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Dynamics of deforestation worldwide: A structural decomposition analysis of agricultural land use in South America

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ABSTRACT

Deforestation, mainly caused by the conversion of forest land to agriculture, threatens the achievement of multiple goals across the 2030 Agenda. This environmental issue is particularly marked in the area formed by Argentina, Brazil, and Paraguay (ABP region), where a net forest loss of more than 5,5 million hectares per year and a simultaneous net gain in agricultural land of almost 3 million hectares were registered during 2000–2015. To identify the main contributors to the growth in agricultural land use driving regional deforestation, a Structural Decomposition Analysis (SDA) is applied on multiregional input-output tables. Results suggest that changes detected within ABP were mainly influenced by shifts in domestic demand and exacerbated by the influence of Brazil within the Mercosur trade agreement. Outside ABP, results show that consumption per capita and population expansion in developed and developing economies (the EU28, the US, and China) are major drivers of regional deforestation. Although globalization led to a surge in the ABP's land displaced to other countries, our results indicate that outsourced agricultural activities did not affect the growth in ABP's agricultural land use. There is thus a need of designing mitigation measures with a global sense that also addresses co-responsibility mechanisms among countries in the region.

1. Introduction

The sustainable management of the world's forests is essential for achieving the Sustainable Development Goals (SDGs) of the 2030 Agenda (UN, 2015), especially those that involve ensuring food security, conserving biodiversity, and tackling climate change. Nevertheless, the global forest area decreased from 31.6% to 30.6% between 1990 and 2015 (Keenan et al., 2015).

Several studies confirm that one of the main causes of forest loss worldwide is the agricultural expansion generated by the growing demand for global food as a consequence of increasing populations and changes in diets in emerging countries like China, Brazil, and India (Byerlee et al., 2014; DeFries et al., 2010; Tramberend et al., 2019).

Fig. 1 presents forest loss through conversion to agricultural areas by regions from 2000 to 2015. As it can be seen, there was an overall decrease in forest area worldwide and an increase in the agricultural area in regions such as Africa and South America. In contrast, developed regions such as North America and Europe or developing areas like East Asia followed an opposite trend over the period.

The case of South America is of particular interest: while experienced a decrease of more than 3 million hectares of forest area, it gained almost 2 million hectares of agricultural land per year over the period (see Fig. 1). Particularly, the most affected area by forest loss was the zone formed by Argentina, Brazil, and Paraguay (the ABP region) where, according to FAOSTAT, a net forest loss of more than 5,5 million hectares[1] and a net gain in agricultural land of almost 3 million hectares per

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[1] Forest and grassland fires have also contributed to forest destruction in these countries, generating a loss of 35 million ha per year over 2003–2012 (van Lierop et al., 2015).

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year was registered.[2]

Brazil, Argentina, and Paraguay are geographic neighbors and the founding partners of *Mercado Común del Sur* (Mercosur). This agreement favored their trade relation, generating an economic dependency between them, mainly characterized by the influence of Brazil. In environmental terms, ABP hosts some of the most important forests worldwide: The Amazonia Rainforest (Brazil), the *Cerrado* biome (Brazil and Paraguay), the *Gran Chaco* (Argentina and Paraguay), and the Atlantic Forest (Brazil and Paraguay).

Although the ABP region includes only three countries and is concentrated in a reduced geographical area, analyzing the changes registered in their land use patterns is of global interest mainly for two reasons. First, deforestation due to agricultural activities has affected all the aforementioned forests, generating an incalculable loss in terms of biodiversity at the global level (Hosonuma et al., 2012; García and Ballester, 2016). In addition, land use changes in ABP contribute to almost 30% of global annual losses on CO_2 emissions (De Sy et al., 2015; Sá et al., 2017). Secondly, the ABP's agricultural sector has a key role to meet global food demand: this region accounted for 13% of the crops and 10% of meat produced in the world, whereas its exports represented 8% of agricultural global exports in 2015 (FAOSTAT, 2019). Therefore, the expansion of agriculture together with the high relevance of land for climate change mitigation, indicates that identifying the ultimate economic drivers of ABP's land use is paramount in the successful application of sustainable land-related policies.

However, fragmented production processes and complex trade relationships due to globalization have complicated the monitoring of agricultural land used through global supply chains and hence the assessment of the driving factors behind its use. Next to the land use due to the production of goods and services (production-based accounting), the consumption-based perspective involves the use attributed to final consumers. Thereby, consumption changes in one country may cause production displacement and thus trigger changes in natural resources used in production processes elsewhere (Meyfroidt et al., 2013). Within this current globalization context, multiregional input-output (MRIO) tables provide a useful basis for tracking the agricultural land that is sourced from a specific region and embodied in trade flows from primary production to its final use (Wiedmann, 2009). MRIO models have been widely applied to analyze land of diverse types at the global level (Bruckner et al., 2019; Chen et al., 2018; Wu et al., 2018; Ivanova et al., 2016; Chen and Han, 2015; Kastner et al., 2014; Weinzettel et al., 2013). Regional analysis has been also performed on the group of EU countries (Steen-Olsen et al., 2012) and a relevant number of them focus on the dynamics of China's embodied land use, such as forest land (Kan et al., 2021), pasture land (Guo et al., 2019) or arable land (Han and Chen, 2018). However, little attention was paid to the important role of the agricultural land in the particular area formed by Argentina, Brazil, and Paraguay and none of these studies explored the specific determinants of ABP's agricultural land use evolution.

Therefore, unlike previous studies, this paper aims to reveal the main global economic forces of the growth of agricultural land use in ABP during 2000–2015 by applying a Structural Decomposition Analysis (SDA). SDA is an exploratory technique that employs IO databases to decompose the observed changes in a variable, such as agricultural land use, into several determinants over time. The contribution of each driver reflects the isolated change in the variable under study if only this factor had changed while keeping the others fixed. In this paper, the use of SDA will allow us to analyze the role played by technological changes, production and demand structures, and population growth in driving up ABP's agricultural land.

Although SDA has been widely used to study the evolution and drivers of changes in environmental variables (see Hoekstra and Van der Berg, 2002, for a review of these issues) to the best of our knowledge, an

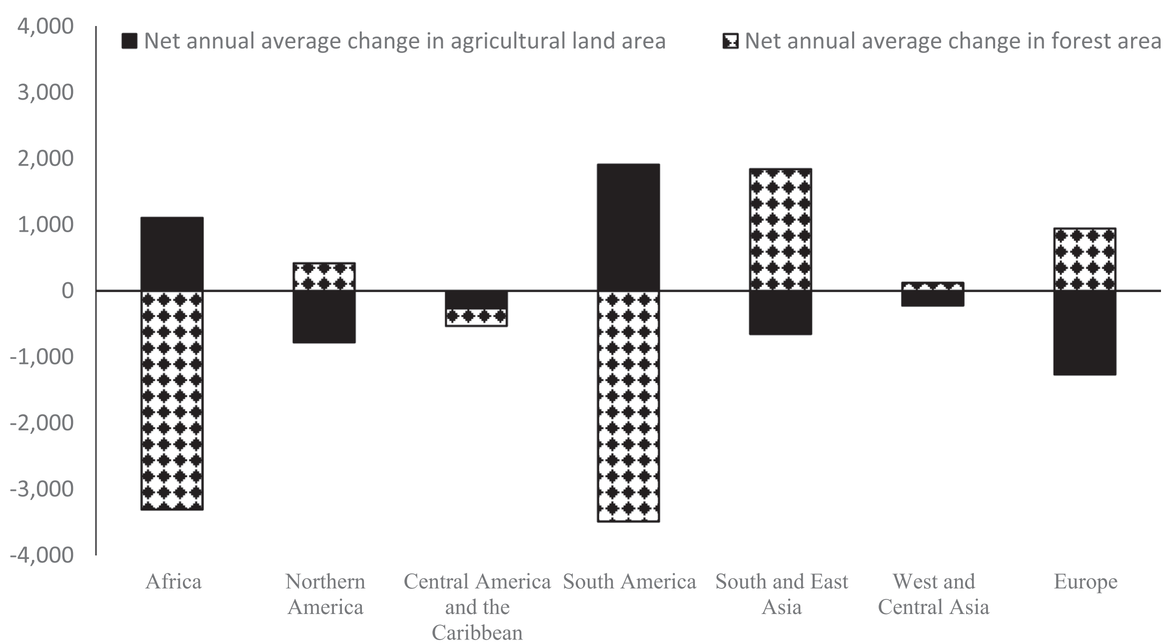

Fig. 1. Net annual average change in agricultural land* and forest area by regions, 2000–2015 (thousand ha). *Note: This category includes croplands, permanent meadows, and pastures.
Source: Own elaboration with data from the Food and Agriculture Organization Statistics (FAOSTAT).

