Frontier metrics for a process-based understanding of deforestation dynamics

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Abstract

Agricultural expansion into tropical and subtropical forests often leads to major social-ecological trade-offs. Yet, despite ever-more detailed information on *where* deforestation occurs, *how* agriculture expands into forests remains unclear. Here, we developed and mapped a novel set of metrics that quantify agricultural frontier processes at unprecedented spatial and temporal detail. Specifically, we first derived consistent time series of land-use/cover to, second, describe archetypical patterns of frontier expansion, pertaining to the speed, the diffusion and activity of deforestation, as well as post-deforestation land use. We exemplify this approach for understanding agricultural frontier expansion across the entire South American Chaco (1.1 million km^2), a global deforestation hotspot. Our study provides three major insights. First, agricultural expansion has been rampant in the Chaco, with more than 19.3 million ha of woodlands converted between 1985 and 2020, including a surge in deforestation after 2019. Second, land-use trajectories connected to frontier processes have changed in major ways over the 35-year study period we studied. For instance, while ranching expansion drove most of the deforestation in the 1980s and 1990s, cropland expansion dominated during the mid-2000s in Argentina, but not in Paraguay. Similarly, 40% of all areas deforested were initially used for ranching, but later on converted to cropping. Accounting for post-deforestation land-use change is thus needed to properly attribute deforestation and associated environmental impacts, such as carbon emissions or biodiversity loss, to commodities. Finally, we identified major, recurrent frontier types that may be a useful spatial template for land governance to match policies to specific frontier situations. Collectively, our study reveals the diversity of frontier processes and how frontier metrics can capture and structure this diversity for guiding spatially targeted policies, and for uncovering high-level patterns of human-nature interactions.

Keywords

Commodity frontiers, deforestation, tropical dry forests and savannahs, agricultural expansion, social-ecological archetypes, Landsat time series.

Introduction

Agricultural expansion into natural areas has helped to meet the growing global demand for food, feed, and fiber (Godfray et al, 2010), but has also produced unsustainable land-use outcomes. This is particularly the case where agricultural frontiers expand into tropical and subtropical forests, triggering globally-relevant greenhouse gas emissions (Carlson et al, 2017), biodiversity losses (Chaplin-Kramer et al, 2015), and major livelihood impacts on forest-dependent people (Andersson & Agrawal, 2011; Oldekop et al, 2020). Yet, much of the agricultural expansion during the past decades has taken place in the tropics (Gibbs et al, 2010), where most of the last uncultivated, productive lands are found (Lambin et al, 2013; Ramankutty et al, 2002). Sustainability planning to prevent or minimize undesirable social-ecological outcomes in regions where agriculture expands is thus needed.

This, first and foremost, requires a robust understanding of where and how frontiers expand. Considerable progress has been made on the prior, that is mapping *where* deforestation takes place (Hansen et al, 2013; Turubanova et al, 2018; Vancutsem et al, 2021; Zalles et al, 2021). Yet, *how* agricultural frontiers progress continues to be weakly understood. For example, some frontiers advance slowly while others erupt rapidly (Kröger & Nygren, 2020), some frontiers grow outward while others leap-frog to remote places (Bowman et al, 2012), and some frontiers accelerate while others consolidate and slow down (Bonilla-Moheno & Aide, 2020). Likewise, a wide range of land-use-actors drive frontier expansion, such as swidden cultivators (Vieilledent et al, 2018), forest smallholders (Phiri et al, 2019; Tyukavina et al, 2018), or agribusinesses (Klink & Machado, 2005). Further, in some regions, frontiers may be considered old or suspended, whereas in other regions new frontiers emerge. Lastly, land-use trajectories after initial deforestation are diverse (De Sy et al, 2019; Hosonuma et al, 2012; Song et al, 2021; Souza et al, 2020). Given this complexity, as well as past policy failures in frontier regions, there are now many calls for more context-specific land governance to address sustainability challenges in frontier regions (Pacheco et al, 2021). Archetype analyses, aimed at identifying high-level patterns of human-environment interactions (Oberlack et al, 2019; Rocha et al, 2020; Sietz et al, 2019), such as typical land systems (Levers et al, 2018; Vaclavik et al, 2013), land-use change trajectories (Levers et al, 2018; Meyfroidt et al, 2018), or land-use outcomes (Cumming et al, 2014; Pacheco-Romero et al, 2021), is a potentially powerful way to structure diversity and complexity for that purpose.

Identifying archetypical spatiotemporal frontier dynamics and what drives them could enable more nuanced land governance (*Table 1*). For example, identifying emerging frontiers would allow for proactive land-use and conservation planning (e.g., zoning), whereas reactive interventions (e.g., forest protection) would be needed where frontiers are particularly active (Hansen et al, 2020). Likewise, where frontiers consolidate, restoration opportunities might unfold, as land-use actors are more interested in long-term sustainability (Latawiec et al, 2015; Lerner et al, 2015; Strassburg et al, 2017). Disentangling frontier dynamics can furthermore help to identify actor-specific governance interventions. For example, historically, frontiers have mainly been driven by smallholders (Barbier, 2012; Godar et al, 2014; Pacheco, 2012), but since the late 1990s, capital-intensive, influential actors have been driving frontiers to produce commodities for global markets (Kröger & Nygren, 2020; Rudel, 2007). Such commodity frontiers are typically characterized by agglomeration effects (Austin et al, 2017; Garrett et al, 2013; Richards, 2018) and sensitive to macroeconomic and trade signals, which can produce abrupt accelerations of frontier dynamics. In addition, land-use actors in commodity frontiers are potentially responsive to market-based interventions and are sensitive to macroeconomic and trade changes (zu Ermgassen et al., 2020). For example, supply-chain governance interventions or certification systems can work well for managing commodity frontiers related to cocoa or coffee (Baynes et al, 2015). Finally, identifying key patterns and types of frontier dynamics can make contributions to build theory in land system science (Meyfroidt et al, 2018; Turner et al, 2020). Yet, we lack a robust understanding and a set of quantitative indicators that capture how frontiers unfold.

Increasing access to satellite images along with new processing capabilities offer new opportunities for understanding frontier dynamics at unprecedented temporal and spatial resolution (Gorelick et al, 2017; Woodcock et al, 2020; Wulder et al, 2019), yet these opportunities have so far not been explored. Prior work on assessing frontiers has mostly focused on mapping deforestation (Griffiths et al, 2018; Hansen et al, 2013; Müller et al, 2016; Vancutsem et al, 2021), what follows deforestation (Song et al, 2021; Souza et al, 2020; Zalles et al, 2021; Zalles et al, 2019) or, most recently, who drives deforestation frontiers (Curtis et al, 2018; Pacheco et al, 2021). The question of how frontier dynamics unfold, beyond identify hotspots of deforestation (Hansen et al, 2013; Hansen et al, 2010; Harris et al, 2017; Instituto Nacional de Pesquisas Espaciais (INPE), 2002; Potapov et al, 2019; Tyukavina et al, 2018), remains largely unexplored. Specifically, remote-sensing time series should allow to describe speed at which frontiers expand (e.g., slow vs. fast progressing), frontier stage (e.g., emerging, active, consolidated) or the frontier diffusion process (e.g., gradually progressing vs. leap-frogging frontiers), but most existing studies often do not translate their land-cover time series into such processed-based system metrics. A reason for this is that describing and understanding frontier dynamics requires deriving consistent land-cover/use time series, which remains a major challenge (Friedl et al, 2010; Liu et al, 2020). Although several dataset contain annual land-cover maps, such as the MODIS land-cover product (Sulla-Menashe et al, 2019), error propagation makes analyzing changes based on such individually derived maps difficult (Friedl et al, 2010). Furthermore, land-cover maps include change that does not represent land-use change, such as natural disturbances (e.g., fire) or management signals (e.g., fallow periods, logging), that need to be separated out (Gómez et al, 2016). Establishing land-cover time series that are consistent in space and time is therefore needed for understanding deforestation frontiers.

