The Social Metabolism of Tropical Agriculture: Agrarian Extractivism in Colombia (1916–2016)

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Para Elvira, Doris y Maia por guiarme con su
sabiduría, coraje y entusiasmo

To Elvira, Doris, and Maia for guiding me with their
wisdom, courage and enthusiasm

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Esta tesis tiene sus raíces más profundas en mi trabajo de fin de grado sobre el sistema agrario en Colombia en el siglo XVI, aunque realmente el planteamiento empezó a tomar forma con las clases y charlas personales que sostuve con Enric Tello sobre metabolismo agrario durante la realización del Máster de Historia Económica en la universidad de Barcelona. A Enric le agradezco el identificar la necesidad de implementar este tipo de estudios en las agriculturas latinoamericanas y la confianza que depositó en mí para tomar parte de esta tarea. A lo largo de estos años como director del proyecto, Enric ha sabido combinar comentarios precisos con debates amplios y relevantes que me han permitido descubrir mis intereses como investigador sin perderme por el camino. Durante el primer año del proyecto, él tuvo la habilidad para definir el marco en el que mi tesis se integraría dentro del proyecto internacional *Sustainable Farm Systems* (SFS) dirigido por Geoff Cunfer desde la Universidad de Saskatchewan en Canadá y que tenía por objetivo estudiar el proceso de transición socio-metabólica de la agricultura en Occidente. Dentro del SFS, mi proyecto debía contribuir a la construcción de lazos entre los desarrollos metodológicos de los equipos de España en Andalucía y Cataluña, y los avances en el estudio de la historia agraria colombiana adelantados por los equipos de Colombia en Cali y Bogotá.

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Chapter 1

The frame of agrarian extractivism

Keywords: agrarian extractivism; domestic and international constraints of agriculture; social metabolism; agrarian metabolism.

1.1 INTRODUCTION

Since the Neolithic Revolution, increasing agricultural output has relied on land intensification and extensification. By increasing inputs such as human labour, animal power, water supply, organic fertilizers and new tools, ancient societies in Sumer, Egypt, the Yangtze River, and Mesoamerica managed to accumulate the agricultural surpluses to give rise cities, states, and even empires. This expansion of production was usually also accompanied by the extension of the agricultural frontier, which took in new land from shrubland, pasture, and forests (E. C. Ellis et al., 2013). The main difference with contemporary agriculture, however, is the great transformation suffered by external inputs from organic to inorganic since the mid-twentieth century. Agrarian change since the end of the Second World War has deepened the intensification of land-based production through the spread of the Green Revolution around the world. Although this process of industrialization is based on replacing land, labour, and other organic inputs with capital, the expansion of the agricultural frontier has also run in parallel.

The intensification and extensification of current agrarian systems through the industrial model are responses to the increasing demands for food, feed, new biofuels, and raw materials, driven by growths in population, urbanisation, and incomes. At the same time, these changes have been responsible for the acceleration of climate change and the socio-ecological crisis. For example, the dietary transition towards the consumption of more meat and dairy products, joined to the rise of income (Smil, 2002), is behind the increasing use of grain production for feed instead of food, the expansion of land use at the expense of family farming and native forests, and the fossil fuel-based intensification that

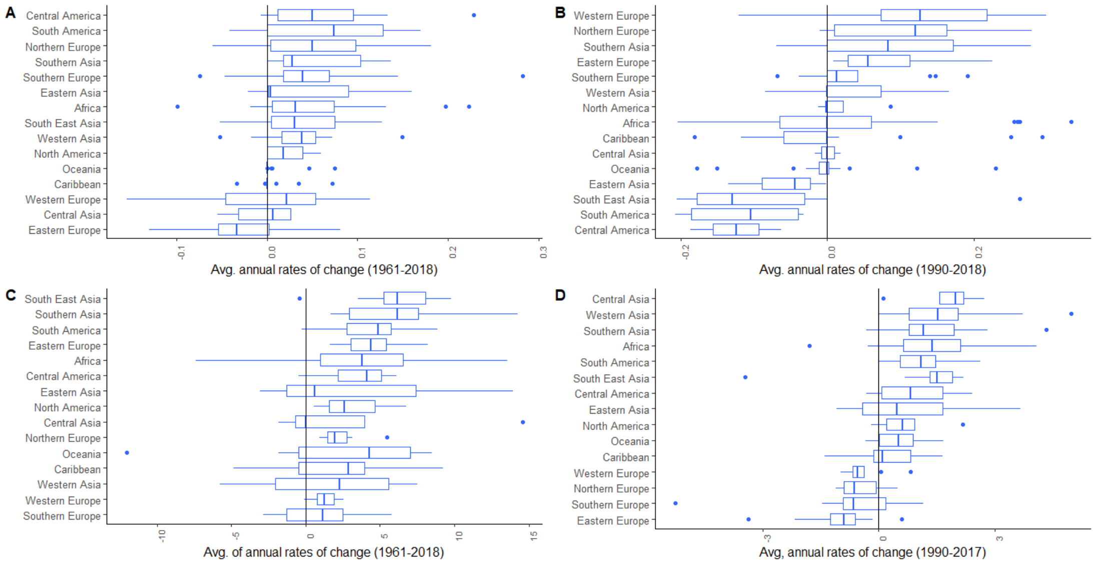

Figure 1.1: Average rates of changes for agricultural land (a) and nitrogenous used in agriculture (d) between 1961 and 2018, and for forest land (b) and CO_2 (eq) emissions IPCC Fifth Assessment Report between 1990 and 2017/18 (d). *Source:* FAOSTAT (2021). ***Note***: to remove outliers, I use IQR method for each country time series and then compute the average of the period.

damages natural cycles and creates dependence. Therefore, current agrarian systems are faced with two main challenges: they should double their production by 2050 (Foley et al., 2011) to secure food provision, while also contributing to mitigating the effects of climate change and the socio-ecological crisis. These challenges are especially true for developing countries, where these agrarian changed have become more intensive.

The ecological impacts on current agriculture from agricultural extensification and intensification are usually related to the same consequences, namely CO_2 emissions, loss of biodiversity, or soil fertility, among others, though they differ in their origins and processes. Through extensification, agriculture drives land-use changes that threaten habitats with a loss of biodiversity and their functionality, reducing the capacity of natural ecosystems to store carbon, contribute to soil deterioration, and increase CO_2 emissions. According to Ramankutty (2008), in 2000 agriculture was the most extensive use of land on the earth's surface; cropland represented around 12% and pasture 28%, which are quite similar to the current estimates in the IPCC's land report for 2015 (Mbow, Reisinger, Canadell, & O'Brien, 2017). Land-use change to increase agricultural activities has caused a net loss of forest, ranging from 7 to 11 million km^2 in the last 300 years (Foley et al., 2005), and 75% of deforestation between 1990 and 2005 is attributed to agriculture expansion (Kissinger, Herold, & De Sy, 2012). However, this process had not been equally distributed around the world regions.

Since the 1980s, deforestation is reported as having been more dynamic in the tropical forests of developing countries than in the temperate forests of the developed ones. Gibbs et al. (2010) confirm that rainforest was the primary source of agricultural land in the tropics from 1980 to 1990. According to the authors, Brazil, Indonesia, and Malaysia adapted quickly in order to supply the increasing demand for sugarcane, soybean, and oil palm crops, but unlike South East Asia, in Latin America this process was mainly driven by the expansion of cattle pastures. Figure 1.1a shows that the average rate of change of agricultural land from 1961 to 2018 was higher in developing and tropical countries from regions such as South and Central America, South East Asia, and Africa than in temperate countries in North America and Europe (except for Northern and Southern Europe), while forest land decreased in developing regions and grew up in the developed ones (Figure 1.1b). This tropical deforestation contributes 12% of total anthropogenic CO_2 emissions and accounts for 98% of CO_2 emissions from land-use change (Foley et al., 2011). Additionally, a recent study of the role of agricultural production in transgressing the earth's planetary boundaries showed that biosphere integrity, which is measured by genetic and losses of functional biodiversity, is one of the two main such transgressions (Campbell et al., 2017). This work especially stresses the main role of tropical agriculture in producing losses of functional biodiversity and suggests that almost 80% of this comes from agriculture.

Through intensification, agricultural change drives water degradation, the increasing use of energy, and rising pollution. The most evident and disruptive of these changes is the expansion in the use of synthetic fertilizers, namely nitrogen (N). This massive transition towards large amounts of nitrogen in agriculture has its deep roots in North America at the end of the 19th century. The First Globalization opened a window for rising grain exports to fit the growing demand in the European markets, especially the United Kingdom (O'Rourke & Williamson, 1999), which led to the nutrients of the rich soils of the Great Plains, where the European farmers settled during colonization, being mined. This began the race to increase organic and mineral fertilizers first and synthetic ones thereafter.

The turning point in this process was the discovery of the Haber-Bosch process to synthesize ammonium, which was extended to the explosives industry during the First and the Second World Wars. During the Cold War, the Green Revolution was applied to agriculture to fight social unrest and other challenges from the expansion of socialisms or the "red revolution". This new way of increasing agricultural output meant simplifying the complexity of nutrient cycling, with two main consequences: the disruption of functioning soil nutrient cycling on ecosystems, and the pollution of groundwater, waterways, and water bodies (Perfecto, Vandermeer, & Wright, 2019).