[2] For other land use in the ABP region, the area occupied by other wooded lands (land not classified as forest, with a canopy cover of 5–10% or with a combined cover of shrubs, bushes, and trees above 10%) decreased by 4.8 million ha between 2000 and 2015 due to agricultural expansion. Argentina has the largest proportion of other wooded lands (by 23% of the total land area of the country) within the ABP region, followed by Brazil (by 5%). Urban areas, that only account for around 2% of the ABP's total land area, have been relatively stable over time (FAO, 2020).

SDA has never been applied to study the changes of agricultural land use, particularly focused in the ABP region. Only Cai et al. (2020) recently explored the driving forces behind the variations in agricultural land use in China by applying an SDA. For this reason, we carry out an SDA within the MRIO framework to determine the main domestic and foreign drivers of the agricultural land use increase in the particular ABP region, which is recognized worldwide for its deforestation.

The remainder of the paper is organized as follows. Section 2 describes the methodological aspects of the SDA application. The results are displayed in Section 3, followed by the discussion and policy implications in Section 4. Finally, Section 5 offers some concluding remarks.

2. Materials and methods

2.1. Structural decomposition analysis

Our MRIO model is based on the multiregional framework of Isard (1951) or Miller and Blair (2009) with *m* countries and *n* sectors. We start with the Leontief inverse of country *r* at time *t:*

$$\mathbf{x}_t = (\mathbf{I} - \mathbf{A}_t)^{-1}\mathbf{y}_t = \mathbf{L}_t\mathbf{y}_t \tag{1}$$

where $\mathbf{A}_t$ is the multi-regional matrix (*nm x nm*) of technical coefficients for *m* economies with *n* sectors at time *t*, $\mathbf{L}_t$ is the Leontief inverse (*nm x nm*), $\mathbf{x}_t$ is the output vector (*nm x 1*) and $\mathbf{y}_t$ is the final demand vector (*nm x 1*). **I** is an identity matrix of appropriate dimensions. The standard input-output notation is used in this paper. Matrices are named in bold capital letters, vectors in bold lower-case letter, and scalars in italic lower-case letters.

Let $\mathbf{d}_t = (d_j)$ be a row vector of direct agricultural land use per sector *j* at time *t* and $\mathbf{k}_t$ another row vector of agricultural land intensities with $\mathbf{k}_j = d_j/x_j$. Then, Eq. (1) is multiplied by the diagonal matrix $\widehat{\mathbf{K}}_t$ (*nm x nm*) of agricultural land use coefficients (thousand ha per million dollars of output). For our study, only the direct agricultural land use corresponding to the ABP region is retained and all other elements associated with the remaining countries are set to zero. This way, we get the agricultural land from the ABP area directly and indirectly used to obtain its final demand, that is the embodied or virtual agricultural land:

$$\boldsymbol{\Gamma}_t = \widehat{\mathbf{K}}_t(\mathbf{I} - \mathbf{A}_t)^{-1}\mathbf{y}_t = \widehat{\mathbf{K}}_t\mathbf{L}_t\mathbf{y}_t \tag{2}$$

To decompose the changes in vector $\boldsymbol{\Gamma}_t$, SDA is employed. We start with a basic three-factor decomposition of $\boldsymbol{\Gamma}_t$ (see SI for the full derivation). Using subscript t_0 for the base year and t_1 for the end year, the additive structural change in ABP's agricultural land use ($\Delta\boldsymbol{\Gamma} = \widehat{\mathbf{K}}_{t_1}\mathbf{L}_{t_1}\mathbf{y}_{t_1} - \widehat{\mathbf{K}}_{t_0}\mathbf{L}_{t_0}\mathbf{y}_{t_0}$) can be decomposed into six different forms as a result of the non-uniqueness problem of SDA.[3] Thus, we take the average of the six exact decompositions[4] to obtain the expression:

$$\begin{aligned}\Delta\boldsymbol{\Gamma} &= 1/6\Delta\widehat{\mathbf{K}}\left(2\mathbf{L}_{t_0}\mathbf{y}_{t_0} + 2\mathbf{L}_{t_1}\mathbf{y}_{t_1} + \mathbf{L}_{t_1}\mathbf{y}_{t_0} + \mathbf{L}_{t_0}\mathbf{y}_{t_1}\right)\\ &+ 1/6\left(2\widehat{\mathbf{K}}_{t_0}\Delta\mathbf{L}\mathbf{y}_{t_0} + 2\widehat{\mathbf{K}}_{t_1}\Delta\mathbf{L}\mathbf{y}_{t_1} + \widehat{\mathbf{K}}_{t_0}\Delta\mathbf{L}\mathbf{y}_{t_1} + \widehat{\mathbf{K}}_{t_1}\Delta\mathbf{L}\mathbf{y}_{t_0}\right)\\ &+ 1/6\left(2\widehat{\mathbf{K}}_{t_0}\mathbf{L}_{t_0} + 2\widehat{\mathbf{K}}_{t_1}\mathbf{L}_{t_1} + \widehat{\mathbf{K}}_{t_0}\mathbf{L}_{t_1} + \widehat{\mathbf{K}}_{t_1}\mathbf{L}_{t_0}\right)\Delta\mathbf{y} = \Delta\mathbf{N} + \Delta\mathbf{T} + \Delta\mathbf{D}\end{aligned} \tag{3}$$

where $\Delta\mathbf{N}$ is the agricultural land productivity effect; $\Delta\mathbf{T}$ is the technology effect, and $\Delta\mathbf{D}$ is the final demand effect.