A better understanding of frontier dynamics is particularly urgent for the world's subtropical tropical dry forests and savannas (hereafter: dry forests). Frontiers have expanded particularly rapidly in these forests over the last decades, but dry forests have received much less attention than rainforests (Miles et al, 2006; Pennington et al, 2018). This is surprising, given that dry forests account for nearly 40% of all tropical forests (Murphy & Lugo, 1986), harbor astonishing biodiversity (Mayle et al, 2007), and account for about 30% of the terrestrial primary productivity (Grace et al, 2006). Dry forest loss has been particularly widespread in South America where agricultural expansion since the early 2000s has turned several dry forests regions into a global deforestation hotspot (Hansen et al, 2013; Pacheco et al, 2021). One of these hotspots is the Gran Chaco, a 1.1 million km^2 region in South America shared by Argentina, Bolivia, and Paraguay, where agricultural expansion has been rampant (Hansen et al, 2013) mostly for beef and cash crop production (Fehlenberg et al, 2017; Gasparri & Baldi, 2013). Where deforestation has occurred in the Chaco is relatively well-understood (Gasparri & Grau, 2009; Killeen et al, 2007; Vallejos et al, 2015), including post-deforestation land-uses (Baumann et al, 2017; Boletta et al, 2006; Caldas et al, 2015; Campos-Krauer & Wisely, 2011; Volante et al, 2012), and the importance of actors in shaping these pattern (le Polain de Waroux et al, 2018; Levers et al, 2021). Yet, how the diversity of actors and social-ecological conditions has produced different types of frontier patterns remains unclear.

Our overarching goal was to develop and test a novel set of frontier metrics that quantitatively describe frontier processes across space and over time. We demonstrate the value of these metrics by deriving archetypical frontier dynamics driven by agricultural expansion for the Chaco (1,1 million km^2), across the entire history of modern agricultural expansion. Doing so required us to develop the first consistent, spatio-temporally detailed land-use/cover reconstruction for this global deforestation hotspot, Specifically, we asked the following questions:

1. How can frontier processes and dynamics be described using time-series of land use?
2. Where and how have agricultural frontiers expanded into the Chaco's forests since 1985?
3. What are archetypical frontier dynamics, including post-deforestation land use change?

Methods

Study area

The Chaco is a 1.1 million km^2 ecoregion in South America, extending into Argentina, Bolivia, and Paraguay. Mean annual temperature in the Chaco is 22°C, and annual precipitation shows a pronounced east-west-gradient from 1200mm in the humid Chaco to 400mm in the driest regions in the southwest (Bucher, 1982). Historically, land use in the Chaco was dominated by small-scale producers, such as the Eastern European colonies in the Chaco province, or forest smallholders who used a few hectares of land for subsistence cropping to sell on local markets, and the surrounding woodlands to gather firewood and material for rural construction, as well as forest grazing of roaming livestock (Bucher & Huszar, 1999; Fatecha, 1989). While smallholders continue to be important in parts of the Chaco (Levers et al, 2021), the emergence and rapid expansion of large-scale agribusinesses has happened over wide areas since the 1990s. These actors have substantial capital and knowledge, allowing them to quickly and efficiently capitalize on opportunities that frontier situations entail (le Polain de Waroux, 2019). Together with the liberalization of genetically modified soybean variants in the Chaco during the 1990s (Reenberg & Fenger, 2011), the introduction of highly productive pasture grasses (e.g., Gatton panic (*Panicum maximum*)) (Vazquez, 2013), and the changing export policies of Argentina in reaction to the peso devaluation in 2001 (Leguizamon, 2014), this has converted the Chaco into a global deforestation hotspot in the 2000s and 2010s (Baumann et al, 2017; Hansen et al, 2013).

Overview of methodology

Our analytical framework contains three main steps (

Figure 1). We provide a summary of our methodology here, and a detailed, step-by-step description in the Supporting Information (Text S1-S3). In step 1, we re-constructed land cover across the entire Chaco, annually and consistently for the period 1985-2020. To do so, we made full use of the Landsat satellite archive (>80,000 images) and derived time series of spectral-temporal metrics (Oeser et al, 2020), which we combined with a comprehensive set of training data in a random forest regression framework to derive annual classification probabilities for the classes: (1) woodlands, (2) other vegetation, (3) croplands, (4) pastures, and (5) other land covers. Using these probabilities, we then mapped six land-cover transitions (Table SI-1). All maps were rigorously validated following best practices (Olofsson et al, 2014). Lastly, we aggregated the 30x30m^2 land-cover maps into two datasets at 1.5x1.5km^2 resolution: (a) a time series of fractional woodland cover 1985-2020, and (b) a time series of dominant agricultural land cover (i.e., pasture or cropland).

In step 2, we identified frontier areas (i.e., areas with at least 0.5% woodland loss during three consecutive years and where the final land use was either cropland or pasture) and derived for these areas a total of six frontier metrics: (a) *frontier timing*, describing woodland change 2016-2020 relative to 1985-2015, (b) *frontier speed*, representing the strongest annual woodland loss, (c) *frontier naturalness*, referring to woodlands left relative to the baseline woodlands, (d) *frontier diffusion*, subdividing frontiers into gradual and leap-frogging frontiers, (e) *frontier onset*, describing the starting year of frontier development, and (f) *frontier land use*, describing land use after woodland loss.

In step 3, we reconstructed how frontiers have unfolded across the region by characterizing the spatio-temporal pattern of our frontier metrics for the time period 1985-2020. First, we assessed frontier dynamics by relating our metric *frontier onset* (i.e., the year of emergence of a frontier pixel) to the other five frontier metrics, and summarized each frontier type for the whole Chaco, the Chaco sections in the three countries, as well as the dry and wet Chaco separately. Second, we identified archetypical frontier dynamics, by (a) identifying typical combinations of frontier metrics across the entire Chaco, and (b) by quantitatively evaluating our metrics across frontier regions, identified from our own previous research. To do so, we the three most common metric combinations per region and assigned the majority of a category.

