LETTER

Increasing expansion of large-scale crop production onto deforested land in sub-Andean South America

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Abstract

A combination of high commodity crop prices, rising global food demand, and technological advances has transformed the scale of global crop production. Farming in South America is a prime example, where large-scale cash crops, such as soy, have transformed the land use dynamics at the forest frontier. We evaluate this transformation in sub-Andean South America by estimating crop and forest cover and detecting individual cropland field parcels using Landsat imagery in 5 year intervals over a 24 year period. From 1990 to 2014, cropland expansion onto deforested land was increasingly driven by large fields (>50 ha), whose contribution increased from 32% to 48% (+16% increase), while the contribution of smaller fields (<20 ha) declined from 36% to 26% (−10% decrease). This shift toward large-scale farming replacing cleared land across the region has important implications for food security and biodiversity conservation. Policy efforts will need to target different actors and transcend national borders in order to tackle the changing nature of South American deforestation.

1. Introduction

Agriculture is the primary cause of deforestation across the planet [1–3]. South America, in particular, is currently undergoing rapid forest loss [4] with a concomitant expansion of agriculture [5], both in terms of extent and the intensity of production [6]. The region is home to the world’s largest contiguous tropical forest, with vast reserves of carbon and biodiversity; thus the rapid forest clearing is of international concern. Numerous governmental and intergovernmental programs have been initiated to slow deforestation, such as the Action Plan for Prevention and Control of the Legal Amazon Deforestation, Reducing Emissions from Deforestation and Forest Degradation, and the voluntary Brazilian Cattle [7] and Soy Moratoriums [8]. Their effectiveness depends on a clear understanding of the causes of deforestation, the nature of the agricultural actors involved, and land use dynamics on recently deforested land.

Ranching has been the principal historical cause of forest loss in South America [2, 5, 9, 10], but observations in Brazil from the mid-2000s found an increasing propensity of large-scale farming to expand directly into forests [11]. Export oriented agricultural production of crops like soy and sugarcane are a leading cause of agricultural expansion across the continent [8, 12–14]. In much of sub-Andean South America, the production of these and other commodity crops is highly mechanized, utilizing advanced farm machinery, modern planting techniques, and inputs such as irrigation, fertilizers, and pesticides. Farming increasingly occurs on large fields in order to save labor and management costs, deploy large machinery, and fully harness other economies of scale [15]. Thus, crop fields as large as 1000 ha can be found in parts of South America, along with subsistence and small-scale peasant agriculture.

Differences in production practices, such as swidden, cash-cropping, or commercial, influence the type of food grown, amount of land cleared for cultivation,
intensity of post-clearance land use, and overall stewardship of land under active management [10, 16, 17]. While large-scale crop production can increase unit profits [15], monoculture cropping and the heavy use of synthetic inputs raise environmental concerns [18]. Further, large-scale crop production affects within-field pest management, and surrounding biodiversity and landscape fragmentation [19]. Thus, short-term gains in production and economic returns are accompanied by environmental costs, along with important implications for food security and smallholder livelihoods [20].

Policies that target reductions in deforestation have to account for the shifting dynamics and actors of land use change. Previous studies have evaluated the effectiveness of such policies in South America by examining agricultural actor dynamics and the scale of forest clearance at the levels of municipality [21], census tract [22], individual property ownership [23–25], and forest patch size [26–28]. These studies shed important light on the nature of deforestation and the effectiveness of the aforementioned policies. Such studies focused primarily on Brazil, and while they analyze ownership or contiguous clearance patches, they do not assess land use dynamics at the field level (i.e., the level of production). Studies examining land use dynamics at the field level are limited in quantity and scope because large-scale field size data at the parcel level are unavailable (with the exception of data from Yan and Roy for the USA [29, 30]). To date, the extent of agricultural expansion across South America has only been examined using a sub-sampling approach [2, 31] and by total area [3]. The scale of cropland production at the field level has not been examined systematically over a large area, and thus, the role of small- and large-scale crop farming in South American agricultural expansion, especially outside of Brazil, is still largely unclear.