In line with Arto and Dietzenbacher (2014), the technology effect ($\Delta\mathbf{T}$) of each economy can be further decomposed to distinguish between changes in the own production technology and changes in the trade structure of intermediate consumption. Starting from:

$$\Delta\mathbf{L} = \mathbf{L}_{t_1}\Delta\mathbf{A}\mathbf{L}_{t_0} = \mathbf{L}_{t_0}\Delta\mathbf{A}\mathbf{L}_{t_1} \tag{4}$$

$\Delta\mathbf{L}$ also can be expressed as the average of the polar decompositions:

$$\Delta\mathbf{L} = 1/2\left(\mathbf{L}_{t_1}\Delta\mathbf{A}\mathbf{L}_{t_0} + \mathbf{L}_{t_0}\Delta\mathbf{A}\mathbf{L}_{t_1}\right) \tag{5}$$

Next, we split the input coefficients a_{ij} of the matrix of technical coefficients ($\mathbf{A}_t$) of (5) into two new components: own technology coefficients, $b_{ij}^r = \sum_s^m a_{ij}^{sr}$, that gives the total amount of input *i* per unit of output *j* in region *r*, and the country trade coefficients, $td_{ij}^{sr} = a_{ij}^{sr}/b_{ij}^r$, that indicate the fraction of each intermediate input that is imported from country *s* (if $s \neq r$) or is produced domestically (if $s = r$). Hence, the change in a_{ij}^{sr} can be written as follows:

$$\Delta a_{ij}^{sr} = \Delta\left(td_{ij}^{sr}b_{ij}^r\right) = 1/2\left(td_{ijt_0}^{sr} + td_{ijt_1}^{sr}\right)\Delta b_{ij}^r + 1/2\left(\Delta td_{ij}^{sr}\right)\left(b_{ijt_0}^r + b_{ijt_1}^r\right) \tag{6}$$

In matrix notation:

$$\Delta\mathbf{A} = 1/2\left(\mathbf{TD}_{t_1} + \mathbf{TD}_{t_0}\right)\otimes\Delta\mathbf{B} + 1/2(\Delta\mathbf{TD})\otimes\left(\mathbf{B}_{t_1} + \mathbf{B}_{t_0}\right) \tag{7}$$

where $\otimes$ indicates elementwise multiplication of the trade coefficients matrix ($\mathbf{TD}_t$) (*nm x nm*) and the own technology coefficients matrix ($\mathbf{B}_t$) (*nm x nm*). This expression (7) is firstly substituted in (5) to subsequently being integrated in (3):

$$\Delta\mathbf{T} = \Delta\boldsymbol{\Omega} + \Delta\boldsymbol{\beta} + \Delta\boldsymbol{\gamma} \tag{8}$$

where: $\Delta\boldsymbol{\beta}$ and $\Delta\boldsymbol{\gamma}$ account for the changes on the domestic and foreign mix of traded inputs contained in the previous trade matrix ($\mathbf{TD}_t$). The first addend ($\Delta\boldsymbol{\Omega}$) shows changes in the purchases of domestic and foreign inputs.

Finally, we split the final demand effect ($\Delta\mathbf{D}$) into the domestic final demand ($\Delta\mathbf{YD}$), and the effect of the exports ($\Delta\mathbf{YX}$**).** In addition, the domestic final demand ($\Delta\mathbf{YD}$) can be further decomposed into four components: final demand structure ($\mathbf{U}_t$)**,** final demand destination ($\mathbf{V}_t$), consumption per capita $\mathbf{YPC}_t$ (affluence), and population ($\mathbf{P}_t$). Each element $u_{ic}^r = f_{ic}^r/g_c^r$ of matrix $\mathbf{U}_t$ represents the part of the domestic final demand in category *c* of country *r* that is spent on products of sector *i* (f_{ic}^r), where g_c^r is the total final demand of category *c* of country *r*. Matrix $\mathbf{V}_t$ is composed of elements $v_c^r = g_c^r/ypc^r$, where ypc^r is the consumption per capita, and matrix P_t is comprised of the population sizes of each *r* country (p^r).

By using the average of the two polar decompositions, we obtain the following expression[5]:

$$\begin{aligned}\Delta\mathbf{YD} &= 1/12\left(2\widehat{\mathbf{K}}_{t_0}\mathbf{L}_{t_0} + 2\widehat{\mathbf{K}}_{t_1}\mathbf{L}_{t_1} + \widehat{\mathbf{K}}_{t_0}\mathbf{L}_{t_1} + \widehat{\mathbf{K}}_{t_1}\mathbf{L}_{t_0}\right)(\Delta\mathbf{U})\otimes\left(\mathbf{V}_{t_0}\otimes\mathbf{YPC}_{t_0}\otimes\mathbf{P}_{t_0} + \mathbf{V}_{t_1}\otimes\mathbf{YPC}_{t_1}\otimes\mathbf{P}_{t_1}\right)\mathrm{e}\\ &+ 1/12\left(2\widehat{\mathbf{K}}_{t_0}\mathbf{L}_{t_0} + 2\widehat{\mathbf{K}}_{t_1}\mathbf{L}_{t_1} + \widehat{\mathbf{K}}_{t_0}\mathbf{L}_{t_1} + \widehat{\mathbf{K}}_{t_1}\mathbf{L}_{t_0}\right)\left(\mathbf{U}_{t_1}\otimes\Delta\mathbf{V}\otimes\mathbf{YPC}_{t_0}\otimes\mathbf{P}_{t_0} + \mathbf{U}_{t_0}\otimes\Delta\mathbf{V}\otimes\mathbf{YPC}_{t_1}\otimes\mathbf{P}_{t_1}\right)\mathbf{e}\\ &+ 1/12\left(2\widehat{\mathbf{K}}_{t_0}\mathbf{L}_{t_0} + 2\widehat{\mathbf{K}}_{t_1}\mathbf{L}_{t_1} + \widehat{\mathbf{K}}_{t_0}\mathbf{L}_{t_1} + \widehat{\mathbf{K}}_{t_1}\mathbf{L}_{t_0}\right)\left(\mathbf{U}_{t_1}\otimes\mathbf{V}_{t_1}\otimes\Delta\mathbf{YPC}\otimes\mathbf{P}_{t_0} + \mathbf{U}_{t_0}\otimes\mathbf{V}_{t_0}\otimes\Delta\mathbf{YPC}\otimes\mathbf{P}_{t_1}\right)\mathbf{e}\\ &+ 1/12\left(2\widehat{\mathbf{K}}_{t_0}\mathbf{L}_{t_0} + 2\widehat{\mathbf{K}}_{t_1}\mathbf{L}_{t_1} + \widehat{\mathbf{K}}_{t_0}\mathbf{L}_{t_1} + \widehat{\mathbf{K}}_{t_1}\mathbf{L}_{t_0}\right)\left(\mathbf{U}_{t_1}\otimes\mathbf{V}_{t_1}\otimes\mathbf{YPC}_{t_1} + \mathbf{U}_{t_0}\otimes\mathbf{V}_{t_0}\otimes\mathbf{YPC}_{t_0}\right)\otimes(\Delta\mathbf{P})\mathbf{e}\\ &= \Delta\boldsymbol{\varepsilon} + \Delta\boldsymbol{\sigma} + \Delta\boldsymbol{\mu} + \Delta\boldsymbol{\varphi}\end{aligned} \tag{9}$$

[3] As the number of factors in the decomposition $\widehat{\mathbf{K}}_t\mathbf{L}_t\mathbf{y}_t$ is 3, there are 6 decompositions (3! = 6).

[4] Another way to overcome this problem was proposed by Dietzenbacher and Los (1998) by taking the simple average of the two polar decompositions.

[5] Where **e** is a summation vector (i.e., a column vector of 1 s).

where $\Delta\varepsilon$ is the final demand structure effect; $\Delta\boldsymbol{\sigma}$ is the final demand destination effect; $\Delta\boldsymbol{\mu}$ is the affluence effect and $\Delta\boldsymbol{\varphi}$ is the population effect.