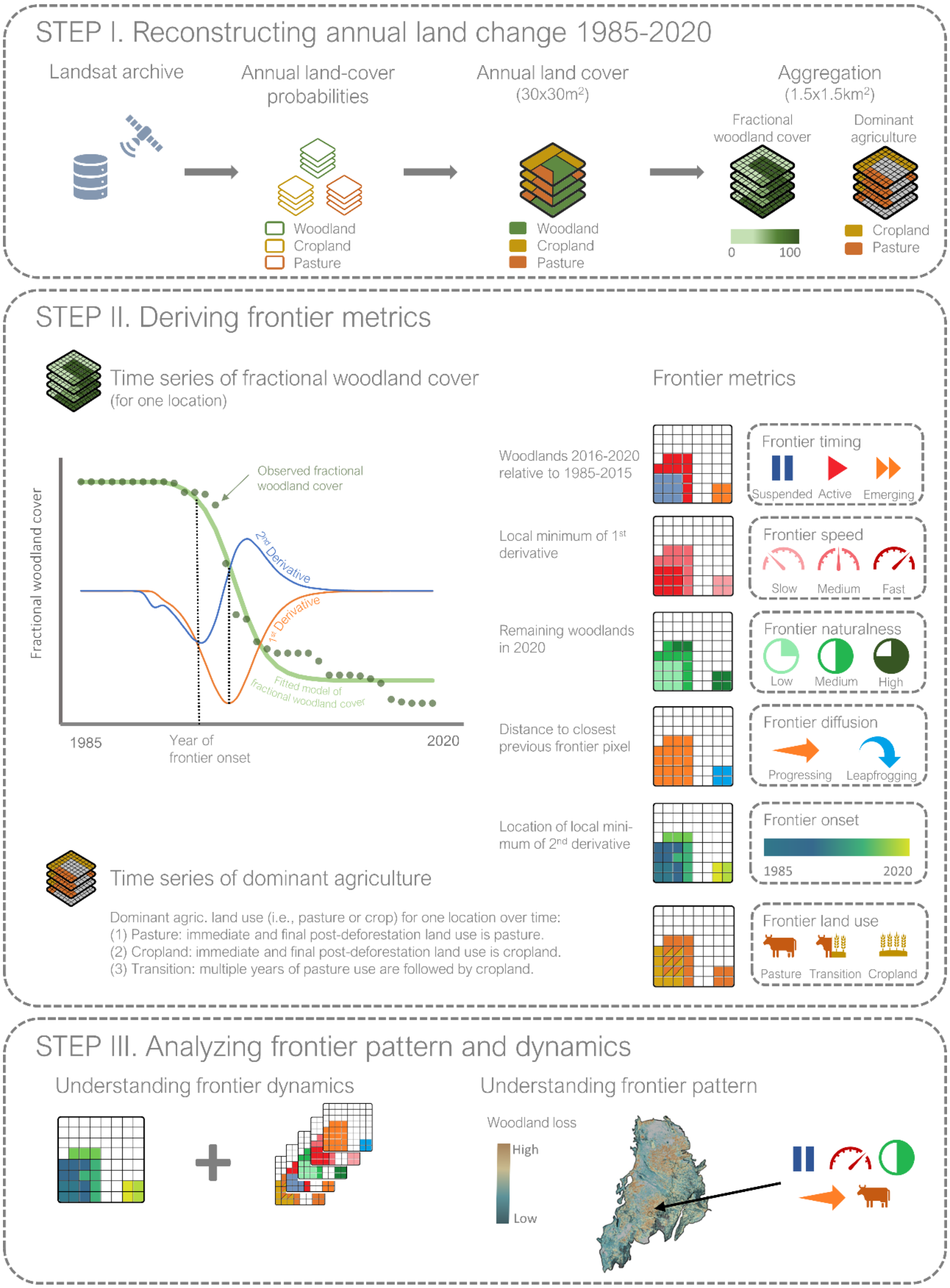

Figure 1*: Framework for identifying and characterizing deforestation frontiers. In STEP 1, we used the Landsat archive to derive consistent land-cover/use time series. STEP 2 then derived*

and mapped six frontier metrics. Finally, STEP 3 uses the frontier metrics to identify archetypical frontier dynamics and analyzes them.

Table 1: Rationale and relevance of the six metrics describing processes in agricultural frontiers.

Metric	Variable	Types and explanation	Rationale and relevance
Frontier activity	Temporal course of the frontier	1. Active (frontiers that are active fronts) 2. Suspended (frontiers that were active but then appear inactive) 3. Emerging (frontiers that are newly appearing)	Different types of activity require different interventions: • **Active frontiers** require urgent stop-gap measures (e.g., strenghthening law enforcement, moratoria etc.). • **Suspended frontiers** require monitoring and measures of land consolidtion and intensification. • **Emerging frontiers** might be targets for various long-term interventions including the development of sustainable production (e.g., certification systems) or community-based natural ressource management.
Frontier land use	Post-deforestation land-use trajectories	1. Pasture 2. Cropland 3. Transition (frontier that was dominated by pasture first, but shifted to croplands)	Different land uses are operated by distinct actors that react differently to incentives and interventions. Supply chain interventions need to target the key commodities in a frontier. • **Pasture frontiers** may be target for implementing more sustainable production systems (e.g., silvopastures). • **Transition frontiers** may represent focus regions for policies that focus on limiting the further expansion of intensive cropping systems.
Frontier speed	Rate of fastest woodland loss	1. Slow 2. Medium 3. Fast	The speed with which frontiers progress determines the focus of regional/national policies aiming at conserving remaining woodlands. • **Fast frontiers** can be hotspots of policy focus. • **Slow frontiers** might be places to develop longer-term interventions.
Frontier diffusion	Spatial distance to other frontiers	1. Progressing (frontiers, that diffuse through spatial contagion) 2. Leapfrogging (new nexus of frontiers that can then diffuse by contagion)	How frontiers diffuse represent the group of actors in these areas and require different types of interventions. • **Progressing frontiers** might be contained by networks of protected areas and land-use zoning (as in the Brazilian Amazon), • **Leapfrogging frontiers** require an understanding of the mechanisms through which these frontiers diffuse to be governed efficiently (social networks, etc.).
Frontier naturalness	Remaining woodland	1. High 2. Medium 3. Low	The level of remaining woodland cover can influence the balance of priorities between conservation and restoration. • In **high woodland frontiers** conservation interventions may be more suitable to avoid tipping points in woody cover below which biodiversity may be lost rapidly. • In **low woodland frontiers**, restoration efforts in degraded areas may be more suitable.
Frontier onset	Year of start of woodland loss	Year	The year of onset represents the timing of frontier dynamics; normally precedes maximum woodland loss.

Results

Forest loss has been rampant in the Chaco with a total of 193,321 km^2 of woodlands lost since 1985 (28%). Woodland loss increased steadily until 2009/10, when we found highest annual loss rates (1.7%, equaling 10,167 km² in 2009 and 9,507 km² in 2010), with loss rates declining thereafter (1.1% on average 2011-2019). Most of the woodland loss in 1985-2020 occurred in Argentina (103,480 km^2; average annual loss rate of 0.9%), followed by Paraguay (77,850 km^2, 1.3%), and Bolivia (11,989 km^2, 0.35%). Alarmingly, our analyses revealed a recent surge in woodland loss, in 2019/20, with among the highest woodland loss rate registered since 1985 (1.7%). These woodland losses occurred primarily in the wet Chaco, where woodland loss was low previously (Figure 2, Figure 3A).