In this study, we examine cropland expansion in sub-Andean South America since 1990 to investigate the role of the scale of crop production on recently cleared land. Using novel datasets of land cover and cropland field parcels spanning five countries, we attribute cropland expansion by individual parcels onto deforested land from 1990 to 2014, in 5 year intervals. We then quantify the contribution of different cropland field sizes that expanded onto former forestland over the 5 year periods. Our data indicate whether large-scale crop farming is increasingly expanding into cleared tracts of forest since 1990, over 5 year periods, but they do not illustrate direct cropland expansion onto forests. Further, our approach is complimentary to studies using administratively tied land ownership data, and an advancement over studies examining forest clearance patches, which overlook sub-patch land management details. The results presented here reveal, for the first time, the evolving scale of cropland production at the field level and its role in South American agricultural expansion and post-deforestation land use.

2. Materials and methods

2.1. Study area and timeframe

We examined the scale of cropland expansion in sub-Andean South America (figure S2 is available online at stacks.iop.org/ERL/13/084021/mmedia) from 1990 to 2014, in 5 year intervals. Each time period was centered on a 1.5 year season from 1 January of the first year to 1 August of the second year (e.g., 1 January 1990 to 1 August 1991) [32]. The two-year combinations for each time period were 1990/1991, 1995/1996, 2000/2001, 2005/2006, 2010/2011, and 2014/2015. Further discussion about the study area can be found in the supporting information.

2.2. Data

We used the following number of Landsat path/rows: 356 for 1990/1991, 351 for 1995/1996, 411 for 2000/2001, 412 for 2005/2006, 408 for 2010/2011, and 408 for 2014/2015. The discrepancies between years are due to path/row exclusion if scene availability was insufficient, particularly in the southern latitudes of the study region. The Landsat data were acquired as surface reflectance climate data record products from the USGS Earth Resources Observation and Science Center Science Processing Architecture (http://espa.cr.usgs.gov). Scenes with 80% or less cloud cover were chosen from the continent. For the 1990/1991 and 1995/1996 time periods, only the Thematic Mapper (TM) sensor was used, for 2000/2001 the TM and Enhanced Thematic Matter Plus (ETM+) Scan Line Corrector (SLC)-on sensors were used, for 2005/2006 and 2010/2011, TM and ETM+ SLC-off were used, and for 2014/2015 the TM, ETM+ SLC—off, and the Operational Land Imager Thermal Infrared Sensor sensors were used.

2.3. Landsat processing and field extraction

We produced a regional cropland dataset with cropland characterized at the level of individual, contiguous field parcels. The methods to process Landsat imagery and extract cropland field parcels consisted of image normalization, temporal compositing of spectral indices, extraction of land cover objects (i.e., groups of pixels), per pixel (30 m) estimates of cropland, forestland, and other broad land cover classes, and the intersection of segmented land cover objects with the pixel-level cropland estimates. A simplified overview of the procedure to produce individual field parcels is described below (see [32] for details).

First, we estimated cropland, forestland, and other land covers from multi-temporal Landsat imagery as outlined in SI materials and methods (see also [32]). Then, individual land cover objects were extracted...
from temporal Landsat composites and intersected with the cropland estimates to produce individual cropland parcels (figures S3 and S4). The result of the intersection between segmented land cover objects and pixel-level cropland estimates is a dataset with more detail, and with potentially different total area, than the land cover estimates by either of the following criterion: (i) individual land cover objects that do not meet size requirements (i.e., <50% of the object is cropland) are removed from the field parcel dataset, in which case decreases the total cropland area of the field size dataset compared to the land cover estimates; and (ii) land cover objects that meet the size requirements but are not 100% cropland (i.e., 50% cropland \(\leq\) land cover object < 100% cropland) are considered 100% cropland, which increases the total cropland area of the field size dataset compared to the land cover estimates (figure S5). Any land cover object with 100% overlapping cropland is kept unchanged.