In matrix notation, and once (9) is incorporated in $\Delta\mathbf{D}$, we obtain:

$$\Delta\mathbf{D} = \Delta\boldsymbol{\varepsilon} + \Delta\boldsymbol{\sigma} + \Delta\boldsymbol{\mu} + \Delta\boldsymbol{\varphi} + \Delta\mathbf{YX} \tag{10}$$

By replacing (8)and (10) for their equivalent expressions in the original (3), we obtain the final SDA that identifies nine factors influencing the evolution of ABP's agricultural land use:

$$\Delta\boldsymbol{\Gamma} = \Delta\mathbf{N} + \Delta\boldsymbol{\Omega} + \Delta\boldsymbol{\beta} + \Delta\boldsymbol{\gamma} + \Delta\boldsymbol{\varepsilon} + \Delta\boldsymbol{\sigma} + \Delta\boldsymbol{\mu} + \Delta\boldsymbol{\varphi} + \Delta\mathbf{YX} \tag{11}$$

A summary of all effects is shown in Table 1:

2.2. Data

The analysis was carried out applying the SDA on a set of annual input-output tables expressed at basic prices for the 2000–2015 period and obtained from the Eora 26 MRIO database developed by Lenzen et al. (2012). They are harmonized time series of 26 sectors and 189 economies worldwide. Compared with other MRIO databases such as GTAP (Peters et al., 2011), WIOD (Dietzenbacher et al., 2013), or EXIOBASE (Tukker et al., 2013), Eora is the only one that, along with a high country coverage, high sector resolution, and a full time-series, also includes specific tables for Argentina, Brazil, and Paraguay. This reduces uncertainties in the analysis, especially where an aggregated IO table for the region is used due to lack of national detail (Stadler et al., 2014). To perform the SDA, the Eora MRIO tables were deflated from their current prices to constant 2015 US dollars using the procedure of double deflation (Lan et al., 2016). To measure agricultural land use, a set of satellite environmental accounts for the same period as the MRIO tables are available in Eora 26. The agricultural land category includes croplands, permanent meadows and pastures. When necessary, this information was complemented with the most updated agricultural land use data covering the land for crop cultivation and animal husbandry from FAOSTAT. Population data were collected from World Development Indicators.

In addition to Argentina, Brazil, and Paraguay, this study focuses on nine of the countries/regions that presented the highest value of agricultural land use worldwide over the period analyzed: Australia, Canada, China, India, Japan, Mexico, Russia, the United States (US), the European Union (EU28, with 28 member states) and one aggregate for the rest of the world (RoW). Also, the SDA is performed for the 26 sectors in Eora 26 (Tables S1 and S2 in Supporting Information, SI). However, the vast majority of land directly used in the economies under study was concentrated in a small number of sectors: "Agriculture" (A1), "Fishing" (A2), "Food and beverages" (A4), "Textiles" (A5), "Chemicals and non-metallic products" (A7), "Electrical and Machinery" (A9) and "Recycling" (A12). These seven sectors accounted for more than 99% of the agricultural land use generated from 2000 to 2015. It should be noted that agricultural land used by households is not considered.

Table 1
Summary of SDA factors.

Factor	Description
Agricultural land productivity effect ($\Delta\mathbf{N}$)	Measures the changes in net agricultural land use per unit of total economic output.
Own technology effect ($\Delta\boldsymbol{\Omega}$)	Measures the changes in a country's requirement for each intermediate input.
Domestic trade effect ($\Delta\boldsymbol{\beta}$)	Accounts for the changes on the local mix of traded inputs.
Foreign trade effect ($\Delta\boldsymbol{\gamma}$)	Accounts for the changes on the foreign mix of traded inputs.
Final demand structure effect ($\Delta\boldsymbol{\varepsilon}$)	Quantifies changes in the domestic demand structure of commodities in every category of domestic final demand: households, non-profit institutions, government, change in inventories, and gross fixed investments.
Final demand destination effect ($\Delta\boldsymbol{\sigma}$)	Measures the changes in the share of each final demand category in the total domestic final demand.
Affluence effect ($\Delta\boldsymbol{\mu}$)	Indicates changes in the overall level of consumption per capita of the country.
Population effect ($\Delta\boldsymbol{\varphi}$)	Accounts for changes in the number of inhabitants of the country.
Exports effect ($\Delta\mathbf{YX}$)	Quantifies changes in the total level of exports of the country.

3. Results

In this section, the results of the application of the SDA proposed in Eq. (11) are presented. The first sub-section provides a retrospective analysis of the agricultural land directly used by the countries and regions under study during 2000–2015. Secondly, an analysis of the evolution and local drivers of changes in ABP's agricultural land use within this region between 2000 and 2015 is provided. Thirdly, we analyze the evolution and foreign determinants of the ABP's agricultural land embodied in trade flows between the ABP region and the rest of the world. Finally, we study the potential role played by outsourced agricultural activities from some developed countries towards the ABP region through a new decomposition of the technology factor.

3.1. Direct agricultural land use changes worldwide

In general terms, there was a 2% decrease in direct agricultural land use worldwide from 2000 to 2015 (Table 2). The main contributors to this decrease were Australia, the EU28, the US, and Canada. At the sectoral scale, the decline was dominated by "Agriculture" (A1), followed by "Food and beverages" (A4) and "Textiles" (A5).

Conversely, the agricultural land use in Argentina, Brazil, and Paraguay, increased around 16%, 8%, and 9%, respectively, over the 15 years. Although Argentina experienced the fastest increase, Brazil added the most direct agricultural land use for the period. These countries exhibited a very similar sectoral growth pattern in terms of land use that emphasizes the role of "Agriculture" and "Food and beverages".

3.2. Analyzing the changes in the embodied ABP's agricultural land within ABP and its local driving factors, 2000–2015

Around 50% of the direct agricultural land increase in the ABP was generated by the local needs of each country (see Table S3). Simultaneously, the other half of the expansion of the agricultural area in ABP was a consequence of the land embodied in international trade.

According to the results obtained from the initial decomposition shown in Eq. (3), changes detected in the ABP's agricultural land used within the region, were mainly influenced by shifts in the agricultural land productivity, affluence, and technology effects (see Fig. 2 and Table S3). In absolute terms, agricultural land productivity ($\Delta\mathbf{N}$) and affluence ($\Delta\boldsymbol{\mu}$) effects were the dominant contributors (with a share of 45% and 34% on the total ABP's change, respectively). By countries, whereas the agricultural land productivity effect was the main responsible for the growth within the entire period in Argentina, the highest increase was exerted by the technology effect ($\Delta\mathbf{T}$) in Brazil and by affluence in Paraguay.

Fig. 2 shows that the use of ABP's agricultural land follows a similar trend within the 3 countries in the region. The evolution of the agricultural land use in ABP can be divided into three periods: 2000–2003, 2003–2012, and 2012–2015. The reduction of agricultural land in the first period was mainly driven by the expansion of the agricultural land productivity coefficients ($\Delta\mathbf{N}$). This can be attributed to the prolonged recession affecting these countries over 2000–2003, which had its peak in 2002 as a consequence of a financial crisis in Argentina (known as the *corralito* or ring-fence). This recession, which began in Brazil in 1998 harmed its economic growth and that of Argentina and Paraguay (Amann and Baer, 2003), damaging their exports growth and

Table 2
Direct agricultural land use changes, 2000–2015 (thousand ha).