Since 1961, the use of nitrogen around the world climbed from 11M tonnes to 109M in 2018, which means a growth of 880%, while phosphorus use grew 300% (FAOSTAT, 2021). Although China, the United States, India, and the former USSR countries are the world leaders as consumers of nitrogen, developing countries have more recently experienced the major growth of fertilizer use in agriculture (see Figure 1.1(c)). This large transition from the organic management of soil fertility to inorganic management in agriculture has led to biochemical flows becoming the second major transgression of the Earth's boundaries (Campbell et al., 2017). Human intervention through synthetic fertilization has transformed natural cycles of nitrogen and phosphorous, which are primary processes in the growth of terrestrial and aquatic plants. This shift in nutrient cycles implies, on the one hand soil erosion and biodiversity loss during its application, and on the other hand increasing emissions of nitrous oxide (NO_2) and CO_2 during its production.

Conventional agriculture is responsible for a third of GHG emissions (Foley et al., 2011) and its associated land use contributes to 23% of anthropogenic emissions of CO_2, methane (CH_4), and N_2O (which is CO_2 (eq)) (Mbow et al., 2017). Developing countries produce the largest share of the GHG emissions related to agriculture (Campbell et al., 2017). Between 1990 and 2017, 82% of the accumulated CO_2 (eq) from agricultural land use came from countries in Africa (55M GG), South America (47M GG), and South East Asia (41M GG). Together with South Asia, these regions released more than half the CO_2 (eq) emissions from the agricultural sector (FAOSTAT, 2021) in the same period. As Figure 1.1(d) shows, the average annual growth of CO_2 (eq) from agriculture between 1990 and 2017 in Asia, Africa, and Latin America increased more dynamically than in North America and Europe.

To sum up, the combination of the extensification and intensification of agriculture in tropical and developing regions has been the main feature of agrarian change globally during the last six decades. Moreover, the deepening of this model is among the major contributors to climate change and the ecological crisis globally. Although this change took place after the Second World War, can we attribute the same timeframe to the experience of tropical agriculture in developing countries? When did this change occur? What were the socioeconomic forces behind this transformation?

The change in tropical agriculture in developing countries was embedded in the institutional changes of the Second Globalization (since c. 1980). Since the 1980s, the adoption of the deregulation function by the state in promoting national policies of agricultural production and establishing the agro-export model has complemented filling the shelves of supermarkets in developed countries (McMichael, 2013). The decoupling of production from consumption, fuelled by international trade (Fader, Gerten, Krause, Lucht, & Cramer, 2013), was designed to serve foreign debt after the 1980s crisis. In this context, the International Monetary Fund demanded structural reforms, which were introduced in more than sixty developing countries involving the promotion of new agricultural products like tropical fruits and fresh vegetables (McMichael, 2013). The new trends in domestic and international investment set the initial conditions for agrarian change socioeconomically in the forms of the capitalization of agriculture, increasing land prices, market and non-market mechanisms of land dispossession, rural migration, the decline of small family farming, social and environmental conflicts (Norberg, 2019), and the progressive abandonment of national policies of food self-sufficiency (O'Hagan, 1976).

According to the literature on food regimes (McMichael, 2009, 2013), the process of deregulation and the diminishing role of the state went hand in hand with the increasing role of international corporations. However, Norberg (2019) proves that national states played a critical role in providing institutional support to these agrarian changes in the context of the expansion of soya in the Southern Cone. In Argentina, Uruguay, and Paraguay, she shows that domestic policies regarding intellectual property rights, the forests, the use of pesticides, fertilizers, genetically modified seeds, labour relations and trade policies came to a breaking point in the 1980s. Moreover, the author also stresses that these agrarian changes were possible due to the long-term relations between the domestic institutional setting and the global market dynamics, which interacted in constructing the path agriculture would take in the region (Norberg, 2019). The traditional bias of inequality in access to land and the force of the agrarian elites in confronting the national states encountered some economic incentives for shaping agriculture according to international demand, especially during the First and Second Globalizations.

Opposed to this agro-export model, which is based on intensive external inputs, consumption, the depletion of ecological resources, and the breaking up social networks (Altieri & Toledo, 2011), an agro-ecological, small-scale, peasant-based family-farming model has been promoted by peasant and other social movements and been supported by international organizations like the FAO and the European Union (LVC, 2019; Patel, 2009), as well as academia (Altieri & Toledo, 2011; Holt-Giménez & Altieri, 2013). Rooted in the understanding of agroecology as a social movement, a practice, and a science (FAO, 2019b), this new model of agriculture allows us to think in terms of the design of resilient agrarian and food systems in both ecological and social respects, thus reconciling sustainable goals with peasant agency. The agroecology practices of family farming reduce dependence on fossil fuel-based inputs, increase biomass production beyond the yields of the traded produce, thus helping restore the soil structure and fertility, and return to shorter chains of commercialization based on more seasonal and local complementary activities producing more varieties and nutritional food products, which in turns reduces the risks of food insecurity and enhances rural incomes (Boeraeve, Dendoncker, Cornélis, Degrune, & Dufrêne, 2020; Chará et al., 2019; Perfecto et al., 2019; Puig-Montserrat et al., 2017;

Reganold & Wachter, 2016; Ribas-Agustí, Díaz, Sárraga, García-Regueiro, & Castellari, 2019; Seufert, Ramankutty, & Foley, 2012; Teixeira, Bianchi, Cardoso, Tittonell, & Peña-Claros, 2021).

The FAO's tool for agroecological performance evaluation (TAPE) measures the level of achievement of this process of transition based on the five levels of the agroecological transition proposed by Gliessman (2016), namely: 1) increase the efficiency of industrial and conventional practices to reduce consumption and the pressure on the ecological systems; 2) substitute industrial and conventional practices and inputs by more agroecologically based ones; 3) redesign agroecosystems according to ecological processes; 4) re-establish connections between farmers and consumers; and 5) build a new global food system based on equity, participation, democracy, and justice, thus going beyond the mere goal of substantiality. Therefore, understanding the interactions between the institutional constraints (both domestically and internationally) and the economy's material bases making the path of tropical agroecosystems and its changes in long-term history become key to informing the process of transitions from the unsustainable model towards more resilient scenarios grounded in agroecology.

This thesis aims to understand the changes in the material bases of tropical agriculture throughout its transition from the organic model to the current conventional one and the socio-environmental consequences of this transformation, as well as the role of institutional settings that have driven this process, both nationally and internationally. I propose a conceptual framework for thinking about the socioeconomic bases of agroecosystems under extractive contexts. Making use of this framework, I study the socio–metabolic transition of Colombian agriculture by means of the agrarian metabolism and the historical analysis during the twentieth century. The thesis addresses three main research questions.

- *How did agrarian change take place in Colombia from a biophysical point of view?*
- *What were the main forces driving these changes?*
- *What were the environmental consequences of this socio-ecological transition of agriculture?*

The main argument is that the extractive profile of the biophysical flows of matter and energy in extractive agriculture simply reflect the extractivism of the institutional setting. The global changes over time in the power relationship between the political elites ruling the state, the local agrarian elites, and the poor peasants, together with the international incentives and constrains, have shaped the material profile of extractive tropical agriculture. This thesis transits through quantitative and qualitative research on the long-term trajectory of Colombian agriculture to answer these questions and prove this argument. I build the biophysical history of the material and energy flows involved in the Colombian agroecosystem system through production, extraction, use, trade, and consumption.

First, I analyse land use and biomass production to set the broad picture of the agrarian system as a system devoted to the extraction of pasture and cash crops. Then, while the historical bias towards cattle ranching and the agrarian policy cast some light on this profile, I introduce the broader context of the ecologically unequal exchange in international trade for the whole economy of the Latin American region and focus on agricultural trade and armed conflict in Colombia to understand the market and non-market mechanisms that have created food dependence and tropical specialization since the Second Globalization. Finally, the analysis of agroecological energy performance and its comparison with temperate agriculture in developed countries helps establish the timing of the socio-ecological transition in Colombia and the environmental burden of the agrarian change towards intensification after the 1980s as a differential trait of tropical agriculture. The overall material profile and its changes are understood in light of the proposed framework of agrarian extractivism and are supported by the stylized facts of the country's agrarian history in the twentieth century.

Following this introductory chapter, I describe the conceptual and methodological framework of agrarian extractivism, together with some basics of the case study to explain the development of the agrarian change in the country. Chapter two quantifies the size of the biomass flows and their chain from net primary productivity up to final uses. Finally, the chapter identifies the contribution of extensification, intensification, and land-use change in increasing crop production. Chapter three deals with the problem of ecologically unequal exchange from wide material flow-accounting methodology at the Latin American regional level. Chapter four goes into the details of the relationship between food trade and food security, and empirically tests the relationship between trade specialization, armed conflict, and relative prices to understand the long path of the market and non-market forces involved in the agrarian change in Colombia since the 1980s. Chapter five assesses the long-term changes in the energy efficiency and sustainability of tropical agriculture and sets its transition into the wide narrative of the socio-ecological transitions of western agriculture. Finally, although each chapter is a self-contained document, some broad conclusions are given in Chapter six.

1.2 SOCIOECONOMIC BASES OF EXTRACTIVE AGRICULTURE

Material and Energy Flow Accounting (MEFA) in social metabolism is recognized as one of the most significant contributions to Ecological Economics as a substantive discipline in opposition to Neoclassical Economics and its formality (Gerber & Scheidel, 2018). Since Ecological Economics aims to deal with the biophysical exchanges between societies and its environment and among societies, and the politico-institutional ground of these material bases, MEFA constitutes a solid tool for analysing these bases. However, some have criticised the lack of a body of theory and of the links between the material flows and the politico-institutional frames of the society being studied (Gerber & Scheidel, 2018; González de Molina & Toledo, 2014). In the case of socio-metabolic studies of agri-food systems, these shortcomings have been highlighted in the spirit of a sort of methodological pragmatism (Gabriel, Madelrieux, & Lescoat, 2020). Despite the criticism, there are some definitions of the concept of social-metabolism, and some attempts have been made to theorize the material and institutional links.