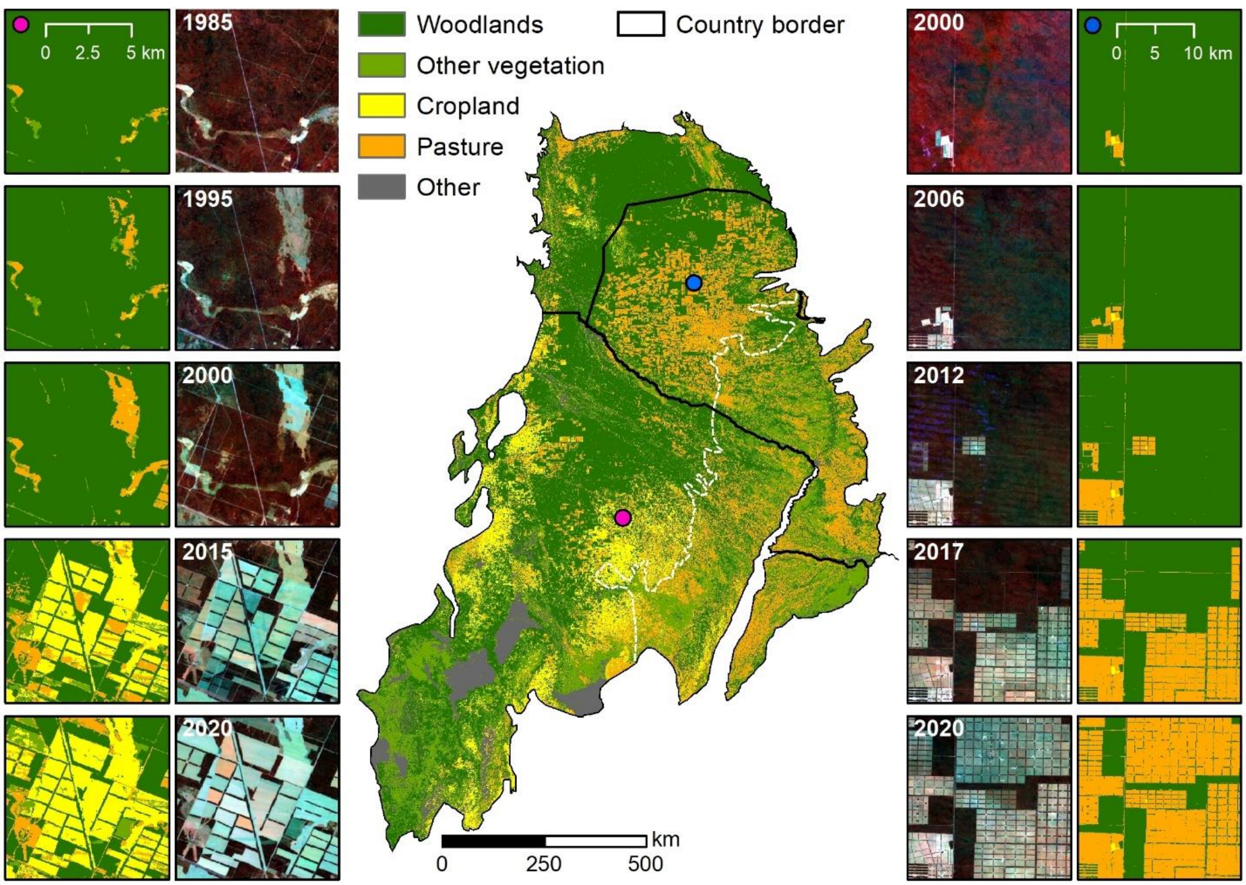

Figure 2: Agricultural expansion into Chaco woodlands. The map shows the extent of natural vegetation and agriculture in 2020; the two times series (Landsat images and classification) show frontier evolution in the Argentinean Chaco (pink marker, left) and the Paraguayan Chaco (blue marker, right). The white line marks the border between the dry and wet Chaco.

Our classifications had high overall accuracies, on average 86.1% (max: 93.9%, min: 77.1%). Average user's and producer's accuracy of the woodland class were also high and ranged between 90.6% and 96.9%, whereas accuracy for the cropland class (73.6% -61.5%) and pasture class (74.1-81.5%) where somewhat lower (see Supplementary Material for more detailed information on class-wise accuracies).

Of the total woodlands loss we identified, the dominant proximate cause was pasture expansion (47%) followed by cropland expansion (2.5%), while 51% were disturbed but did not show an immediate land use after woodland loss. These patterns varied slightly across countries, as well as for the dry and wet Chaco. In Argentina, pasture expansion was the dominant proximate cause of deforestation (34.4%), whereas only 3.6% were deforested for being immediately used as cropland. An additional 64,000 km^2 of woodlands were disturbed (62%). In Bolivia and Paraguay, pasture expansion was the dominant proximate cause of deforestation (57.1% and 61.4% of all woodland loss, respectively), whereas cropland expansion (2.0% and 0.7%, respectively) only had a minor importance as a proximate cause. An additional 4,908 km^2 (40.9%) and 29,570 km^2 (37.9%) of woodlands were disturbed in Bolivia and Paraguay, respectively. In the dry Chaco, pasture expansion was the most dominant proximate cause of deforestation (51.8%), followed by cropland expansion (2.9%). Contrary, only 28.0% and 0.4% of woodland loss in the wet Chaco was due to pasture or cropland expansion, respectively (Figure 3B).

Land use in 2020 often differed compared to the initial post-deforestation land use. Across the Chaco, nearly 37% of all woodlands that were not converted into agriculture immediately, (i.e., were classified as disturbed forest) were later converted to pastures (29,635 km^2) or cropland (6,707 km^2), and 17% of all areas initially converted into pastures became cropland later on (15,279 km^2). This trend was strongest in Paraguay, where 43.2% of all deforested areas became agriculture by 2020, from which 98.2% became pasture (42.5%), and 1.8% cropland, followed by Bolivia (35.35% of all deforestation, 94.8% of these became pasture and 5.2% cropland) and Argentina (34.1% of all deforestation, of which 70.1% for pasture and 29.9% for cropland). In Argentina, 40.1% of all areas where post-deforestation land use was pastures later became cropland (14,244 km^2), whereas in Paraguay (1.3%) and Bolivia (6.0%) this trend was weaker (Figure 3).