	A1	A2	A4	A5	A7	A9	A12	Rest of the economy	Total	Δ
ARG	17,663	0	1769	544	105	7	29	69	**20,186**	15.71%
AUS	-78,224	0	-8106	-2354	-455	-87	-123	-245	**-89,592**	-19.67%
BRA	19,359	0	1984	596	117	0	32	86	**22,174**	8.48%
CAN	-3575	-561	-585	-131	-50	-1	-38	-29	**-4972**	-7.35%
CHN	5807	0	572	179	34	0	34	0	**6627**	1.27%
IND	-1126	0	-90	-25	-5	0	-6	0	**-1253**	-0.69%
JPN	-621	0	-85	-17	-8	0	-4	-26	**-762**	-14.49%
MEX	-2680	0	-273	-82	-16	0	-5	-11	**-3067**	-2.88%
PAR	1611	0	163	50	10	0	3	7	**1844**	9.07%
RUS	397	64	66	15	6	0	4	3	**556**	0.26%
USA	-6637	0	-672	-198	-39	0	-39	0	**-7587**	-1.83%
EU28	-15,613	0	-1531	-452	-90	0	-91	0	**-17,777**	-8.88%
RoW	-8780	-2999	-6668	-3275	-342	-3	-160	-519	**-22,745**	-0.97%
Total	**-72,419**	**-3497**	**-13,455**	**-5149**	**-734**	**-84**	**-364**	**-665**	**-96,367**	

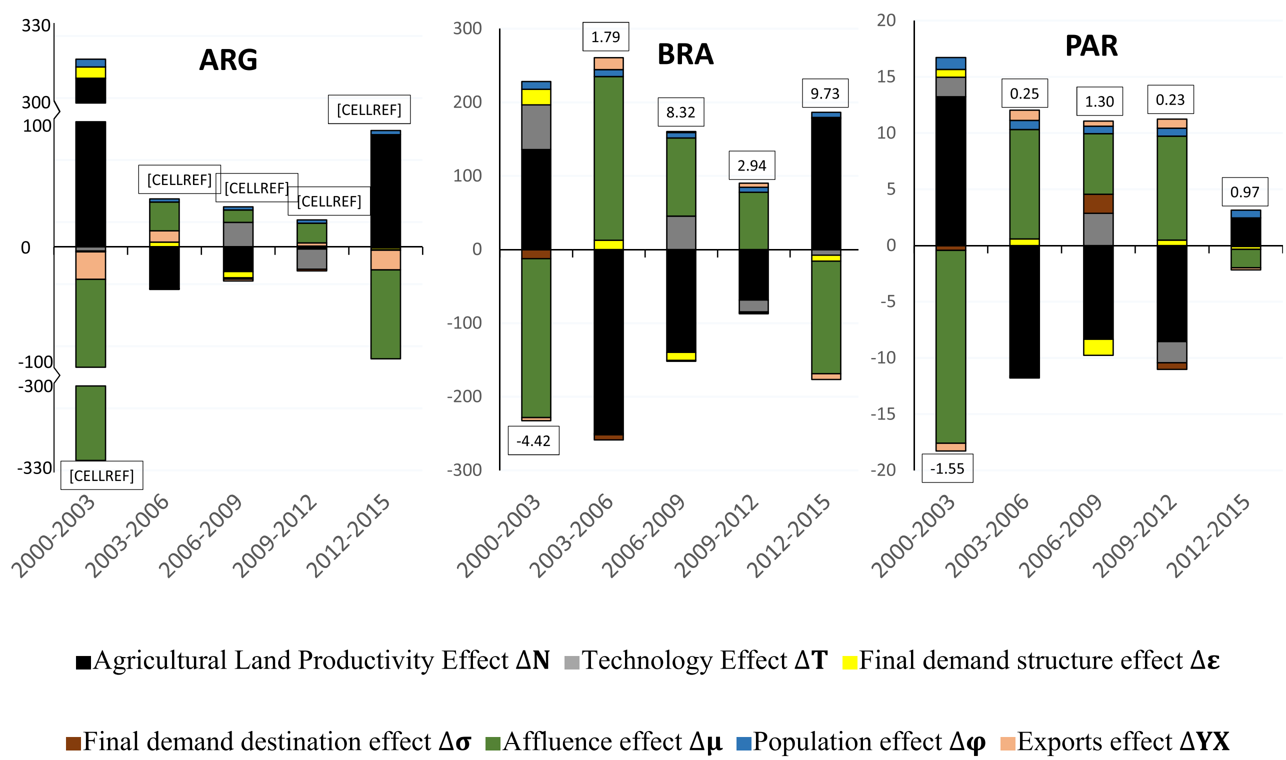

Fig. 2. Contribution of each local driver to the changes of ABP's agricultural land use in Argentina, Brazil, and Paraguay, 2000–2015 (million ha).

consequently, their output, which favored a large increase in the agricultural land productivity effect (agricultural land use per unit of output). Likewise, with almost half of the Argentinian population living below the poverty line, there was a large reduction in consumption per capita (affluence effect). As major trading partners of Argentina, Brazil and Paraguay received the rebound effects of this crisis.

The expansion of agricultural land in the second period 2003–2012 was mainly driven by the growth of consumption per capita ($\Delta\boldsymbol{\mu}$). Furthermore, the global financial crisis of 2008 seemed to contribute to a shift towards production technologies that are more dependent on agricultural land-intensive sectors ($\Delta\mathbf{T}$) in the three countries over 2006–2009. However, these increases were somewhat offset by improvements in direct agricultural land productivity of industries, all other things being constant, especially in Brazil, and Paraguay. In other words, their productive sectors used less agricultural land per unit of output. This decline can be partially linked to agricultural intensification measures on existing land as a result of mechanization, agrochemical inputs, or irrigation development (FAO, 2016). Despite the differences in the database used, our results of drivers of ABP's agricultural land use in Brazil are consistent with the findings of Lenzen et al. (2013). Finally, agricultural land productivity effects accelerated in the third period 2012–2015 and offset the reductions generated by consumption per capita.

To fulfill their final demand, Argentina and Brazil also imported 592 and 14,295 thousand ha of agricultural land (accounting for 20% and 44% of their total needs), respectively. Conversely, the amount of embodied agricultural land used in Paraguay decreased over the study period 2000–2015 and, as a result, this country did not require any agricultural land from outside to fulfill its final demand. Thereby, the agricultural land requirements of Paraguay and, at a lesser extent, those of Argentina, were satisfied only by local resources.

On the other hand, Brazil imported around 88% of embodied agricultural land from Argentina and Paraguay to meet its final demand (Fig. 3). Almost 6000 thousand ha of this land were explained by the affluence and population effect in the country. Furthermore, from 2000 to 2015, Brazil's imports of agricultural land from Argentina and