In this chapter, I build on the basis of such definitions and the theoretical efforts to extend the conceptual frame of social and agrarian metabolism into the analysis of extractive agriculture. I begin from the basic definition of social metabolism as the exchange of energy and materials both between societies and nature, and among societies as open systems. I then complement this approach with a consideration of the inner and foreign dynamics of the social relationships that guide the biophysical bases of agriculture through time. In this conceptualization, I define the inner dynamics by focusing on the relations between the political elites ruling the state, the rural elites, and the (poor) peasants according to the literature on the political economy of agrarian change, and the foreign dynamics as the economic incentives to specialize and the framework ruling agricultural production and trade under twentieth-century food regimes.

1.2.1 Social and agrarian metabolism

Social metabolism has been defined as a broad process of symbolic representations of the material world guiding the interaction between human societies and nature by its similarity to metabolism in biology (Fischer-Kowalski, 1997). From a biological point of view, human beings, as heterotrophic organisms, obtain energy from organic complex compounds (food) for their maintenance (catabolism) and reproduction (anabolism), however, the social nature of human beings have led to collective solutions to fit these needs by creating institutional mechanisms to rule the exchange of energy and materials with the environment and with other

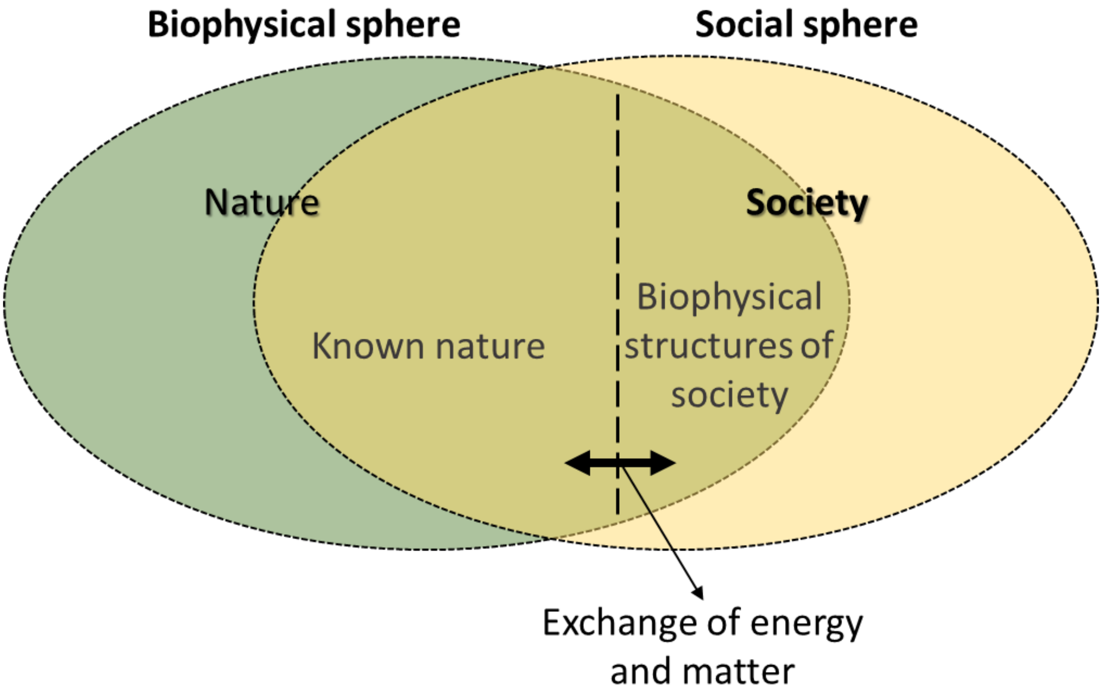

Figure 1.2: Biophysical bases of society and the interactions between society and nature. Based on Pauliuk and Hertwich (2015, 86).

social groups. Following the biological definition of metabolism, Fischer-Kowalski (1997) suggests including in social metabolism «those material and energetic flows that sustain the compartments of the system» (1997, 131), which in social systems refers to the physical facilities that are reproduced by work, such as population, machinery, buildings, livestock, and crops.

In a more recent definition, Pauliuk and Hertwich (2015) delimit the concept in three steps: first, they differentiate the transformation and distribution of biophysical objects from the stocks due to their static nature and call the latter 'complementary biophysical structures' of the society; second, with respect to the boundaries of the system, the authors draw a line between socioeconomic metabolism and nature in respect of the limits of human control over the transformations and distribution of the biophysical objects; and third, social-metabolism, say the authors, should not prescribe a top-level concept, but be obtained from detailed studies at the lowest level. In this way Pauliuk and Hertwich (2015, 85) propose the following definition of socioeconomic metabolism as:

> [...] the self-reproduction and evolution of the biophysical structures of human society. It comprises those biophysical transformation processes, distribution processes, and flows, which are controlled by humans for their purposes. The biophysical structures of society ("in use stocks") and socioeconomic metabolism together form the biophysical basis of society.

In distinguishing between the biophysical and social spheres of causation (see Figure 1.2) Pauliuk and Hertwich (2015) also solve the embedded definition of the whole economy as a subsystem of the environment and keep only the socioeconomic metabolism as a subset of the biophysical sphere of causation. However, they do not consider the role of the institutional setting in ruling the biophysical bases of the society and the process of exchanging matter and energy.

In an effort to provide a solid theoretical basis related changing to political and institutional social formations, González de Molina and Toledo (2014) state that socio-metabolic research neglects what occurs within societies and the interaction between its material and immaterial bases. To solve these lacks, the authors first defined five main functions of the social metabolism that takes place in society: appropriation, transformation, circulation, consumption, and excretion. Although these functions are observable, there is an immaterial dimension characterized by flows of information that guide the process: "the flows of matter and energy that are the material or tangible part of the metabolism between nature and society, are always conditioned, regulated, and articulated by these intangible super-structures that exist and persist by means of flows of information" (González de Molina & Toledo, 2014, 67).

Following the authors, I posit eight elements ruling the factors of the metabolic process inside societies: ideology, knowledge, technology, juridical regulations, and political, economic, cultural and property rules. Thus, the way these juridical, economic, and social relations act in respect of the five metabolic functions will also be the way the society organizes the exchange of flows of energy and materials with its environment and with other societies. At the same time, this interaction will also rule such changes through history. However, little is known about the class relations that underpin the social relations of material extraction

1.2.2 Class relations in extractive agriculture

The political consequences of modern state formation in Latin America were discussed by Huber and Safford (1995) in accordance with the agrarian class relations depicted by Moore et al. (1993). In this argument, the prevailing authoritarianism of the rise of Latin America's modern states was the result of a reactionary alliance between landlords, the state, and a weak bourgeoisie, though, strong enough to avoid a peasant revolution. The main goal of this coalition, therefore, was the conservation of the past social structure, especially the maintenance of coercive labour relations in agricultural production and the supply of cheap labour (Huber & Safford, 1995). Although historically it is argued that the landowners threatened the stability of democracy, there is also evidence of their support of this process, namely during the third wave of democratization

(1970–80s). In this case, the landowners gave support to democratization due to the economic profits they could earn from financial integration and foreign land investment on the one hand, and the fear of redistribution from autocratic rulers and the civil conflicts of the previous periods on the other (Albertus, 2017).

Due to the barriers to parliamentary control, the redistributive land policies in Latin America took place more often under authoritarian regimes than democratic ones. The key point of this argument is that, in the context of a split among the elites, the political elites that ruled the state under authoritarian regimes use land redistribution as a tool against the landowners to extend their period of office. This "attack" on the economic bases of the landowners is positive for the political elites when the initial coalition giving support is composed of non-agrarian elites. Thus, the erosion of the economic power of the rural elites could be positive for the other members of the initial coalition. However, when the landowners are important in giving support to the ruling of the political elites, land reform becomes a threat to the maintenance of the political elites in office. In this scenario, a lack of reform would be the best option for political elites in maintaining their ruling position in the office as puppets of the agrarian elites (Albertus, 2015, 71-77).

We can extend this political economy frame beyond land reforms to understand agrarian policies by saying that, depending on the capacity of the agrarian elites to influence the ruling political elites, the formulation and application of agrarian policies may become more or less positive in respect of the peasant's interests. Under both democratic and autocratic regimes, when the initial coalitions are largely based on the support of the landowners, the latter can exert an influence formally or informally to overturn the agrarian policies that threaten their status quo or to shape these policies according to their interests. Although most agrarian policies are depicted as a function of the coalition between the agrarian elites and the political elites, regressive policies could increase social unrest and the threats of violent revolution from the peasants. This challenge can be contested by repression or by more redistributive policies counterbalancing the power of the landowners.

What is relevant regarding this frame for the social metabolism of extractive agriculture is the role of the class relations that make the political and institutional environment more or less redistributive, or rather, how social class relations affect the regressive or progressive nature of agrarian policies (Figure 1.3), thus, making agrarian metabolism more or less extractive. The material bases of agriculture maybe are more or less extractive according to the role played by the social actors involved in the metabolic processes, especially the processes of appropriation, transformation, and distribution mentioned earlier. The outcome of a redistributive land policy could increase the number of units of appropriation and reduce the differences in size. In this case, the extractive process would bear on the intensive use of labour under medium and small family farming, which is more compatible with agroecological management. Under an opposite policy, the appropriation would act on large plots and cheap supplies of labour to favour the development of scale economies and the intensive use of fossil fuel-based inputs (capital), which is comparable to the conventional model of landscape homogenization and environmental pollution.