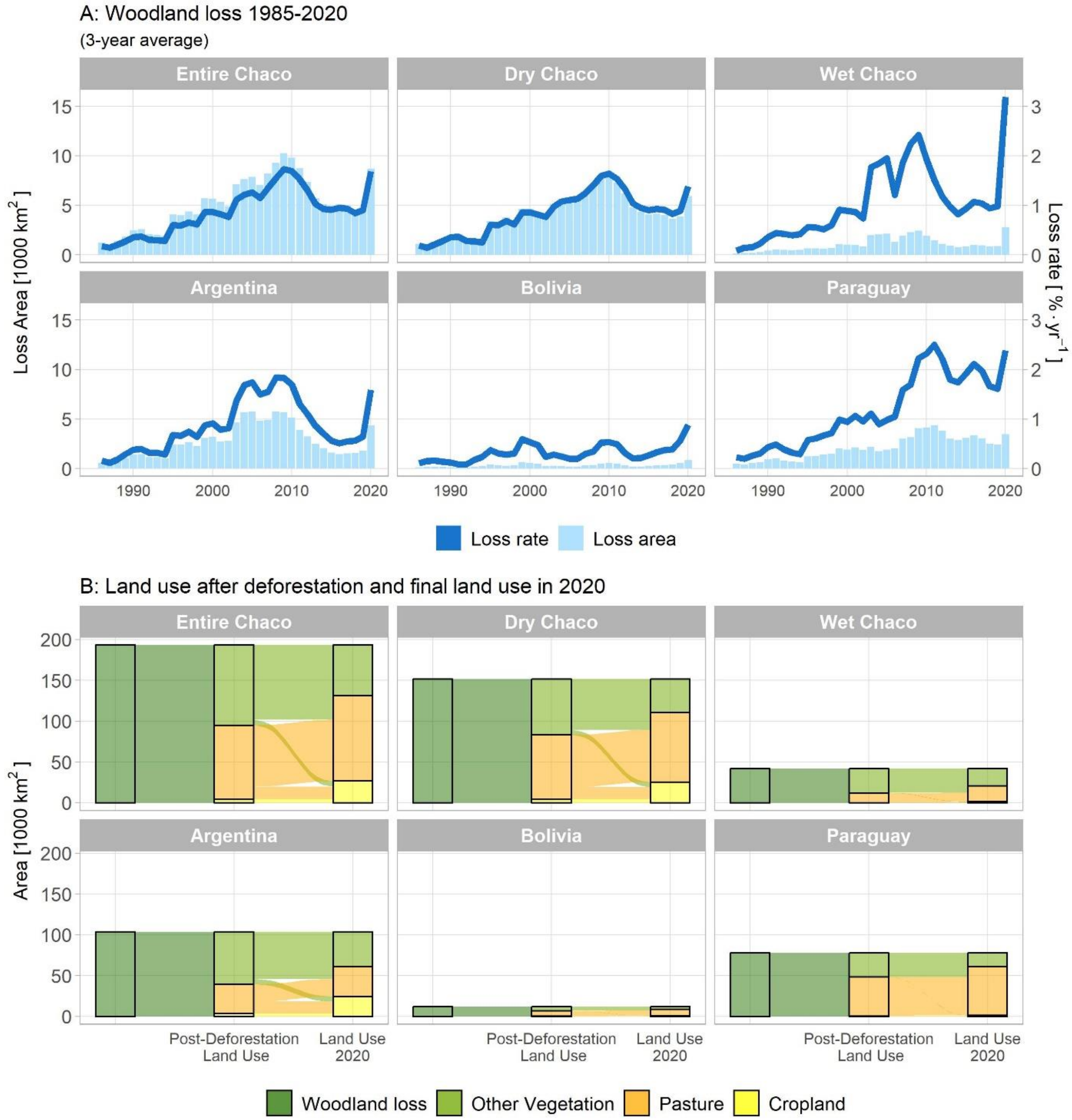

Figure 3: Woodland loss in the Chaco1985-2020. (A): Annual areas and rates of woodland loss for the entire Chaco, the dry and wet Chaco, and the three Chaco countries. (B): Initial land use after deforestation and land use in 2020.

Our six frontier metrics provided further insight into the dynamics of land-use change in the Chaco, revealing typical frontiers patterns. Most frontier areas were identified as old frontiers, classified as either suspended (48.0%) or active (51.2%), whereas we classified only a minor proportion of the Chaco as emerging frontiers (0.7%, primarily in Paraguay). As highlighted above, only a minor proportion of the frontier areas were classified as cropland frontiers (2.2%, direct conversion from woodlands to croplands), whereas most frontiers were due to pasture expansion, either directly (80.3%) or with a time lag (e.g., 17.5%, with a time lag of >3 years; *Figure 4*). Most frontiers in the Chaco were characterized as slow (63.2%), with fast (28.2%) and medium frontiers (8.6%) less common. As can be expected, progressing frontiers formed the overwhelming type of frontier expansion (98.8%) compared to leapfrogging frontiers (1.2%; primarily in Argentina and Paraguay). Lastly, remaining woodlands in frontiers were either low (45.6%) or medium (32.8%), whereas in only 21.6% woodlands were high.