### 2.4. Per parcel attribution to cropland expansion

We calculated cropland expansion onto deforested land from 1990 to 2014, and attributed deforested area at each 5 year interval to individual field parcels. Parcels that expanded onto deforested land within a 5 year period were considered short-term forest-to-cropland transitions. Longer-term transitions were those where cropland expanded onto previously deforested land (e.g., a transition from forest to pastureland from 2005 to 2010, followed by pastureland to cropland from 2010 to 2014). Thus, we considered cropland expansion onto deforested land regardless of the time between clearance (figure S6). It is important to note that we did not make assumptions regarding the direct cause of deforestation between the 5 year periods. We only required that cropland expand onto land cleared of forest at some point in time to be included in our calculations. For simplicity, though, we refer to all forest-to-cropland transitions as ‘cropland expansion onto deforested land’. When calculating the area of deforested land that individual crop parcels expanded onto, we treated each crop field as one unit and forest area by individual pixels. Therefore, a crop field only had to expand onto a minimum of one forest pixel for that particular field parcel to be considered as a forest-to-cropland conversion. The per parcel deforestation totals, however, were only calculated from individual forest pixels that were replaced by a crop field. Examples of forest-to-cropland transitions over 24 years are illustrated in figure S7.

We evaluated the scale of cropland expansion onto cleared forestland at 3 levels. All forest-to-cropland calculations were applied at the field parcel level, and then aggregated to arbitrarily-shaped hexagonal units (115 km\(^2\)) and ecoregions (figure S2). A total of 56 432 hexagonal units covered the study region. Cropland fields were binned into 10 field size clusters (0.45–1.99; 2–4.99; 5–9.99; 10–19.99; 20–49.99; 50–99.99; 100–199.99; 200–499.99; 500–999.99; > 1000), in hectares. For discussion, we considered small fields as those <20 ha and large fields as those > 50 ha.

### 3. Results

#### 3.1. Changes at the ecoregion level

From 1990 to 2014, an increasingly greater proportion of cropland expansion onto deforested land was attributable to large cropland fields (defined here as greater than 50 ha, see materials and methods), an increase from 32% to 48%, while the contribution of fields smaller than 20 ha declined from 36% to 27%, and the contribution of fields 20–50 ha decreased from 32% to 26% (figure 1 and table S1).

Cumulative cropland expansion (summation at each 5 year time step from 1990 to 2014) onto deforested land was highest in the Cerrado (111 478 km\(^2\)), followed by the Dry Chaco (100 789 km\(^2\)), the Alto Paraná Atlantic forests (49 017 km\(^2\)), and the Mato Grosso seasonal forests (39 608 km\(^2\)) (figures 2 and S2). In the Cerrado of central Brazil, the contribution of fields >50 ha in cropland expansion onto cleared forestland increased from 37% in the 1990–1995 period to 50% in the 2010–2014 period. Elsewhere, the...
contribution of large fields increased from 40% to 56% in the Dry Chaco, from 28% to 37% in the Alto Paraná Atlantic forests, and from 45% to 59% in the Mato Grosso seasonal forests.

3.2. Changes at the sub-ecoregion level
From 1990 to 2014, 1277 hexagonal zones (a unit of analysis used here; see materials and methods) with \( > 50 \text{ km}^2 \) of forest loss per zone accounted for 27.17% (104 022 km\(^2\)) of cumulative cropland expansion onto deforested land, but only comprised 2.19% of all zones. Zones of high forest loss (\( \mu \) field size = 29.14 ha; 50th = 27.04; field size \( \sigma = 13.23 \)) were in the northeastern Cerrado quad-state region of Maranhão, Tocantins, Piauí and Bahia, the Amazon frontier where the Cerrado meets the Mato Grosso seasonal forests, the southwestern Chiquitano, the eastern and western Dry Chaco, and the southwestern Alto Paraná Atlantic forests (figure 3). Zones with 10–49 km\(^2\) of forest loss (N hexagons = 8631; \( \mu \) field size = 23.95 ha; 50th = 22.49; field size \( \sigma = 12.71 \)) were 14.8% of total zones and accounted for 47.42% (181 700 km\(^2\)) of cumulative cropland expansion onto deforested land. These zones were found in the northern Espíritu, southern Brazil along the eastern Alto Paraná Atlantic forests, and in the eastern Amazon ecoregion, the Tocantins/Pindare moist forests. Zones with 5–9.99 km\(^2\) of cumulative forest loss (N hexagons = 6607; \( \mu \) field size = 23.03; 50th = 20.15; field size \( \sigma = 14.99 \)) were generally found in the same regions as those above. Zones with 1–4.9 km\(^2\) of cumulative forest loss comprised the largest number of zones (33 175, or 56.9% of all zones), but only accounted for 13.05% (49 996 km\(^2\)) of cumulative cropland expansion onto deforested land. Zones of low forest loss (\( \mu \) field size = 17.29 ha; 50th = 10.84; field size \( \sigma = 18.99 \)) were found throughout the Cerrado u-shaped agricultural belt, the Brazilian-Paraguayan border, and across the Uruguayan savannas and Humid Pampas.

