can clearly be identified in satellite imagery). To account for this, we applied the following approach to estimate the total number of forest-smallholder homesteads for the Chaco. First, we spatially rarefied our database to a 1×1-km^2 grid by randomly selecting one forest-smallholder homestead per grid cell. These rarefied locations now represent forest-smallholder presence instead of homestead numbers. Second, we cross-checked and reassessed the entire rarefied database (23,954 homesteads) using one independent interpreter and added or removed locations as needed to homogenize our dataset. The reassessment was done homestead by homestead, again starting at 30-km initial viewing height. The zoom level was gradually increased until the respective homestead could be identified with certainty (in case of uncertainty, we removed the location). Third, we randomly selected one-sixth (n = 94) of our sampling rectangles and digitized all visible homesteads in them for the year 2015 (even if they were clustered), again starting at 30-km initial viewing height and gradually increasing the zoom level until the homesteads could be identified with certainty. Fourth, we estimated the number of individual forest-smallholder homesteads for the entire study area using both the rarefied and complete digitization databases. To do so, we fitted a Bayesian generalized model (69) to our discrete data (complete digitization) to estimate the probability distribution and derive the mean and 95% credible intervals. Given the type of data (counts), we tested a Poisson distribution and a negative binomial distribution. The posterior predictive checks (density overlay, *SI Appendix*, Fig. S9) indicated overdispersion for the Poisson model, and we therefore selected the negative binomial model that showed no overdispersion, resulting in a better model fit. In 2015, the estimated average number of forest-smallholder homesteads per grid cell where we found forest-smallholder presence after the rarefication was 1.30, with a lower bound of 1.27 and an upper bound of 1.33 (*SI Appendix*, Fig. S9). We applied these estimates to the rarefied database to calculate the total number of homesteads for each location of forest-smallholder presence, including credible intervals.

In step three, we established a spatiotemporal database of forest-smallholder homestead patterns at the 1×1-km^2 resolution in 5-y intervals between 1985 and 2015. Identifying the exact year of emergence or disappearance was sometimes difficult, especially before 2010 when imagery is coarser in Google Earth. We therefore decided to use 5-y intervals to define homestead emergence and disappearance, which provided sufficient temporal detail for our analyses given the temporal resolution of the land-cover data (1985, 2000, and 2015). We matched the year of emergence or disappearance of each homestead to the closest target year (e.g., years 1988 to 1992 were assigned to target year 1990).

Forest-Smallholder Dynamics We assigned all forest-smallholder homesteads present in 1985 and 2015 to the class "persisting." If a homestead was present in 1985 but not in 2015, we assigned it to the class "disappearing" and noted the year of disappearance. If a homestead was not present in 1985 but identified in 2015, we assigned it to the class "emerging" (noting the year of emergence). Initially, we also identified "temporary" forest-smallholder homesteads, which emerged after 1985 and disappeared before 2015. However, because of the small number of homesteads assigned to this trajectory (~150), we decided to not include these homesteads in our analyses. We used our spatiotemporal database containing persisting, emerging, and disappearing forest-smallholder homesteads to summarize forest-smallholder dynamics across the Chaco and for each the three countries that comprise it.

Assessment of Ecological Marginalization We assumed ecological marginalization of forest smallholders in the Chaco to be the case if at least one of the two following conditions was met. First, if forest smallholders experienced a substantial resource base loss in the surrounding of their homestead. Such resource base losses signal a deterioration of forest-smallholders' livelihoods. Second, if forest-smallholder homesteads were increasingly found in the environmentally most marginal locations. Commodity agriculture advances preferentially into the least marginal areas, possibly pushing forest smallholders out of these areas, or decreasing their resource base via deforestation. Disappearing forest-smallholder homesteads can hence be expected to be predominantly located in agroclimatically more favorable and accessible areas, and persisting and emerging forest-smallholder homesteads should be located in less agroclimatically favorable and less-accessible areas.

We assessed how deforestation affected forest-smallholders' resource base by overlaying our spatiotemporal database with maps of land-cover dynamics in the Chaco with 30×30-m^2 spatial resolution (18). We used the existing land-cover map for 1985 and produced a map for 2015 using the same procedure as in Baumann et al., 2017 (18) to match our study period. These land cover maps were generated based on Landsat satellite imagery composite stacks and by using a random forest classifier and an extensive set of training and validation data (see ref. 18 for details). The overall accuracy (85%, *SI Appendix*, Table S4) indicated a reliable mapping of land-cover patterns and changes, which was underlined by high to very high class-wise accuracies (producer's accuracy: 58 to 94%; user's accuracy: 58 to 91%). We estimated average cover and change of forested land (i.e., classes "forest" and "open woodland" in ref. 18) and agricultural land (i.e., classes "cropland" and "pasture" in ref. 18) for each forest-smallholder change trajectory and calculated CIs for each estimate. Both agricultural activities (i.e., cropping and ranching) play an important role in driving deforestation trends in the Chaco. Importantly, our land-cover data captures only full conversions from forest to agricultural use, not forest degradation. About 40% of the total forest lost during the study period (~140,000 km^2 or 20% of all Chaco forests) was replaced by croplands and about 60% by pastures, which in turn are often converted to croplands after a period of pastoral use (18). For our estimation, we used concentric ring buffers around homesteads with radii of 100, 250, 500, 750, 1,000, 2,000, 3,000, 4,000, and 5,000 m, where the latter is the approximate maximum distance of forest-smallholder influence on forests due to livestock grazing activities (35, 36, 70). Estimates represent conditions within each ring buffer and hence the additional area (change) for the sequence of distances from homesteads.