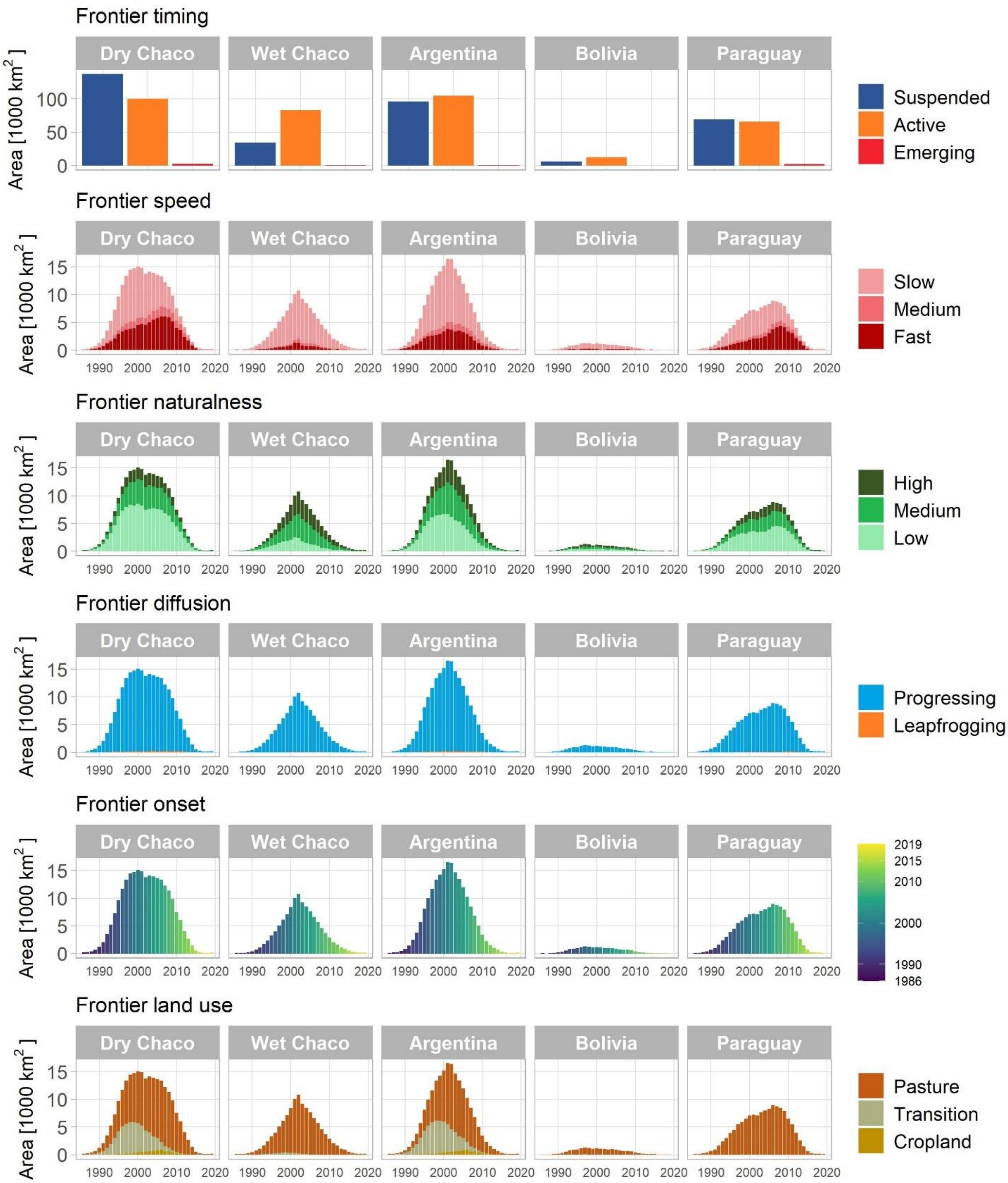

Figure 4: Frontier dynamics in the Chaco according to five frontier metrics. For a map of each metric as well as a map of frontier onset, see Figure SI-1.

Integrating our frontier metrics across the Chaco showed that the Chaco is dominated by a set of archetypical frontier types. The top-10 frontiers were all characterized as *progressing* frontiers with frontier land use *pasture* or *transition* and represented 59.8% of the study area. However, they were distinctly different in their frontier timing (39.8% are *active* vs. 19.9% *suspended*) and their frontier naturalness (13.5% *high*, 17.8% *medium,* 27.9% *low*). The most common metric combination comprised 17.8% of the study area and had the metric combination (*progressing, medium* naturalness, *active, pasture, slow*). This picture was distinctly different across countries. In Argentina, the most common metric combination covered 32.0% of the country's frontier areas, and was *progressing*, *active,* with land use *pasture, slow* speed, and *medium* naturalness. Of the top-10 frontier archetypes, however, only two were considered *active* (55.6% of the area). For Bolivia, the most common frontier type comprised 32.3% of all frontier areas (*progressing, active, pasture, slow, high*), whereas in Paraguay, the most common frontier archetype (34.7% or the area) was *progressing, suspended, pasture, slow* and in low naturalness (Figure 5)

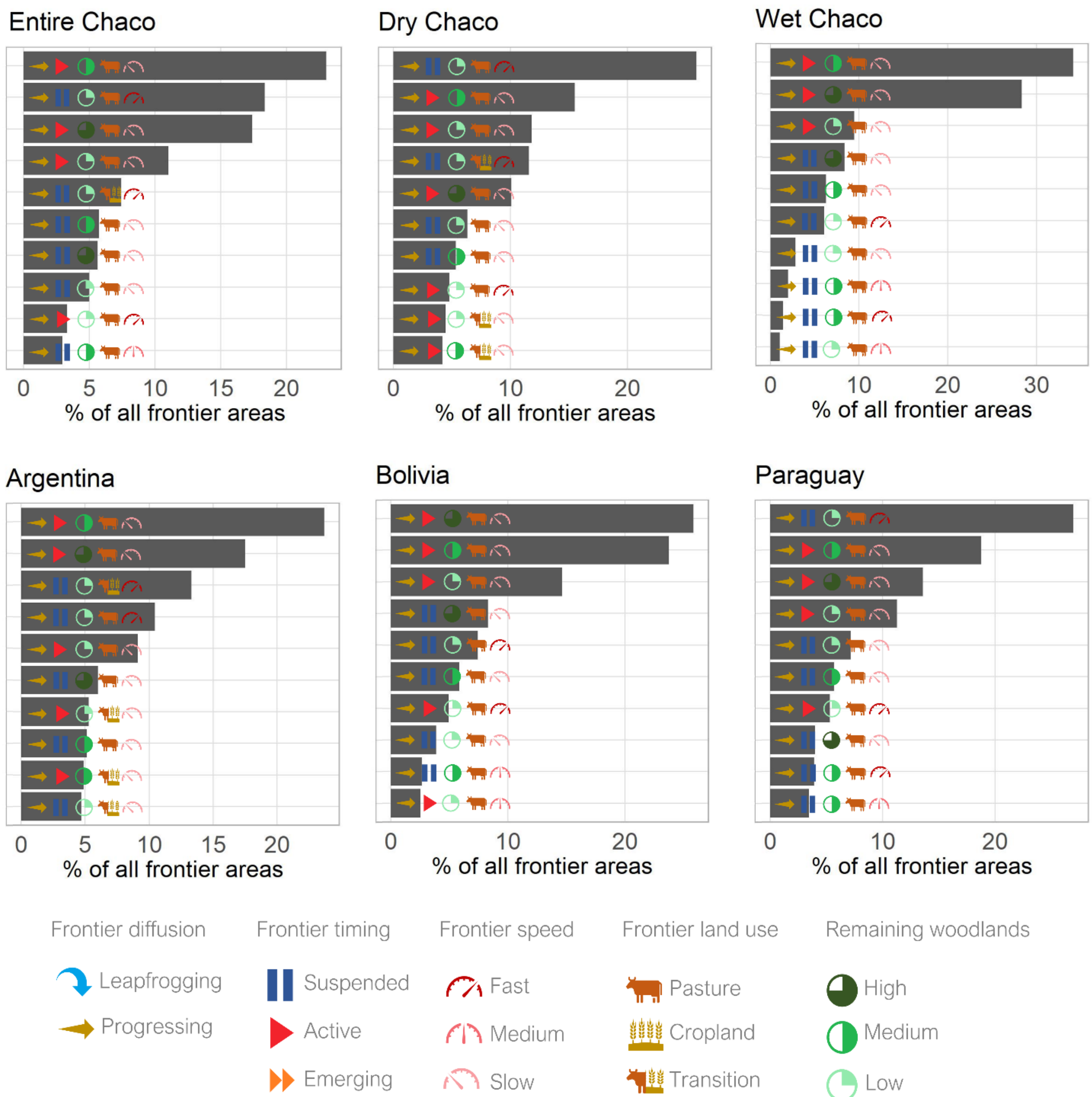

Figure 5: Top10 combinations of the five frontier metrics, and their relative share on all frontier areas. Results are presented for the entire Chaco and separated by the dry/wet Chaco and the three countries.