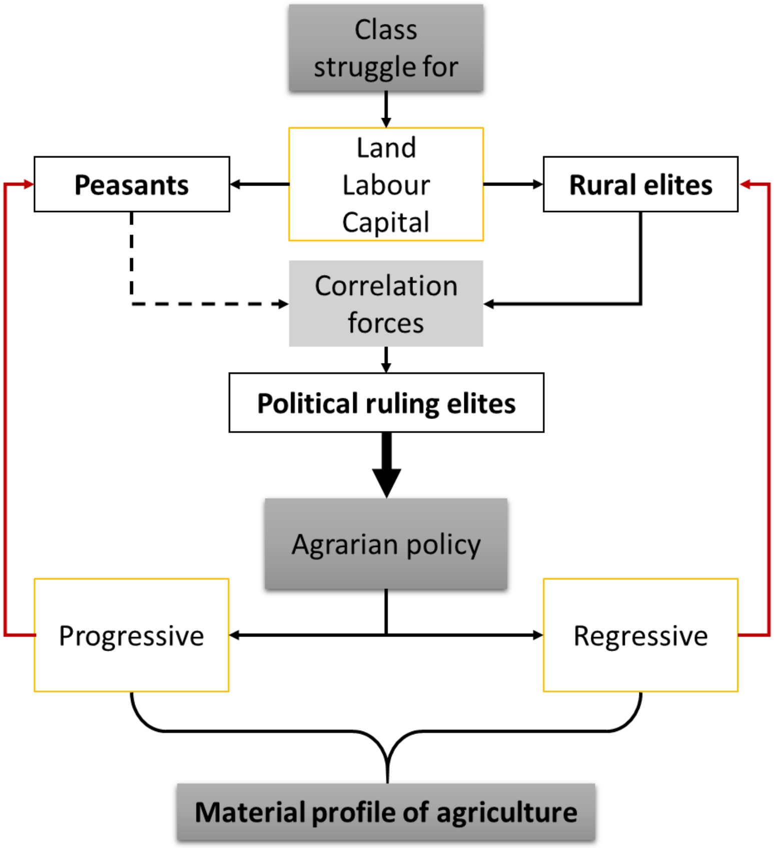

Figure 1.3: Class relations and material profile of agriculture

As defined by González de Molina and Toledo (2014), the appropriation of nature is the main process in rural societies, and the primary sector is the site of the transformation, process and preparing of food for the intake when the supply chain of distribution is based on very local markets. However, as markets become more integrated and societies more fossil-fuel dependent, commercialization and the food industry gain in relevance. Therefore, the economic incentives and the capacity to fill domestic and international demand will increase the role of the actors involved in the transformation and distribution processes. In this context, for example, policies guaranteeing access to new technology like tractors or fertilizers and the capacity to connect with markets will define the amount and the type of agricultural output, and even the way of the extraction used by the units of appropriation.

To sum up, the material bases of agriculture are defined by the agrarian policies of the state, but at the same time, these policies depend on the class relations between the actors involved in the agrarian metabolism. Up until this point, I have only spoken on the inner relations underpinning the material bases of extractive agriculture. However, there are also foreign forces shaping the energy and material flows of the agrarian sector.

1.2.3 Biophysical trade and extraction

As open systems, societies exchange energy and materials with other societies to reproduce their dissipative structures. However, the energy and materials that contribute to maintaining internal order and instilling more complexity into one system can be obtained at the expense of increasing or displacing entropy to other systems. This principle is the basis of ecologically unequal exchange theory, which analyses the exchanges of energy and materials in international trade (Hornborg, 1998; Muradian & Martinez-Alier, 2001c). The ecologically unequal exchange hypothesis rescued the unequal exchange hypothesis in Prebisch-Singer's thesis, which was extended by Emmanuel (1972) into the asymmetries in labour markets between "centre" and "periphery", and other critical development approaches in respect of the world-system (I. Wallerstein) and dependence theories (A. Gunder Frank) (Bunker, 1988; Pérez-Rincón, 2006b)[1].

In a broad sense, Bunker (1988) brought together the ecologically unequal exchange and the development of the modern state by distinguishing between "extractive" and "productive" economies. In extractive economies, the local elites organize the extraction of commodities to suit their interests. This exchange of material and energy flows between centre and periphery, according to world-system theory and the law of entropy, enhances the complexity of the social organization in productive economies, while undermining the organization and disrupting the ecosystems of the periphery, thus explaining the differences in development.

This approach goes beyond the unequal exchange based on the wage differentials between centre and periphery (Emmanuel, 1972; J. Ocampo, 1986) by accounting for the ecological interdependencies between extractive and productive economies, and by exploring the internal dynamics of the extractive systems as a socioeconomic type that is distinct from productive systems (Frey, Gellert, & Dahms, 2018).

In S. Bunker's words:

> "The flow of energy and matter to productive societies permits the increased substitution of non human for human energies, allows for increased scale, complexity, and coordination of human activities, stimulates an increasing division of labour, expands the specialized fields of information which this entails, makes possible increasingly

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[1] For a detailed criticism of world-system theory, see Tilzey (2017, Ch.3).

> complex systems of transport and communication, and engenders the means of technological and administrative innovation by which the crises of resource scarcity are overcome. The mode of extraction, on the other hand, loses energy, and so becomes socially and economically simpler, less diversified, and subject to technologically determined changes in market demand which the modes of production generate." (Frey et al., 2018, 31)

Therefore, Bunker (1988) brings together the depletion of natural resources and underdevelopment as a consequence of modes of extraction being created at the local level (national and regional) and the unequal exchange in the world system (Givens, Huang, & Jorgenson, 2019). Moreover, she linked this profile to the inner structures of the extractive systems. The organization of this extraction, declares the author, is the elite's answer provided to the demands of international trade on natural resources.

The desire to obtain some benefits from international markets in commodities creates a conflict of interest between the social groups that organize the extractive process. At this point, Tilzey (2017) also recognizes that the "political dynamics of accumulation and resistance", where "social-property relations determine the class structure", are materialized in the modes of extraction 2017, 28[2]. Although different from Tilzey's argument (2017), our point about the outcomes of agrarian policies is also based on these same class relations which drive the organization of the metabolic process.

Therefore, in addition to the domestic class relations, I argue that agrarian policies at the domestic level and the derivative positions of the actors in the metabolic process of extractive agriculture also depends on the foreign forces that rule the exchange of agricultural products, these forces being the bases of the extractive exchange and the incentives to participate in it.

Here I have only depicted the biophysical bases of the exchange of energy and materials between societies, the environmental implications for unequal trade from the entropy law, and the relationship between this ecologically unequal exchange and the organisational capacity of the elites at the domestic level to extract commodities for international markets. However, this biophysical frame of trade still lacks the economic incentives and the historical framework to guide the motivations and decisions of these elites to participate into this unequal exchange. To address this issue, I build on the initial factor endowments leading to comparative advantages and specialization, and then on the geopolitics that ruled agricultural production and trade during the different food regimes of the twentieth century.

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[2] For more on the dialectical relationship between the extraction mode and political relations, see Tilzey (2017)

1.2.4 Economic and historical roots of agrarian specialization

Ricardo's theory of comparative advantage states that there are gains from trade when economies become specialized. In line with this, the Heckscher-Ohlin model predicts that once two countries open up to trade, the opportunity cost of producing "A" instead of "B" will be determined by the relative prices of factors. So, countries will specialize in exporting products that are intensive in the use of its most abundant and relatively cheap factor, while they would import those products that are intensive in the use of their scarce and relatively expensive factors. After specialization, there will be a convergence in the prices of factors between the two countries.

Grounded on this model, O'Rourke and Williamson (1999) show how the New World into the Atlantic Economic specialized in the use of the abundant land to produce agricultural products such as grains in the United States and the redistributive effects of this process in the two sides of the Atlantic. Following this argument, the abundance of land in some Latin American countries would have led to the same process of specialization, but, different to the United States, the specialization on primary products became the rule and these countries did not succeed in generating linkages with the rest of their economy.

Going more deeply into the nature of the product exported, structuralism blamed this long path dependence on the primary sector. The classical economists held that there were increasing improvements in the terms of trade of primary products due to the inelastic supply of land and natural resources, but the Prebisch-Singer thesis challenged this idea (Hadass & Williamson, 2003). The original formulations of the Prebisch-Singer thesis combined two complementary hypotheses. First was the negative effect of low-income elasticity of the demand for commodities on the terms of trade affecting developing countries versus the higher income elasticity of the demand for manufactures. Second were the asymmetries in the labour market between the centre and periphery (J. A. Ocampo & Parra, 2003b).

The subsequent analysis of unequal exchange came from each one of these hypotheses: the study of the deterioration of the barter terms of trade and the consequent deepening of specialisation, on the one hand, and the unequal exchange studies of the wage differential model as a way to transfer value from the periphery to the centre proposed by Emmanuel (1972), on the other[3]. The former is more common in economic history studies, while the latter, as shown before, is more common among the ecologically unequal arguments.

The interest in testing the relative prices hypothesis led to the construction

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[3] For a synthesis of the main developments in trade theory and less developed countries until the eighties, see J. Ocampo (1986) and the appendix IV in Emmanuel (1972).

of time series on the evolution of the terms of trade for commodities and manufactured goods. These studies agree on the improvements to the terms of trade during the First Globalization (J. A. Ocampo & Parra, 2010) and their deterioration since the Great Depression (J. A. Ocampo & Parra, 2003b). Analysing agriculture and the food trade, Pinilla and Aparicio (2015) and Serrano and Pinilla (2011) also proved this decline in relative prices, especially among the less processed products. However, greater than the deterioration would have been the volatility, even during the phase of improvement, which would have led to the asymmetries in economic growth and development. This would be the factor explaining the increasing divergence between the commodity exporters in the periphery and the core economies during the First Globalization (Blattman, Hwang, & Williamson, 2003, 2004, 2007; Hadass & Williamson, 2003; J. Williamson, 2008; J. G. Williamson, 2011).