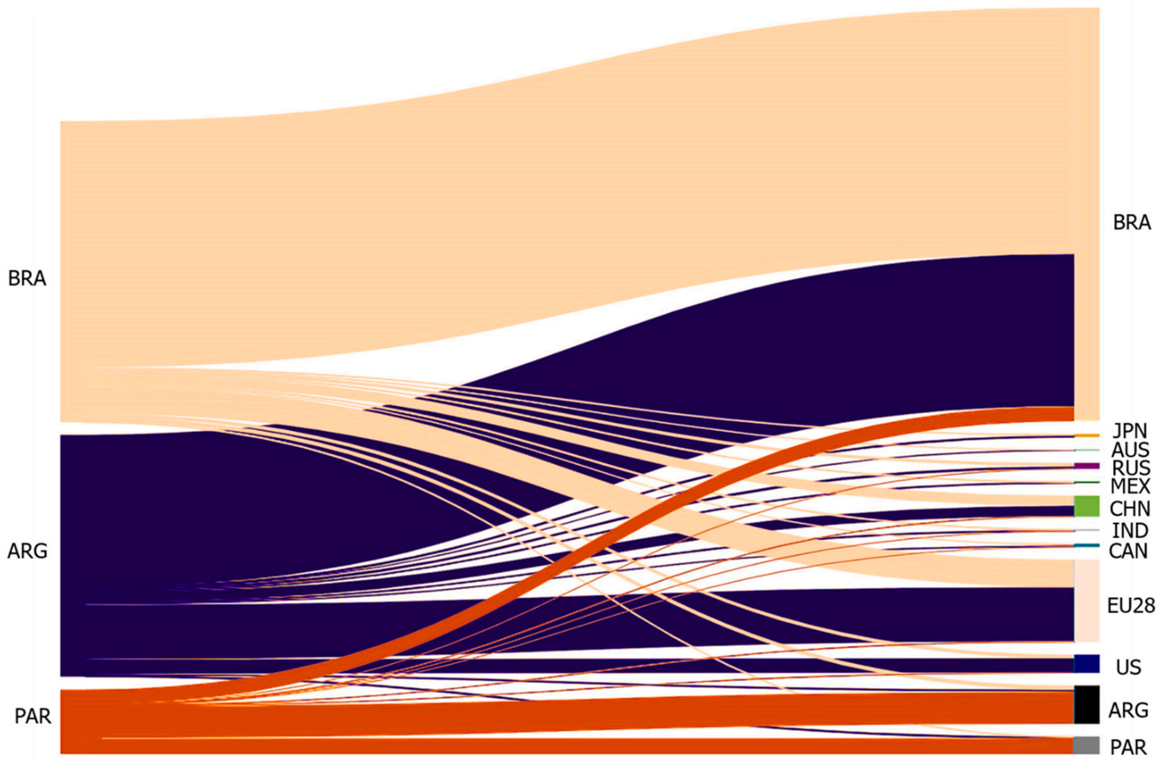

Fig. 3. Trade connections of the embodied ABP's agricultural land between the economies analyzed, 2000–2015 (million ha).

Paraguay soared around 202%. This reflects the role of Mercosur in facilitating increases in intra-regional trade[6] of intermediate products and, consequently, agricultural land displacement from Argentina and Paraguay to Brazil.

3.3. *Analyzing the changes in the embodied ABP's agricultural land outside ABP and its foreign driving factors, 2000–2015*

In this section, we measure the embodied agricultural land from ABP imported by the rest of the world and study its underlying economic factors. We focus on those nations accounting for about 66% of the total agricultural land changes worldwide during 2000–2015. The growth in the total ABP's agricultural land embodied in the imports of these countries contributed to around 24% (see Table S4) of the direct agricultural land increase in the region. This means that ABP used an extra 10,340 thousand ha, induced by changes in other countries to satisfy their final demands.

According to the results, the largest importers of ABP's agricultural land were the EU28, China, and the US (Fig. 3). Particularly, the surge in the agricultural land embodied in imports of the EU28 surpassed by four times those of the US and China (see Weinzettel et al., 2013; Chen and Han, 2015, for similar results). Although these three countries used most of the hectares of agricultural land increase in ABP, the embodied flows of this resource increased faster in India (257%), China (240%), and Russia (205%). In fact, the growth rate registered by the EU28 (50%), the US (19%), and other developed countries, like Australia (44%), Canada (30%), or Japan (10%) was relatively less significant. Whereas the agricultural land sourced from ABP by these countries experienced positive growth, the use of local agricultural land by the EU28 and the US decreased by −11,22% and −4%, respectively, during the period. Conversely, China, India, and Russia increased their use of local agricultural land by 4%, 3%, and 2%. However, these growths were relatively much smaller than those of their imports of embodied ABP's agricultural land. Therefore, our results suggest that a relevant amount of agricultural land were displaced from the ABP countries to other nations which have also been validated by other studies (Tian et al., 2019; Chen et al., 2018).

As observed in Table S4 of SI, the largest increases in the embodied flows of ABP's agricultural land were explained by the affluence effect. While consumption per capita ($\Delta\boldsymbol{\mu}$) was the main contributor in the EU28, China, and Russia, the highest portion of the growth in the US is attributed to the surge in the agricultural land productivity effect ($\Delta\mathbf{N}$). This effect, which is partly explained by the land-intense production processes in ABP, was also a consistent driver to the agricultural land embodied in other nations' imports (see Fig. 4). The results of the MRIO by Tian et al. (2019) are similar to the findings for China presented here, regarding the importance of affluence as the major driving factor for China's land consumption. Table S4 also highlights the expansion of population ($\Delta\boldsymbol{\varphi}$), especially in the US and the EU28, as an important factor in the increases of embodied ABP's agricultural land that is imported by these countries.

Interestingly, technological changes ($\Delta\mathbf{T}$) in other countries limited the growth of ABP's agricultural land use, i.e., less agricultural land was used by intermediate inputs transactions. In particular, changes in the EU28, China, and the US during subperiods 2000–2003 and 2012–2015 caused considerable reductions. These results suggest that agricultural land-intensive parts of global value chains could have been outsourced from these nations towards the ABP countries. As such, these impacts are further explored in the following paragraphs.

Regarding different subperiod changes, a more consistent pattern emerges among most developed nations due to the global financial crisis during 2006–2009 and the subsequent reduction in their imports of embodied ABP's agricultural land. Conversely, the regional economic crisis over 2000–2003 positively contributed to increases in the embodied flows of ABP's agricultural land due to the growth in the agricultural land productivity effect of the nations.

[6] According to COMTRADE Database (2019), intra-Mercosur trade grew by 9.83% during the time studied.

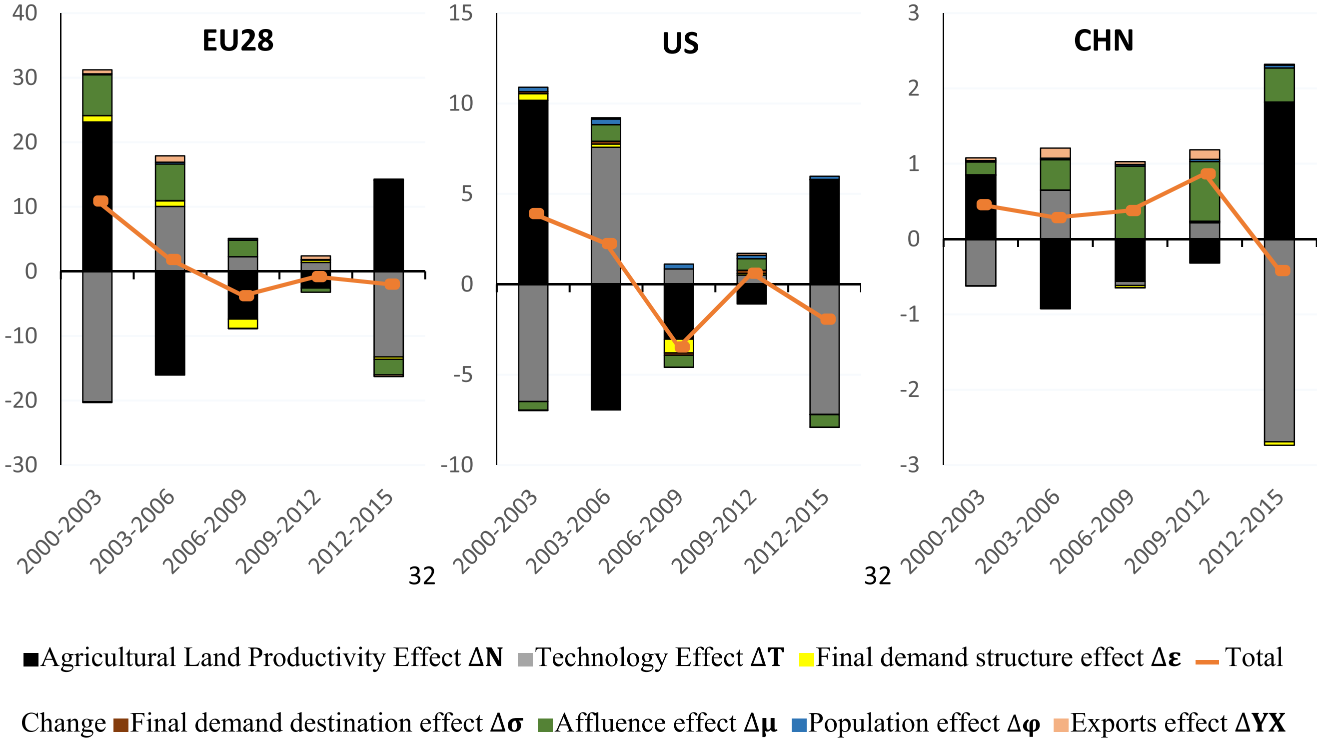

Fig. 4. Contribution of each driver to the changes of ABP's agricultural land in the EU28, the US and CHN, 2000–2015 (million ha).