Associating our metrics with previously outlined frontier regions (le Polain de Waroux et al, 2018) suggested four clear groups of frontier types. Group I (blue color, Figure 6)) was characterized as *suspended* frontiers, with *low* naturalness and where frontier land use was either *transition* or *cropland* (i.e., Anta I, Córdoba, San Luís, Bandera, and Chaco-Santiago I). Group II (yellow) was similar to group I, except that the frontier land use was *pasture* (i.e., Tartagal, Chaco-Pantanal, and Central Chaco). Group III (green) were *active* frontiers in which remaining naturalness was either *high* or *medium* (i.e., Andean Foothills, Anta II, Chaco-Santiago I, Corrientes, Formosa). Lastly, group IV (red) encompassed all frontier regions, where naturalness was already *low,* but which were identified as *active*, independently from the frontier land use (i.e., Santa Cruz, Tucumán, Semiarid Chaco, Figure 6).

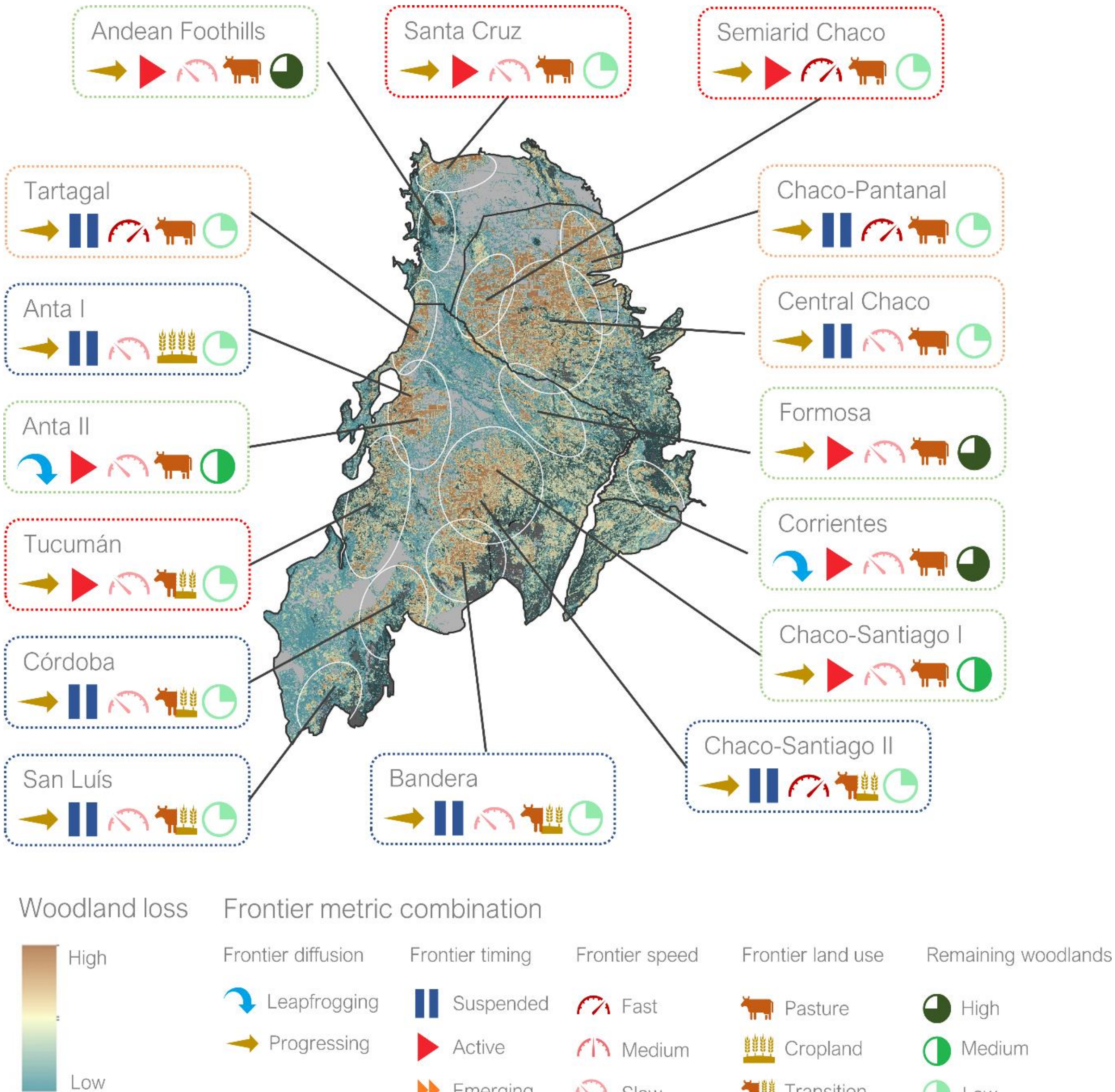

Figure 6: Characterization of different frontier regions based on the metrics. The background layer indicates woodland loss. For information on how the metric categories were assigned please refer to text SI-3 in the supplementary information. The different colors around each

frontier represent groups of frontiers (group I: blue, group II: yellow, group III: green, group IV: red) with similar characteristics.

Discussion

Better understanding how agriculture expands into tropical and subtropical forests is important for addressing the major sustainability challenges associated with frontier expansion. This is particularly urgent for the world's tropical dry forests, many of which are hotspots of deforestation, carbon emissions, and biodiversity loss. Here, we developed a novel approach to characterize frontier dynamics, based frontier metrics, and how these can be used to identify typical frontier dynamics. We demonstrate this approach for the entire South American Chaco, highlighting three key insights. First, reconstructing frontier dynamics since 1985 revealed rampant agricultural expansion, with 193,321 km² of Chaco woodlands being converted. Importantly, we here for the first time document a recent surge in woodland loss (after 2019). Second, translating land-use/cover time series into frontier metrics uncovered distinct frontier processes. For example, whereas ranching expansion drove woodland loss in Paraguay and Bolivia, cropland expansion since the mid-2000s in Argentina. Similarly, we uncover typical land-use trajectories following woodland loss, such as initial conversion for pasture and a later shift to cropping, or a considerable fallow period before agriculture is established. Fourth, the multidimensionality of our metrics allowed us to identify groups of frontiers with similar characteristics and development stages that are characterized by similar underlying processes and sustainability outcomes. Our metrics hence provide a deeper understanding of frontier processes while allowing to better target land governance policies to sustainable manage frontier regions.

Land-use change in the Chaco had previously been mapped (Guyra, 2018; Hansen et al, 2013; Song et al, 2021; Vallejos et al, 2015; Zalles et al, 2021), but never with the spatial, temporal and thematic detail that we provide here. Specifically, our mapping goes beyond prior efforts in at least four ways. First, our analysis reconstructs land-use/cover change back to 1985 at annual resolution, covering the entire history of modern agricultural expansion in this deforestation hotspot. Importantly, we developed an approach that ensures consistent, logical land-use trajectories, avoiding pseudo-change. Second, our analysis, for the first time, separates agricultural expansion from forest disturbances, which constituted a substantial share of the woodland loss in the Chaco (34%, *Figure 3*). Third, because our assessment was rigorously validated, we were able to derive the first robust area estimates of frontier dynamics in the Chaco. Fourth, our approach is novel in disentangling post-deforestation land-use changes, including multiple, subsequent land-use transitions. This revealed, for example, that deforested areas in Argentina are often eventually used for cropping, although initial deforestation occurs for ranching. It is important to highlight that our land-use reconstruction is solely based on satellite imagery, allowing for subsequent analyses (e.g., statistical analyzing of drivers of change). Likewise, our approach is easily transferable, can be scaled up to even larger regions, and can be updated as satellite image archives grow. This, we humbly suggest, constitutes a step-change in our ability to monitor land-use change.