3.3. Cropland expansion and land cover predictions
The majority of cropland expansion onto deforested land occurred within 5 years after forest clearance (figure 4). After 2010, expansion onto land 5+ years post-clearance accelerated, increasing by 252% in the Cerrado, 236% in the Amazon ecoregions, 73% in the Dry Chaco, and by 41% in the remaining ecoregions. The Dry Chaco region accounted for the largest area of cropland expansion onto deforested land until the 2010–2014 period. From 2010 to 2014, though, total cropland expansion onto cleared forestland increased by 92% in the Cerrado, compared to 24% in the Dry Chaco, 87% in the Amazon ecoregions, and 19% in all other ecoregions.

We conducted an independent accuracy assessment of 870 random samples throughout the study area (SI table S4). The F-score (the harmonic mean of Producer’s and User’s accuracy) for cropland was 0.83 while the forest F-score was 0.78. Our data generally over-predicted cropland (User’s and Producer’s accuracies of 78% and 87%, respectively) while forest predictions were more balanced (User’s and Producer’s accuracies of 79% and 76%, respectively). The samples were temporally biased toward the late 2000s, with cropland and forest F-scores falling, respectively, from 100% and 88% in 2000, 90% and 78% in 2005, 79% and 80% in 2010, and 83% and 75% in 2014.

4. Discussion
Our study shows that cropland expanded onto deforested land over the 1990–2014 period through increasingly larger field sizes. An immense amount of forest within our study area was already cleared prior to 1990. Rampant deforestation rates before 1990 had already shaped the agricultural landscapes in the Brazilian state of Rondônia [33] and in the Atlantic Forest of eastern Paraguay [34], and large tracts of forest were cleared elsewhere in the Brazilian Amazon [35] and the Argentine Chaco [27]. However, these cleared areas were largely used for pastureland or managed by smallholder crop farmers. Since the 1990s, there has been an increase of large-scale cropland farming near forest frontiers.

4.1. The rise of large-scale cropland farming
Many factors undoubtedly influenced the shift to larger-scale cropland expansion in sub-Andean South America, but the rise of soy as a major commodity market was perhaps the most instrumental. Twentieth century advances in the soybean sector and rising global demand for beef, poultry, and pork instigated an unprecedented expansion of soy area throughout South America [35]. In the late 1990s, soy expanded rapidly outside of core regions and into new territory, such as the Dry Chaco and Cerrado ecoregions. Thus, it is no surprise that the scale of cropland expansion onto deforested land increased over this same time.
First, soy production in South America is highly mechanized and therefore benefits from having large tracts of land compared to other agricultural operations [20, 36, 37]. The tightly integrated soybean supply chain also requires efficient transportation and storage logistics [20]. Demand for these types of infrastructure increases as more farmers expand or resettle into sparsely populated frontiers, and in turn facilitates the expansion of the agricultural core [16]. Second, technological advances that brought new soy cultivars to tropical soils [38] and no-till farming [18], increases in precipitation [39], and limitations to expand in traditional regions enabled farmers to produce crops in areas once thought of as marginal [40]. However, drier, marginal regions such as the southern Pampas and Dry Chaco require that farmers manage cropland on larger scales to obtain similar levels of production as their central Pampas counterparts. Third, lower land prices outside of more densely populated and more densely farmed regions allow farmers to expand their operations. Farmer credit access and business-friendly politics attracted large-scale farmers and corporations to the Argentine Chaco [41, 42], Santa Cruz, Bolivia [16], and Mato Grosso, Brazil [43], and our results confirm that large-scale farming was a key driver behind cropland expansion onto cleared forestland within these regions.