Although this pattern of deterioration involves the need to increase the amount of energy and materials that are exported to avoid the loss of purchasing capacity, the path dependence of primary specialization also depends on the nature of the product exported and the institutional setting. Under the export-led growth model, the chances of generating linkages between the commodity exported and the domestic economy on the one hand, and the distribution of the gains of trade within society on the other, are key to understanding the success of diversification (North, 1959): unequal structures of political and economic institutions are a barrier to the development but not to the economic growth. In the context of extractive institutions, the export sector brings together the economic interests of the local (rural) elites around one common project. The political elites ruling the state use such concessions in exchange for support or to avoid confrontation (North, Wallis, & Weingast, 2009).

In the case of extractive agriculture and its tropical exports, the evolution of international prices for tropical commodities relative to grains during the twentieth century helped to maintain the economic incentive of tropical specialization among the rural elites. Though the prices of food commodities fell, the relative prices guaranteed the economic profits from tropical exports. The index for coffee prices grew by 45%, while banana and oil palm fell by -7.5% and -1.3%, respectively, with the sole exception of sugar, which fell as much as cereals. By contrast, maize, rice, and wheat fell by -62%, -67%, and -46%, respectively (J. A. Ocampo & Parra, 2003b).

Rural elites' economic incentives for entering international trade, therefore, could be laid on the comparative advantages of producing tropical products. This incentive would have been sustained throughout the twentieth century by a minor reduction in the international prices for tropical products relative to the prices for grains. Meanwhile, the decline in the terms of trade of primary products would act as the force leading to the growth of tropical output to avoid the loss of purchasing power, while the actual trap of remaining with tropical specialization would be the nature of extractive institutions (Figure 1.4). In this context, export-led tropical agriculture would become the way the political elites pay for the support of the local rural elites during modern state-building.

Nonetheless, and as I shall show, the domestic level of agricultural production also depends on the geopolitics that rule the course of history.

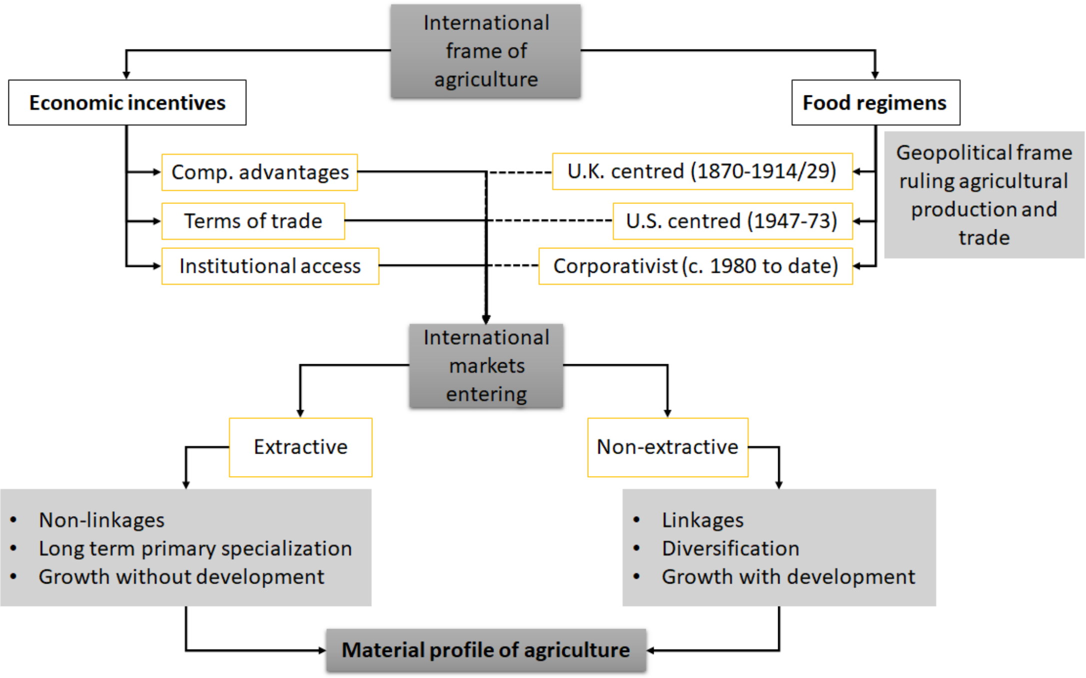

Figure 1.4: International constraints and the material profile of agriculture.

1.2.5 The food regimes framework

Once the economic incentives have been defined and the relationship with the institutional setting has been established, we must fit them within their geopolitical and historical framework. This frame, called the "Food Regime", which is dynamic and changing, has been defined as a succession of stable systems of relationships between states, firms, and farmers (McMichael, 2009, 140) that have shaped the rules of domestic production and the international trade in agri-food products since the end of the nineteenth century. The classical periodisation of food regimes divides the history of these relations into three phases, namely: the British-centred period (1870–1914/29), the United States regime (1947–73), and the corporatist regime (c. 1980 and ongoing) (McMichael, 2013).

The first regime developed during the First Globalization, the role of the United Kingdom being to bind international trade as the main exporter of capital and manufactures to the New World, and the main importer of food from its rich and abundant soils (Krausmann & Langthaler, 2019). Coal and steam used in transport helped reduce the cost and integrate the domestic and Atlantic markets for wheat and meat from the New World (O'Rourke & Williamson, 1999), and the tropical and mineral commodities from Latin America (Cárdenas, Ocampo, & Thorp, 2000b).

The export-led model in Latin America left some room for the early rise of modern states thanks to the revenues coming from tariffs (Coatsworth & Williamson, 2004), which avoided conflicts over taxing the lands of the rural elites, but created new social claims. The ties to international trade opened a window to economic growth and the development of the domestic economy across the region while at the same time contributing to the rise of conflicts over the distribution and participation of the gains from international trade (Norberg, 2019). This struggle revolved around the material bases of the food regime, namely land abundance and the expansion of the agrarian frontier (Krausmann & Langthaler, 2019). Therefore, the social struggle was characterized by peasant claims to land and the definition of property rights (LeGrand, 1986).

The shocks of the two World Wars and the Great Depression between 1914 and 1945 led to the collapse of the Gold Standard system and all it meant for international trade relations, namely the replacement of the United Kingdom as the main supporter of the flows of goods and capital globally with the United States in the leading position. International relations of production and the trade in food became the primary role of the United States as the centre of the international monetary system and the domestic policies of agricultural promotion. The new Bretton Woods monetary system characterized by the restrictions on capital flows to avoid foreign investment distorting the development of the domestic economy (Eichengreen, 2019). In this same vein, agriculture was excluded from the General Agreements on Tariffs and Trade, thus stressing the role of food self-sufficiency as a policy of national security and domestic development.

As in the case of the rest of the economy, national states promoted the industrialization of agriculture during the second food regime to guarantee the goal of self-sufficiency (O'Hagan, 1976), but also as a tool of economic development, especially across the "underdeveloped" world. In these countries, however, fossil fuel-based agriculture also served the United States as a weapon to fight against the threats of communism, which gave technical support and food aid (McMichael, 2013), and promoted land redistribution policies (Botella-Rodríguez & González-Esteban, 2021). However, this "development project" also served to cultivate transnational agribusiness capital (McMichael, 2009).

In Latin America, the aim of increasing agricultural output went hand in hand with the emergence of the active role of the state in economic development. There, nation states promoted the creation of network infrastructures and experimental centres and provided institutional support and credit facilities to help spread the new technologies of the Green Revolution. Foreign and domestic state intervention would therefore be primary in contributing to economic growth, structural change, and some reduction in inequality across the region (Arroyo Abad & Astorga, 2016; Astorga, 2017; Cárdenas, Ocampo, & Thorp, 2000a; Tafunell, 2013; Thorp, 1998) during the years of the second regime.

Although land reforms and cheaper food benefited peasants and urban actors such as industrial elites and workers, the rural elites managed to capture the new sources of profit, namely the technological innovations from the Green Revolution (Griffin, 1979), which paved the way to the emergence of a new regime characterized by agro-export specialization and food dependency.

The price rises for grains at the beginning of the 1970s increased the tensions within the second food regime; in Northern agriculture, especially in United States, the subsidies scheme continued, and the agricultural lobby of exporter farmers was replaced by agri-food corporations. In Southern agriculture the shocks of oil prices on foreign debt led to structural reform programs and the promotion of "non-traditional" agricultural exports (Bernstein, 2016). These two trends laid the foundations of the unbalanced food trade between developed and developing regions during the Second Globalization (Kumar Sharma, 2016). Though the definition of the third food regime has been debated, related to the replacement of key role the state in production and trade by international institutions and agri-food corporations (McMichael, 2013), it seems clear that the main feature of this period was the application of the neo-liberal project to the agri-food sector, namely market liberalization and the privatization of some public services (Bernstein, 2016), such as ensuring food self-sufficiency.