The land-use patterns and trends we derived here are highly plausible. For example, our results suggest that frontiers expanded particularly rapidly in the 2000s in Argentina, but slowed down after 2010. The agricultural expansion boom in the 2000s was the result of several factors, most importantly the currency devaluation in 2001, which strongly increased profits from soy exports (Gasparri & Baldi, 2013) and the introduction of genetically modified soybean in the Chaco (le Polain de Waroux, 2019; Reenberg & Fenger, 2011). Indeed, most of the cropland frontiers emerged during that time (*Figure 4*). Later, increasing taxation, economic instability, an outflow of capital (le Polain de Waroux et al, 2019), increasing land-use restrictions through Argentina's zoning law (Marinaro et al, 2020), and the increasingly more marginal conditions for sites on which remaining forests are found (Houspanossian et al, 2016) lowered cropland expansion rates after 2010. In contrast, capital that accumulated in the soybean boom (in the Chaco or elsewhere, such as Brazil), combined with evolving know-how and infrastructure to optimize cattle ranching in the Chaco (le Polain de Waroux, 2019) explains surging woodland conversion we found in the Paraguayan Chaco after 2010. As a final example, the recent, more than 2-fold surge in deforestation after 2019 (Figure 3A) that we here document for the first time converges well with reports of increasing forest conversion, both legal and illegal, during the lockdown situation –in the Chaco and other deforestation frontiers globally (Fair, 2020; Price, 2020).

A major surprise in our findings was that most converted woodlands did not transition to agriculture right away, and many never. Four complementary explanations for this finding are plausible. First, natural disturbances, such as from fires or river-bed migrations are common in the Chaco (Adamoli et al, 1990; Bravo et al, 2001; De Marzo et al, 2021). However, disturbance attribution is not always straightforward. For example, fires occur naturally, are used as a management tool to control woody encroachment, or are associated with the deforestation process (Boletta et al, 2006). Second, woodland conversion may not be driven by the goal to immediately produce agricultural commodities, but might happen to secure land, to prepare land for resale, or simply in fear of tightening regulations (Seghezzo et al, 2011). Third, given that removing woodland and preparing land for agriculture requires capital (e.g., sowing with productive pasture grasses), there may be a time lag between deforestation and agricultural use, which we found for 34% of all woodlands converted to agriculture (Figure 3B). Finally, silvopastural systems, where parts of the tree canopy remain, are becoming more common in Argentina (Baldassini et al, 2018; Fernández et al, 2020), and these areas would fall outside of our pasture class. All of these factors point towards the importance to move beyond simply mapping forest or tree loss to quantify agricultural expansion in the tropics or to understand the causes and mechanisms of deforestation. This, in turn, is critical for properly attributing environmental trade-offs properly to commodities, which is a key research frontier for achieving supply chain sustainability (Gardner et al, 2019; Pendrill et al, 2019; zu Ermgassen et al, 2020).

Translating our land-use time series into a consistent set of frontier metrics, allowed us to move beyond land cover to characterizing land-use change processes. In our case, this enabled us to identify distinct frontier types, characterized by similar land-use and woodland loss dynamics in space and time. Such archetypical, high-level patterns and outcomes of human-environment interactions can help to structure complexity in land-use change (Levers et al, 2018; Pacheco-Romero et al, 2021; Vaclavik et al, 2013), foster a more mechanistic understanding of land-use change (Magliocca et al, 2018), and contribute to developing theories of the middle range (Meyfroidt et al, 2018). Importantly though, identifying archetypes, such as recurring frontier types, allows for the more context-specific, regionally-targeted land governance increasingly asked for (Christie et al, 2020; Kuemmerle et al, 2016; Thomson et al, 2019) (Pacheco et al, 2021). For example, *suspended* frontier with *low remaining* naturalness (i.e., group I (blue), Figure 6) are regions where restoration efforts in degraded lands are most suitable. Likewise, *pasture* or *transition* frontiers with *low* naturalness (i.e., groups I and II) may increasingly experience pasture to cropland conversions in the future, and hence actor-focus interventions may be most effective. Contrary, *active* and *fast* frontiers with *high* or *medium* naturalness (e.g., group (green)) should become hotspots of policy focus with the goal to develop and implement conservation interventions to avoid tipping points in woody cover, for example through urgent stop-gap measures. Hence, by transitioning from land-cover time series to process-oriented frontier types we now allow a framework for more targeted interventions that have the potential to steer frontiers towards more sustainable outcomes.

Our analyses provide the most detailed reconstruction of woodland and agricultural dynamics for the Chaco, including novel insights into how agricultural frontiers have expanded.

A few limitations still need to be mentioned. First, we only mapped agricultural expansion and intensification, but nor agricultural abandonment. Abandonment is not (yet) a widespread process in the Chaco and vegetation recovery on abandoned fields takes time (Basualdo et al, 2019). Still, adding de-intensification and abandonment processes would be a useful expansion of our approach in future work. Second, we describe frontier expansion related to intensified, medium-to-large-scale agriculture, but did not explicitly address forest smallholders practicing subsistence agriculture inside forests. While these actors are important in the Chaco, dynamics in forest smallholders mainly are due to agribusiness expansion (Levers et al, 2021), and so are indirectly captured here. Third, while our accuracy assessment suggests robust maps, we highlight remaining uncertainty, including confusions between natural vegetation and pastures that might be particularly the case for silvopastures.

Agricultural expansion into tropical and subtropical forests contributes heavily to many global sustainability challenges. Steering these frontiers towards more sustainable outcomes requires a better understanding of the dynamics of frontier processes. Here, we developed and demonstrated a novel approach to generate such understanding on the basis of frontier metrics derived from freely available, high-resolution satellite imagery. For the Chaco, our frontier metrics characterize and structure the complexity of frontier dynamics, for example revealing slow vs. rampant frontiers, where frontiers are emerging, or when frontiers were particularly active. This allows for exploring the underlying drivers of these frontier processes, including testing hypothesis about causal mechanisms. Equally importantly, our metrics reveal so far unaccounted for, substantially post-deforestation land-use change, highlighting that about 34% of the deforestation in the Chaco might be wrongfully attributed to commodity agriculture, and another 17% might be attributed to the wrong commodity depending on which baseline is chosen. Our transferable, repeatable, scalable, and extendable approach allows for comparative research across regions to find rules governing frontiers in many situations, as well as to identify generalizable patterns and processes that shape frontiers in different regions. In the Chaco and elsewhere this can enable cross-regional learning and the more regionally targeted, context-specific policy-interventions that are often asked for. More broadly, our study highlights the opportunities of the big data era of remote sensing for creating a step change in our understanding of land-use change and for uncovering high-level patterns of human-environment interactions.

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