To assess how advancing agricultural commodity frontiers impacted forest cover around homesteads, we focused on persisting homesteads and assessed how forest cover changed between 1985 and 2015. For each buffer radius, we calculated the share of all persisting forest-smallholder homesteads that was affected by a low (0 to 25%), medium (25 to 50%), high (50 to 75%), or very high (>75%) decrease in forest cover in their surroundings. We then linked forest-smallholder homesteads to active deforestation frontiers by deriving frontier types for 10-km diameter hexagons (*SI Appendix*, Figs. S10 and S11), following the protocol outlined in le Polain de Waroux et al. (2018) (7).

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According to this protocol, active deforestation frontiers are characterized by high forest cover (>66%) and high deforestation rates (>2.5% per year), high forest cover (>66%) and medium deforestation rates (1.0 to 2.5% per year), or medium forest cover (33 to 66%) and high deforestation rates (>2.5% per year). We calculated and mapped forest loss between 1985 and 2015 (18) for each active deforestation frontier hexagon in which forest-smallholder homesteads were present in 2015 to estimate the pressure on forest-smallholder' resource base. Finally, we identified hotspots of disappearing forest-smallholder homesteads by first classifying forest-smallholder occurrence frequencies per hexagon for 1985 (max = 37) into low (one homestead), medium (two to six homesteads), and high (more than six homesteads) using Jenks natural breaks optimization (three breaks), and then calculating disappearance rates, defining rates <30% over the study period as low, 30 to 70% as medium, and >70% as high, in agreement with le Polain de Waroux et al. (2018) (7). Based on this, we defined hotspots of disappearing forest-smallholder homesteads as hexagons with high or medium forest-smallholder density and high or medium disappearance rates. We overlaid active deforestation frontiers and hotspots of disappearing forest-smallholder homesteads to assess their spatial co-occurrence.

We assessed the relationship between disappearing, persisting, and emerging forest-smallholder homesteads and agroclimatic conditions and accessibility. Specifically, we overlaid our three forest-smallholder trajectories with one key agroclimatic indicator [the aridity index for the 1981 to 2010 normal period at $1 \times 1\text{-km}^2$ spatial resolution; data generated with the ClimateSA version 1.0 software package available at http://tinyurl.com/ClimateSA, based on the methodology described by Hamann et al., 2013 (71)] and one accessibility indicator [travel time to major cities >50,000 inhabitants for the year 2015 at $1 \times 1\text{-km}^2$ spatial resolution (72)]. We used accessibility as a time-invariant indicator, as the expansion of main roads did not greatly affect the region during the study period (28). We assessed differences in indicators values between all trajectories of forest-smallholder homestead dynamics using two-sample Wilcoxon tests separately for homesteads in Argentina, Bolivia, and Paraguay. We identified the locations of the ecologically most marginalized forest-smallholder homesteads according to our two marginalization criteria (resource base loss and forest smallholders increasingly found in marginal areas). Specifically, we first calculated the share of resource base loss in a 1-km buffer around homesteads and extracted travel time and aridity index values at the homestead location for all homesteads. We then identified all homesteads with indicator values 1 SD above (resource base loss, accessibility) or below (aridity index) the Chaco-wide average.

Data Availability. A gridded version of the rarefied forest-smallholder homestead database is available on Dryad (https://doi.org/10.5061/dryad.8931zcrrj) (73). The data provides the following information on forest-smallholder homestead distributions and dynamics across the Gran Chaco ecoregion at $10 \times 10\text{-km}^2$ spatial resolution: 1) presence of forest-smallholder homesteads for target years in five-year intervals from 1985 to 2015 [% per grid cell], 2) net loss of forest-smallholder homesteads between five-year intervals from 1985 to 2015 [% per grid cell], and 3) net gain of forest-smallholder homesteads between five-year intervals from 1985 to 2015 [% per grid cell]. The original, digitized point data are maintained at the Conservation Biogeography Lab at the Geography Department of Humboldt-University Berlin (http://hu.berlin/biogeo). Please contact Tobias Kuemmerle (tobias.kuemmerle@hu-berlin.de) for more information.

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