We illustrated that a proportionally small area accounted for a large share of cropland expansion onto deforested land in sub-Andean South America. These areas had, on average, the largest fields driving expansion onto cleared land. It is no surprise that these areas were all located in the interior deforestation hotspots. However, the size of fields within these regions

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**Figure 3.** Average field size of cropland expansion onto deforested land, from 1990 to 2014. The hexagon color illustrates the cumulative forest area replaced by cropland over 24 years, while the hexagon size displays the average size of crop fields that expanded onto previously forested land over the 24 year period. Ecoregions include: MT: Madeira-Tapajós moist forests; TX: Tapajós-Xingu moist forests; XTA: Xingu-Tocantins-Araguaia moist forests; TP: Tocantins/Pindare moist forests; MS: Mato Grosso seasonal forests; CR: Cerrado; BI: Bahia interior forests; CH: Chiquitano dry forests; DC: Dry Chaco; HC: Humid Chaco; AP: Alto Paraná Atlantic forests; AR: Aracuraria moist forests; UY: Uruguayan savannas; HP: Humid Pampas; ES: Espinal; LM: Low Monte.

**Figure 4.** Cumulative cropland expansion onto deforested land. At each 5 year timeframe, cropland expansion is measured as expansion onto deforested land within 5 years, or as expansion onto deforested land 5+ years after clearance. The dashed lines illustrate the cumulative cropland expansion onto deforested land that occurred within 5 years. The solid lines illustrate total cropland expansion onto cleared forestland. Shaded areas highlight cropland expansion onto land that was deforested for more than 5 years. The Amazon ecoregions included in the calculations were the Madeira-Tapajós moist forests, the Mato Grosso seasonal forests, the Tapajós-Xingu moist forests, and the Xingu-Tocantins-Araguaia moist forests.
revealed that large-scale farming was driving expansion across multiple countries.

4.2. The implications of large-scale production

Our findings demonstrate that large-scale farming is becoming more commonplace within deforested areas. These results suggest a change in production practices of existing crop farmers and/or the movement of large-scale farmers closer toward forest frontiers. Our results align with the findings of Godar et al [22], who found that the largest share of Brazilian deforestation from 2004 to 2011 came from large landholders, and Richards and VanWey [23], who highlighted that remaining forest cover in Mato Grosso lies in the hands of large landowners. Our results illustrate changes in the scale of cropping heighten large-scale agriculture’s role in post-deforestation land use and inform aforementioned studies that focus on farm or property size. Agricultural production occurs at the field level, and the differences between property or farm size and field size is important. Large farms can produce crops in a variety of ways, and do not necessarily require that they cultivate over large fields. Fields are a direct unit of observation for agricultural practices and provide important information for monitoring landscape changes.

Expansion of large-scale farming will have important economic, socioeconomic, and environmental implications. Few can deny commercial agriculture’s macroeconomic impact in the study region. Large-scale agriculture is a major contributor to national GDP [44]. Soy, in particular, consists of a tightly integrated, export oriented supply chain controlled by large-scale operators [45, 46]. This type of commercially marketed agriculture attracts foreign farmers and investors, and increases production and economic returns. However, this agricultural export model also inspires mechanization and land consolidation. Small and medium-sized producers are allegedly indirectly excluded from the prospering soy market because of equipment expenses and land access [37]. In previous decades, when frontier stakeholding was encouraged, smallholders could sell land and continually move farther down roads on the frontier. Tighter regulations today could leave smallholders who are forced to sell their land with fewer options. Moreover, the rapid expansion of large-scale crop producers indicates that agrarian structure across the study region could be changing. In past decades, this has been reflected in land concentration, labor loss in the agricultural sector, and an unequal distribution of food access [47, 48] because large farms focus on export crops and have the technological capacity and capital to produce more efficiently.