From a national perspective of the different ABP's countries, a vast majority of the increase in the embodied ABP's agricultural land in the US (78%) and the EU28 (66%) was originated in Argentina, while slightly more than half of the embodied land flows imported by India and Russia is from Brazil. The amount of this natural resource used in China is over 50% equally distributed between agricultural lands sourced from Argentina and Brazil. The largest importers of Paraguay's agricultural land were the EU28 and China (41,54 and 36,39 thousand ha, respectively), while India accounted for the fastest increase (3%).

3.4. *A further decomposition and analysis of the technology effect* (Δ**T**) *in the embodied ABP's agricultural land, 2000–2015*

The increases in the imports of embodied ABP's agricultural land previously analyzed were partly offset by the technology effect that could include a shift to less intensive land sources, efficiency gains and/or changes in the input structure of different sectors. Hence, to get a better understanding of the underlying factors driving these impacts, a new technology decomposition was proposed in Eq. (8).

Similar to the air pollution haven hypothesis (Copeland and Taylor, 2004), a key interest for this analysis is the role of displacement of agricultural land-intensive parts in global value chains from some affluent countries to the ABP region. If the hypothesis were true, along with a reduction in the domestic trade effect ($\Delta\boldsymbol{\beta}$), we would expect positive effects from the changes in the import structure ($\Delta\boldsymbol{\gamma}$) of affluent countries. This is because domestic agricultural goods are expected to be substituted for cheaper ones produced by companies set up in the ABP region to avoid the cost of environmental regulations and gain easier access to land resources.

By applying the additional decomposition, we found that the results overall do not support the land version of the pollution haven hypothesis (see Table S5). Our conclusion is based on two observations. On the one hand, import structure changes ($\Delta\boldsymbol{\gamma}$) in these economies, induced a predominantly negative pattern on the embodied agricultural land from ABP over the analyzed period. On the other hand, while goods that are produced domestically should have been substituted for imported goods from ABP and negatively affect the amount of embodied agricultural land, we found that changes in purchases of inputs locally produced ($\Delta\boldsymbol{\beta}$) contributed to an overall increase in the embodied flows of the resource.

More specifically, the findings for subperiod 2009–2012 in the EU28, the US, and China are in line with the observations previously quoted (see Fig. 5). The same applies for 2003–2006 in the US and China. However, although changes in the foreign trade effect ($\Delta\boldsymbol{\gamma}$) drove imports of embodied agricultural land upward during these subperiods, these net increases were insufficient to offset the drops in agricultural intermediate imports from the ABP region over 2000–2003 and 2012–2015. The drop downturn in the Chinese economy during 2012–2015 caused a decline in demand and a further fall in prices of agricultural commodities (CEPAL, 2015) that justified that last reduction in the import effect.

Therefore, although our results suggest that globalization led to a surge in the ABP's agricultural land use embodied in trade and displaced to affluent countries, they also indicate that outsourced agricultural activities were not a determinant of the growth in ABP's agricultural land use.

All in all, our main results highlight the relevance of transfers of embodied agricultural land in the global trade network. These findings are in line with Ivanova et al. (2016) and Wu et al. (2018) who also reported the role of global trade flows in the expansion of agricultural land use. Nonetheless, as our study specifically focuses on the ABP area, we provide a more local and regional evaluation of the economic driving forces of changes in ABP's agricultural land use inside and outside this region. On one hand, our results suggest that technological structure and increasing individual standards of living in Brazil caused most of the overall growth in the use of ABP's agricultural land. In fact, a vast majority of this increase has occurred in supply chains from Argentina and Paraguay to fulfill Brazil's final demand. This amount of embodied agricultural land imported by Brazil has been, furthermore, exacerbated by the low productivity of lands in Argentina and Paraguay. On the other hand, as trade with ABP is likely to continue increasing within the globalized world, improving local productivity in the use of ABP's agricultural land is fundamental to satisfy growing global demands

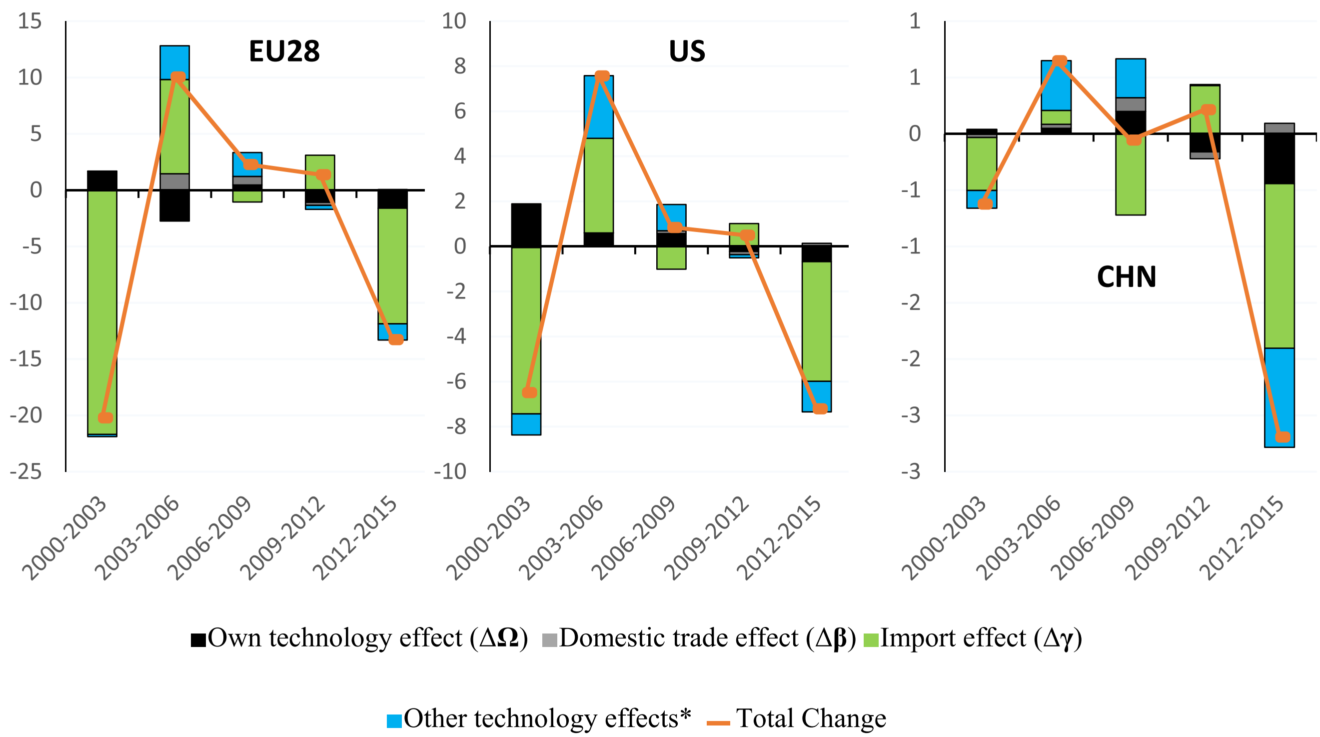

Fig. 5. Contribution of each driver to the technology effect change in the EU28, the US and CHN, 2000–2015 (million ha).*It isolates the contribution of changes in the production structure of other countries.

sustainably, especially as a result of the rapid economic development in countries such as the EU28, China and the US. Finally, our geographical localized approach centered on ABP can help policymakers to design more effective land policies with a regional perspective to achieve a more reasonable allocation of agricultural land resources from the ABP region.