Trade liberalization and the deregulation of financial capital created the incentives and offered the means for agro-export businesses in the South to grab land and launch the supermarket revolution in the North. The extreme decoupling of food production and consumption since the 1980s (Fader et al., 2013) was accompanied by international corporations investing in both developing and developed countries (McMichael, 2013), and currently by the focus on the food industry and services (Bernstein, 2016). This liberalization of agricultural trade, which was one of the main characteristics of the third food regime, emerged with the ending of GATT and the setting up of the World Trade Organization in 1995.

Food dependency and agro-export specialization in high value crops (tropical fruits, fresh vegetables, feed, and industrial inputs) in developing countries were the main consequences of this new regime, while the schemes of rural support in developed countries guaranteed cheap cereals and the re-allocation of agriculture in developed countries (McMichael, 2013).

This transformation increased the dependence on the use of fossil fuel-based external inputs with negative ecological and social impacts. On the side of the ecological burden, as shown above, the results were tropical deforestation, soil deterioration, biodiversity losses, and increasing Greenhouse Gas Emissions (Campbell et al., 2017; Foley et al., 2005; Kissinger et al., 2012; Mbow et al., 2017; Ramankutty, 2008). On the socioeconomic side, there was the destruction of peasant cultures, knowledge and social networks (Altieri & Toledo, 2011) throughout market mechanisms that drove the displacement of small family farming and promoted land accumulation and intensive agriculture (Norberg, 2019).

In opposition to this model, agroecological, small-scale, peasant-based family farming has gained support among the peasant movement, international organizations like FAO, UN (LVC, 2019; Patel, 2009), and academia (Altieri & Toledo, 2011; González de Molina & Lopez-Garcia, 2021; Holt-Giménez & Altieri, 2013) to conciliate peasant agency and sustainable goals in managing agri-food systems. These claims have been joined up under a big tent called “food sovereignty”, advocating the right of nations to produce basic food, respect cultural and productive diversity, guarantee agrarian reform, and protect natural resources, social peace, and democratic control. This international peasant movement has raised its voice against the policies of trade liberalisation, the economy of poverty and hunger, the destruction of community networks and their bio-cultural heritage, and the depredation of natural ecosystems (LVC, 1996).

1.2.6 The inner and external forces making extractive agriculture

Figure 1.5 synthesizes social class relations, the economic incentives of international trade, and historical food regimes as the socioeconomic forces defining the material profile of agriculture. According to its interaction and levels, the material profile of agriculture can be more or less extractive.

As inner factors (in axis x) I mainly include the class relations between the rural elites, the ruling political elites, and the poor peasants. These relations shape the framework of domestic and trade policies in relation to agriculture in a more regressive or progressive way according to whether they are more or less unequal. Under a domestic institutional setting involving extractive agriculture (on the right bottom of the matrix), agrarian policies would create a bias towards the landowner’s economic interests by offering to them better access to land, labour, and technology. The countries in Latin America where the state-led policy has prompted the industrialization of agriculture and the increase of production in the domestic markets during the ISI period could fit this category well. In these cases, despite the aims of land redistribution (Botella-Rodríguez & González-Esteban, 2021) and to be “modernizing” agriculture, the final result was the promotion of commercial agriculture and the bias in accessing the new technologies and better lands for rural elites (Griffin, 1979). Conversely, cases of

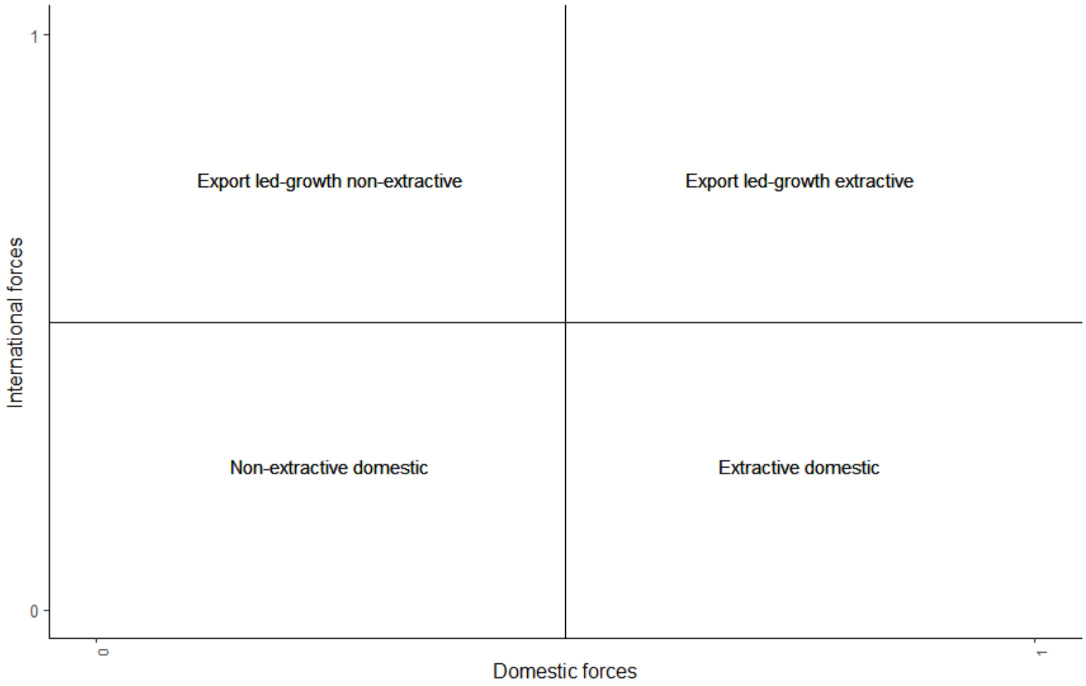

Figure 1.5: Extractive agriculture framework: domestic and international forces making extractive agriculture. The x axis represents the level of institutional inequality (e.g . land distribution) while in the y axis there are the forces from international markets (e.g. trade integration). The intersection of these socioeconomic forces defines the material bases of agriculture into one of the four quadrants.

agrarian colonization under family farming, as was the case with British colonies in north-west America between the mid-seventeenth and the late eighteenth centuries could be taken as examples of non-extractive domestic-based agriculture (left bottom quadrant).

In axis y, I relate the foreign forces to the economic incentives and historical constrains the food regimes that encourage entry into international markets, thus being this a level of trade integration. Throughout the twentieth century, these forces have acted in two ways. First, despite the long-term deterioration of the terms of trade, factor endowment and price mechanisms have led to specialization and profitability from tropical export promotion. Second, agricultural production for international markets ruled agrarian policy during the first and third food regimes globally, namely the First (1870–1914/30) and the Second Globalizations (c. 1980 up to date). When these external forces push for integration with international markets, the initial institutional setting can lead to two versions of the agro-export model, namely non-extractive and extractive. While non-extractive agriculture, which is highly integrated into international markets but based on family farming, could lead to economic growth and development due to its linkages with the domestic economy (North, 1959), the predominance of agrarian elites and unequal land tenure could drive towards an extractive model of specialized agricultural exports, which could lead to economic growth but without development (North et al., 2009). In the former case, we can cite the historical examples of the New Europe economies during the First Globalization (i.e. U.S., Canada, and Australia). In the latter case, the situation is closer to the experience of the Caribbean sugar colonies, the southern plantations in the United States, and the current tropical export specialization of developing countries such as Colombia.

1.3 FROM THE ECONOMY–WIDE MFA TO AGRARIAN METABOLISM

This dissertation starts with the Material (and Energy) Flow Accounting (MEFA) and then moves to the analysis of the agrarian system from an agroecological perspective. The MEFA helps to track the exchange of the flows of matter and energy between human societies and nature to measure the metabolic profile of the national economy and the environmental impacts associated with extraction, production, exchange, and consumption. These flows are aggregated into four major categories, namely biomass, metal ores, non-metallic minerals, and fossil fuels (Eurostat, 2018; Krausmann et al., 2015), which give a clear picture of the material grounds of the economic process. Based on this accounting system, this work focuses on the biomass accounting of the main flows associated with the agrarian sector but also seeks to go beyond this. The thesis also adopts an agroecological approach by introducing the entire chain of biomass from net primary production (NPP) to its final uses. In including all the NPP, we are accounting for the piece allocated to the reproduction of the living funds of the agroecosystem in the way proposed by agrarian metabolism (Guzmán & González de Molina, 2017; Haberl et al., 2007).

The NPP is the available portion of phytomass required for the maintenance, growth, and reproduction of all heterotrophic organisms, including, of course, human beings, domesticated animals, and wild species in nature (Smil, 2013, 31). Therefore, human appropriation of the NPP (or HANPP) entails that the larger the fraction of NPP harvested, the smaller the portion left for the reproduction of the wild species (Schandl, Grünbühel, & Weisz, 2002). This affects biodiversity, soil quality (Bardgett, 2005) and the global cycle of carbon both directly and indirectly. This basic definition, which is at the core of the understanding of how agroecosystems function and of the biomass accounting of agriculture, lays the foundations for the two methodological frames of agrarian metabolism, namely agroecology, and material and energy analysis.

Agroecology analyses the relationship between societies and ecosystems that is channelled through agriculture (Altieri, 2018). while stresses the role of managing and conserving farm–associated biodiversity by enhancing energy recycling and reducing fossil–fuel–based inputs dependence. It stresses the role of managing and conserving farm-associated biodiversity by enhancing energy-recycling and reducing fossil fuel-based input-dependence. This science and practice of recycling and managing matter and energy according to the natural cycles is not only useful in light of ecological restoration, it is also critical to achieving the social aims claimed by the United Nation's agenda (Nations, 2021). Agroecological practices contribute socially to reducing rural poverty and food insecurity, especially in developing countries (Perfecto et al., 2019; Vandermeer & Perfecto, 2017). In these contexts, the key role of small-family farming (Perfecto et al., 2019) and silvopastoral systems (Chará et al., 2019) fits well with labour-intensive biomass-recycling as a way to reduce dependence on external inputs and to design new agroecological landscapes.