The expansion of large-scale farming also has important environmental consequences. Crops such as soy are sold to farmers and produced as a ‘mechanized package’ that requires the application of synthetic inputs [20]. Runoff from pesticides and herbicides degrades water sources and negatively impacts biodiversity [58]. The traditional agricultural regions contain important biodiversity, but they pale in comparison to the biodiversity found in the Dry Chaco, Cerrado, and Amazon, where large-scale cropland expanded most rapidly. Further, changes in field size can alter landscape dynamics such as fragmentation and diversity, which can isolate species and limit migration [49]. Clearly, more efforts are needed to better understand these changing land use dynamics in post-deforestation agricultural frontiers.

4.3. The implications for deforestation regulations

From an economic perspective, the future of farming in South America is bright. There is an ample supply of arable land that is increasingly accessible through road and fluvial infrastructure. Farmers in the region are highly innovative and business minded, and they stand to prosper from continued demand from regional urbanization [50] and global dietary shifts [51]. However, cropland farming has become more specialized and market-oriented since 1990, and the market is increasingly expanding onto newly deforested land. As a recent study pointed out, companies favor agricultural investments close to their current holdings and where forestland is available and cheap, even in the presence of policy restrictions and enforcement [16].

In Brazil, deforestation regulations successfully inhibited the ability of farmers and ranchers to clear forests after 2006 [8, 52, 53]. The absence of similar policies elsewhere in Brazil and neighboring countries, though, has led researchers to question whether policies might indirectly cause cropland expansion [54, 55]. Moreover, countries such as Argentina, Bolivia, and Paraguay, which border Brazil, have actively promoted investments by large-scale agriculture [16]. Our findings track cropland expansion outside of the Amazon region after 2006. For example, there were large percentage increases from 2010 to 2014 of cropland expansion onto 5+ year deforested land in the Amazon and Cerrado ecoregions. These increases indicate farmers expanded more rapidly onto long-term pasturelands instead of onto newly cleared forests. The spike in total cropland expansion from 2010 to 2014 in the Cerrado compared to other regions could point to indirect consequences of deforestation policy during a period when forest regulations were said to have slowed Amazonian deforestation rates. As studies have shown (e.g., [55]), though, the issue is likely more complex than simply enacting policy in one location. A causal link between deforestation rates and policy is not clear from this study, and further research is needed before trans-national ‘leakage’ in South America can be fully understood.

Clearly, deforestation is not just a problem in the Brazilian Amazon, so there must be consistency in
cross-border regulations to tackle the issue across the region. In particular, policies need to target large-scale cropland expansion, as it was responsible for the largest proportional expansion onto cleared forest.

4.4. Uncertainty of the land cover predictions

Cropland area, and the field size within expanding cropland, increased over the study timeframe, and these increases were accompanied by a decline in land cover accuracy from 2000 to 2014 (see table S4). Additionally, there is lower agreement between Landsat- and MODIS-based [5] cropland change at the end of the study timeframe (figures S8 and S9). The increase in cropland area from our predictions are, therefore, likely overstated. However, our principle objective was to investigate the changing scale within expanding cropland, and not necessarily to quantify the total area of cropland and forestland. To this end, we argue that our findings of increasingly larger field sizes expanding onto deforested land match to what: (ii) we saw on the ground; (ii) has been reported in the literature; and (iii) we interpreted from satellite imagery (see SI accuracy assessment and uncertainty for further discussion).

5. Conclusion

South America contains the largest area of tropical forest across the world, which combined with favorable available land for agriculture, makes it a key region for agricultural expansion. Improved access, high commodity crop prices, and favorable exchange rates have aided the expansion of row crop agriculture and pastureland for livestock grazing across the continent [11, 56–58]. The technological advances behind large-scale cropland expansion in South America are remarkable. They have transformed tropical and sub-tropical land into one of the most productive contiguous agricultural regions on the planet. But large-scale agriculture is increasingly expanding onto cleared forestland, particularly along the forest frontiers. This rapid expansion of large-scale crop production into forested regions will have important—positive and negative—long-term economic, environmental, and socioeconomic implications for the region. Our study finds that there are six frontier hotspots of large-scale cropland expansion: the Mato Grosso seasonal forests/Cerrado border, the MaToPiBa region in the northeastern Cerrado, the Chiquitano dry forests, eastern Paraguay Atlantic Forests, and the northwestern and eastern Argentine Dry Chaco. Policies directed at limiting large-scale cropland expansion into forests should target these regions.

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