4. Discussion and policy implications

Our findings confirm that there is a need for targeting the agricultural land-related policies both from inside and outside the ABP region by mainly addressing three domains: consumption per capita, evolving global supply chains, and land-use productivity.

From the perspective of production, increases in agricultural land productivity of ABP economies seem one of the key elements for land use reduction. Adoption of precision agricultural technology and investment in infrastructure are clear routes to increase land productivity and output. Specifically for the smaller-scale agriculture, which makes a fundamental contribution to the economies in the ABP region (FAO, 2014), the building of collective institutions, such as cooperatives, is essential to help farmers to get better access to information and credits for agricultural innovations.

The implementation of some of these measures is paramount given the pivotal role of ABP as a supplier of agricultural products to meet the world's future food security. This prediction generates great concern since agricultural production sites are less visible and located far away from final consumers in industrialized regions such as the EU28, the US, or China. Thereby, government actions in these nations should focus on offsetting the strong growth in embodied ABP's agricultural land due to the increasing level of individual wealth. However, given the difficulty of governments to regulate consumption levels, measures should be rather taken to influence consumption patterns or regulation of those products originating from deforested lands.

Furthermore, our SDA results highlight that while growing population and consumption per citizen in the EU28, the US, or China indirectly increased ABP's deforestation, the use of local agricultural land in these countries reduced. This may be associated with effective land use policies, such as those based on improving productivity to halt agricultural land expansion applied by the US (Terry, 2016), the Environmental Policy Integration framed within the Common Agricultural Policy of the EU28 (Alons, 2017; Paleari, 2017) and the application of the *Natural Forest Conservation Program* in China (Wang et al., 2007; Viña et al., 2016). All these programs and policies highlight the efforts of these countries to fight agricultural expansion in their domestic territories.

Regarding domestic environmental policies within ABP, Brazil developed the most extensive environmental protection of the region, but it also presented the most serious environmental problems. Although its policies successfully lowered Amazon deforestation rates (Arima et al., 2014; Rochedo et al., 2018), the expansion of agricultural activities was transferred to the *Cerrado* biome due to the low protection of this area (Soares-Filho et al., 2014; Strassburg et al., 2017). Argentina for its part developed the *Ley Forestal* in 1996 and *Ley Nacional* in 2006 to promote forest conservation and regulate agricultural expansion (Nolte et al., 2017; Sans et al., 2018). However, this country is still an object of global concern because of the deforestation levels in the dry forests of *Gran Chaco* (Hansen et al., 2013). Paraguay took very small steps to stop deforestation through the enactment of the *"Zero deforestation Law"* that prohibits clearing forests in Eastern Paraguay, that is, within the Atlantic Forest (Szulecka and Zalazar, 2017). Despite forest loss has decreased in this area, it rapidly advanced towards the *Gran Chaco* (Aide et al., 2013; Caldas et al., 2015).

As such, although ABP has a regulatory framework to stop deforestation, it is clear that the implementation of national policies had strong limitations. Our results suggest that weaknesses in domestic policies placed ABP as an ideal cornerstone of the global agricultural supply chain. Although changes in national productive structures and domestic demand of ABP indeed led to forest conversion, the influence of foreign demand on this environmental issue is undeniable. In addition, impacts from other countries were exacerbated by the intra-regional transactions framed within the Mercosur integration process. In other words, the countries of the ABP region jointly improved their competitive capacity in agricultural markets thanks to the significant cost advantages derived from their land endowments and the facilities for input mobility provided by the trade agreement. As such, this environmental issue should be addressed with a common regional scope.

Although the environmental aspect has always been on Mercosur's agenda, regional policies are still underdeveloped. The original document to formally conform Mercosur, the Treaty of Asunción, expressed some ideas about the integrated quality of life and sustainable development. Mercosur also has a permanent working group (SGT6) that discusses regional environmental issues related to trade and offers an institutional framework for members with weaker environmental protection institutions (Doctor, 2013). However, environmental agreements are still weak and have declined over the course of the agreement, supported by the limitations of national policies (Tussie and Vásquez, 2000; Hochstetler, 2013).

The assessment of the environmental consequences of the expansion of the agricultural sector as a regional issue becomes even more urgent given the imminent trade agreement between the Mercosur and the EU28. Signed in June 2019, after more than 20 years of negotiation, the ratification of this free trade agreement could irreparably damage forest and biodiversity in ABP. Hence, the ABP region needs to take palliative and protective measures, similar to those of mechanisms such as Reducing Emissions through Reduced Deforestation and Forest Degradation in developing countries (REDD+), which should be integrated into the Mercosur trade agreement and subsequently applied within the framework of this Treaty.

5. Concluding remarks

Agriculture is still the most significant driver of global deforestation. Given the importance of both agriculture and forests to the future of the planet, understanding the factors that drive the conversion of forests to agriculture and promoting positive interactions between these two systems are essential to achieve some of the SDGs. This paper reveals the main global economic forces driving agricultural land use changes in the most affected area by forest loss worldwide, the ABP region, by applying a Structural Decomposition Analysis (SDA).

Our findings illustrate that the exploitation of ABP's agricultural land is pushed by demand from within and outside the region during 2000–2015. On the one hand, globalization has led to the increase of agricultural land embodied in trade, displacing this resource from ABP to countries such as the EU28, China, and the US. In particular, increases in per capita consumption and population in these nations between 2000 and 2015 fostered the expansion of agricultural land in ABP. In contrast, changes in their intermediate input structure and hence the impact of a potential land-haven phenomenon had a minor effect on the agricultural land increase in the ABP region. Simultaneously, the use of local agricultural land of those affluent countries was reduced.

On the other hand, our outcomes reflect the intensive relation between Argentina, Brazil, and Paraguay, framed within the integration process, and illustrated by the increases in the use of common agricultural land, especially driven by the Brazilian economic growth. Therefore, the environmental issue and the threat to the sustainable development in ABP should be approached from a regional point of view. In this case, the Mercosur trade agreement can be an important ally to establishing clear environmental policies and helping to strengthen the national measures that have already been implemented in each country.

As a final point, it should be noted that there are limitations for the further extension of our work. First, several uncertainties arise from the Eora 26 database and its satellite environmental accounts, since the estimation of some of these data is only possible through the use of prorating, concordances matrices, interpolation, or purely algorithmic processes. As a result, some of the statistics provided may become distorted during the database creation process and conflict with those reported by any primary data provider. Nonetheless, Lenzen et al. (2012) constructed a comprehensive standard deviation table for Eora Database and confirmed the reliability and validity of the data. Second, a usual drawback in the analysis of embodied agricultural land based on IO tables has been the loss of detail at the product level, as land use is highly dependent on different types of agricultural products, which are usually aggregated into few sectors in these databases. Thus, this sectoral aggregation may carry some uncertainties in the calculation of embodied agricultural land values. Finally, as previously stated, the non-uniqueness decomposition problem complicates the process of achieving a unique solution using the SDA methodology. Hence, it is important to note that our results show the average effect of all equivalent decomposition permutations for each factor in the SDA.

Supporting Information

Additional material concerning methods and detailed results is available. This material is available free of charge via the Internet at http://pubs.acs.org.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2021.105619.

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