Coming from a different direction, energy studies of agrarian systems have integrated the fund–flow theory of ecological economics (Giampietro, Mayumi, & Sorman, 2011) and the critics on conventional economic analysis (Couix, 2020; Georgescu-Roegen, 1971). These efforts in opening up the black box of the energy returns of agriculture to multiple analyses have led to a sort of convergence between the agroecological framework and agrarian metabolism (González de Molina, Petersen, Peña, & Caporal, 2019; González de Molina et al., 2020; González de Molina & Toledo, 2014; Tello et al., 2016), also known as the energy analysis of agroecosystems (AEA) (Hercher-Pasteur, Loiseau, Sinfort, & Hélias, 2020). This new approach includes the marketable and non-marketable flows involved in agriculture and its related ecosystems.

Thus, in the material and energy analyses of agroecosystems, living funds transform matter-energy flows to meet social needs while also require a fraction of this production to be consumed to guarantee its reproduction over time. For example, the microbiota living in the soil help to recycle nutrients into new phytomass from the organic matter that has been turned back. Although this biomass is critical to keep the soil alive (Bardgett, 2005) and guarantees the extraction of crops, it is not accounted for in the market system. This accounting system, proposed in agrarian metabolism, highlights the energy cost of the reproductive functioning of agroecosystems as a co–production with nature (Van der Ploeg, 2013), since it includes maintenance of the biodiversity–related ecosystem services on which society depends (Galán et al., 2016; Guzmán & González de Molina, 2015, 2017; Padró, Marco, Font, & Tello, 2019; Padró et al., 2020).

Following this methodological framework, I estimate the national accounting of biomass in Colombia and its distribution from the NPP to its final uses to measure the size of the agricultural sector and its main flows (Chapter 2).I then integrate these flows into the fund–flow and multi–Energy Returns On Investment (EROI) analyses to assess the changes in the energy efficiency of biomass production and the reproductive capacity of the whole agroecosystem (Chapter 5).

Together with this material and energy analysis, I include qualitative and quantitative historical approaches. I base myself on the historical narrative of agrarian change, focussing on social class relations, the domestic agricultural policy, and the incentives and constraints from international trade under the twentieth-century food regimes. This narrative is supported by the building of long-term time series, decomposition analysis, time-series modelling, and structural break analysis. This combination of methodological approaches contributes to the biophysical history of agrarian change in the whole of Colombia's agroecosystem, identifies some of its socioeconomic drivers and considers the process of the socio–ecological transition of tropical agriculture in light of the changes to temperate agriculture in developed countries during the twentieth century[4].

1.4 BASICS ON THE CASE STUDY

Colombia is a South American country of 1.1 million km^2 situated into the tropical climate zone. The temperature changes according to altitude, not latitude. The lowlands between 0 and 1000 masl. cover most of the country with temperatures above 18ºC (Figure 1.6), but there are temperatures colder than 18ºC in the zones of the Andean mountains. According to the Köppen classification, the country has mostly tropical rainforest, monsoon, and savanna types of climate, together with smaller areas that are oceanic, tundra, desert and semi-arid (Wikipedia, 2021a, 2021b).

The Andean range is split into three cordilleras which cross the country from south to north. These cordilleras almost define the country's five natural regions, one of which the Andean zone, comprising the mountains zones of the cordilleras and its valleys. In a broad sense the other four regions share as a common feature the predominance of lowlands, though climate and vegetation differ among them. In the Caribbean region, in the north of the country, the main climate type is the tropical savanna, and most of the land is covered by pasture, shrubland and tropical dry forest (Figure 1.7). Next to the Venezuela border is the Orinoquía region, where a tropical monsoon climate and shrubland vegetation covers are predominant. Finally, the Amazon and Pacific regions in the southeast and west respectively are characterized by a rainforest type of climate and vegetation. These two regions host almost the entire share of the country's forest. This variability in geography makes Colombia's ecological potential among the leading on the earth, as it is the second most biodiverse country worldwide, with 58,312

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[4] For details of the methodology used, see the methodology section in each chapter and its corresponding appendixes.

registered species of plants and animals (SiB, 2020).

As can be seen in Figure 1.7, much of the land use associated with human activity such as mosaics, cropland, and urban areas is clustered in the Andean mountains. This and the Caribbean region have been where population settlement took place historically. However, as agrarian colonization spread, new settlements were established in the lowlands of the tropical forest after the 1970s (Etter, McAlpine, & Possingham, 2008). This second expansion has affected and led to deforestation and forest fragmentation (Armenteras, Rudas, Rodriguez, Sua, & Romero, 2006; Ayram et al., 2020), especially in the Amazon region.

Agricultural expansion and intensification have been parallel processes in the twentieth-century history of Colombian agriculture. The mid-century demographic expansion (1955–75) lead to a doubling of the population density between 1975 and 2015 (Table 1.1). Despite this, the current population density of the country remains very low (40 h/km^2 on average 1998–2015). This relative abundance of land is characterized by the predominance of the forest and pasture land, as is well depicted in the composition of the land-use map. In 2010, 52% of the land was forest, 33% shrubland and pasture, and only 11% was under mosaics including mixed forest, pastures, and croplands. Moreover, cropland only reaches 1.6% (Figure 1.7). This composition, however, is also observed historically if it is compared to pastureland. Despite the expansion of the harvest area, which was faster than the growth in pasture, the predominance of these has been a long-term feature of the land-use pattern, which makes sense given the country's low population density (Table 1.1).

Table 1.1: Average performance of socioeconomic indicators by periods

		1916-32	1933-54	1955-75	1976-97	1998-2015
1	Population [M]	6.9	10.6	19.3	32.0	44.0
2	Agr. labour [PJ]	6.1	8.4	9.2	10.4	12.3
3	Density [pop/km^2]	6.2	9.5	17.4	28.8	39.6
4	Pastureland [Mha]	9.8	12.2	16.1	22.3	24.1
5	Area harvested [Mha]	0.9	2.3	3.3	4.3	4.0
7	GDPpc [2011US$]	1718.9	2683.9	3956.2	6739.5	9202.2

Notes: Source: Own elaboration, from the sources given in 5.2.2 and appendix B; GDP is from MPD (2018)

Compared to other developing countries in tropical zones, and with more than 40-50% of its territory cover with forest (FAO, 2021), Colombia can be defined as a medium-size country both demographically and economically. In 2019 the population surpassed fifty million, which is higher than Bolivia (11 M), Cambodia (16 M), Ecuador (17 M), Malaysia (31 M) or Peru (32 M), though lower than the DRC (86 M), Vietnam (96 M), Brazil (211 M) or Indonesia (270 M) (WB, 2021b). Economically, the country is classified as an upper-middle-income country with

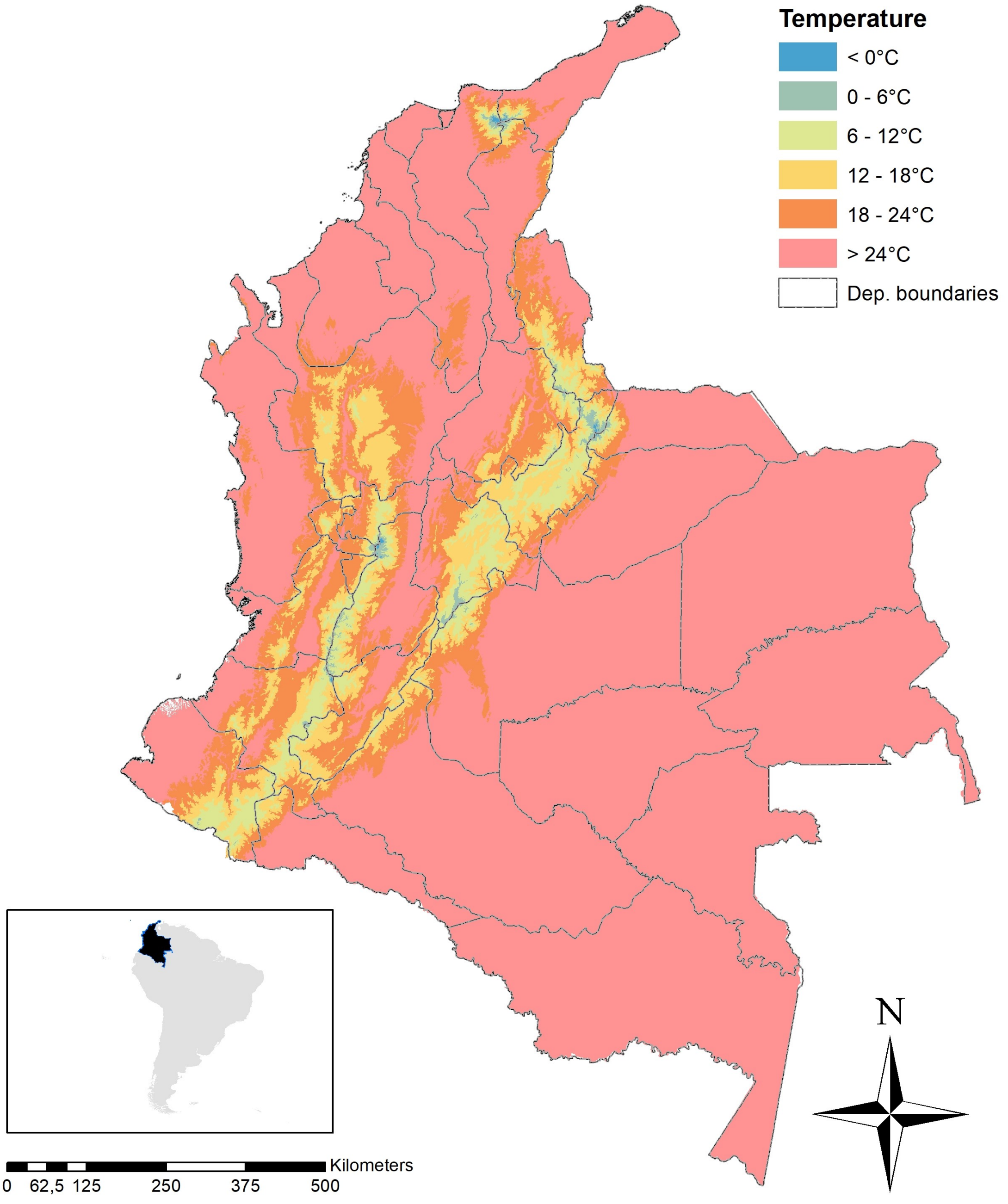

Figure 1.6: Temperature variation across the country . Own elaboration. Source: IDEAM

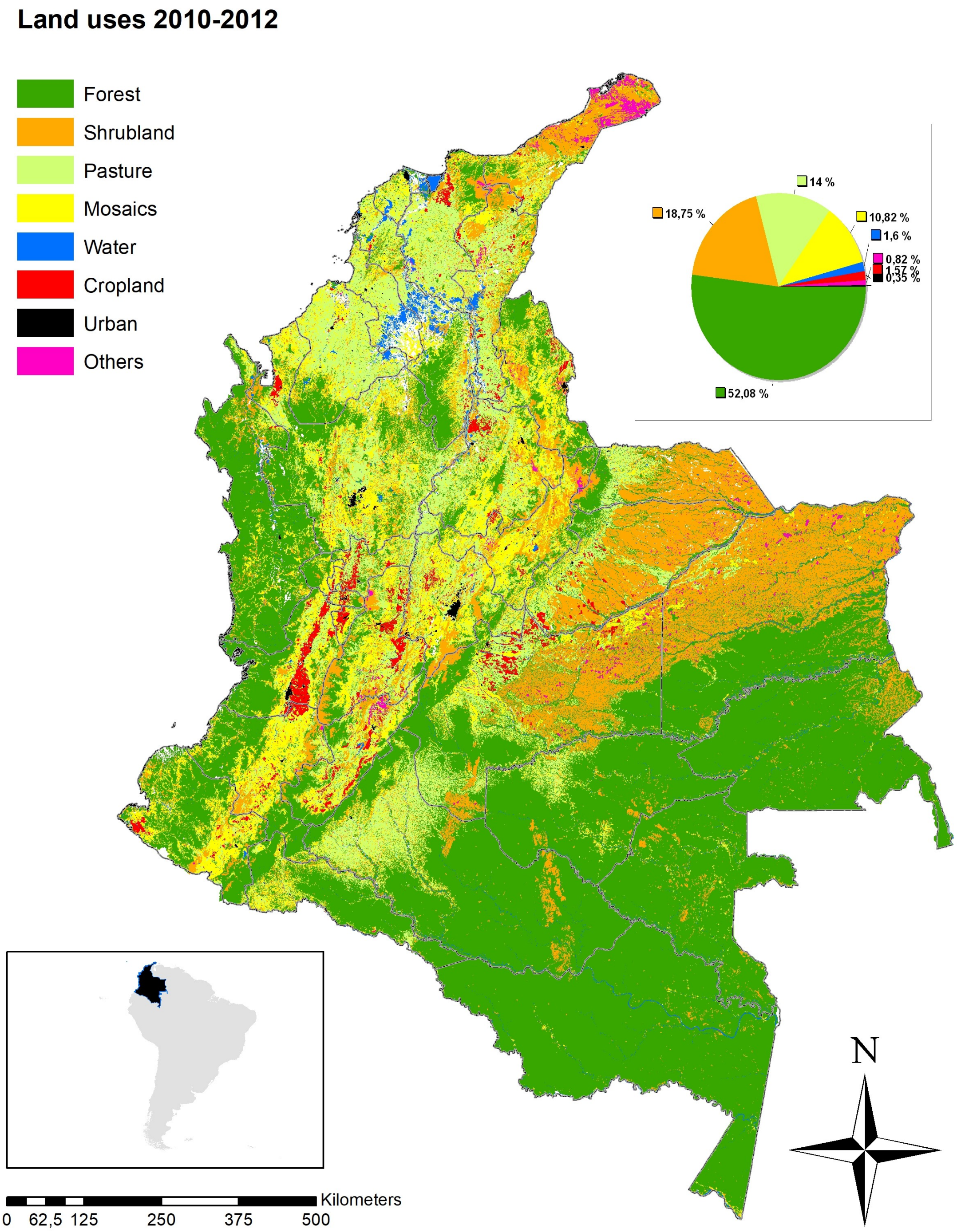

Figure 1.7: Land uses in Colombia (2010–12). Own elaboration. Source: IDEAM

incomes ranging from $4,046 to 12,535 GNI per capita, generally speaking, higher than those of its African and Asiatic equivalents, but lower than those of most counties in Latin America (WB, 2021a).

These geographic, demographic, and economic features make the Colombian case study representative of tropical agriculture and its transition among the developing countries of the Global South. But the intricate of its history also makes the country a good case of study since it helps to understand the role of class struggle and international trade in making the material bases of agriculture, as declared in the conceptual framework (see Section 1.2) .

The agrarian history of the country has been shaped by the influential power of the rural elites over the making of agrarian policy. Although most of the time this influence has been supported by the state, the emergence of other interests among the industrial classes, like the bourgeoisie and urban workers, and the increase in the bargaining power of peasant movements and their claims over land are also key to understanding agrarian colonization, the attempts at agrarian reform, and even the repression[5].

The twentieth-century history of the country can be split into four major periods: the expansion of the coffee economy during the First Globalization (1916–34); the birth of the modern state and its role on the development of the domestic economy (1934–74); the process of structural reforms that started after the 1980s debt crisis, which led to a renewed agro-export model (1980s–90s); and the last period of intense violence and increasing trade specialization in agriculture up to the peace agreements (2000–12).

During the First Globalization, the agrarian elites won the support of conservative governments in entering the international coffee market, but they also managed to ensure themselves the control of labour under the hacienda system and access to land thanks to public adjudications. Although coffee was boosted as the project that brought together the economic interests of the elites, who had become divided after years of civil war (Safford, Palacios, et al., 2002), the export economy changed the country and the previous social class relations.

The economic boom during the 1920s encouraged the peasants to demand better labour conditions in rural areas and, thereafter, to call into question the land titles of the landowners. The rise of the small-scale family-farming model in the coffee sector, together with the rise of food and manufacturing industries, were among the factors in the weakening of the rural elites, who had to face attempts at rural reform in the 1930s and 1960s. According to Bejarano (2011), the processes of land parcelling and land titling, and the rise in wage labour

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[5] For more details about the history of the country, each chapter introduces some of the most relevant elements for the understanding of the development of agriculture throughout the twentieth century: the bias of agrarian and trade policy in Chapter 2, a brief sketch of the evolution of the agrarian conflict in Chapter 4, and a periodisation of agricultural intensification in Chapter 5.

served to consolidate the small properties around the big estates and weakened the landlords during the Liberal Republic. This did not mean the end of the influence of the rural elites, who were represented by the Sociedad de Agricultores de Colombia (Colombian Agricultural Society –SAC) and were faced by the surge in attempts at rural reform by the state during the 1930s and 1960s according to the goals of industrialization and development.

Therefore, the development of agriculture from 1945 to 1960 was especially marked by the phenomena of La Violencia (1948–58), and between 1950 and 1970 it was state intervention that helped to “modernized” the agricultural sector. This intensification of agriculture, however, was conceived as a way of achieving national industrialisation. In this context, agriculture had to become the main supplier of raw materials and food to the emerging industries and cities.

From ca. 1980, the ending of the state led-growth model led to the emergence of specialization based on the expansion of tropical exports, accompanied by a process of the decentralization on the part of the state (1983–99) and the liberalization of the economy during the 1990s. This process provided a material and institutional basis for the strengthening of the regional elite and its economic interests.

This change marked a breaking point in the history of the country, creating the ruling framework of rural social relations and the return to influence of the rural elites in agrarian policy-making until today. After the 1970s, state support for extensive cattle-ranching and export agriculture was formalized with the aim of capitalizing on the sector and promoting agricultural exports. New crops such as flowers, sugar or tropical fruits increased their share of exports, while the growing imports of cereals and labour regulations helped to reduce the cost of labour in the search of international competitiveness (Patel-Campillo, 2010).

The social response to this project came from the radicalization of the peasant guerrilla groups that adopted communist ideologies, mainly the Fuerzas Armadas Revolucionarias de Colombia–Ejercito del Pueblo (FARC–EP), as well as the emergence of regional movements based on specific claims. From the 1980s peasant movements from the new zones of agrarian colonization in the southern lowlands began to emerge that were linked to coca-growing. Also relevant was the the opposition of small and medium farmers of coffee and potatoes to the economic opening of the 1990s, which also saw the emergence of cultural and identity issues embedded in the environmental claims of indigenous peoples, afro-descendants, and women peasant movements (Archila & Pardo, 2001). Finally, after years of increasing violence and agricultural specialization (2000–12), new hopes for agrarian reform surged during the peace agreements, though implementation remains at a halfway point. Conversely, in 2020 the country became the most dangerous place in the planet for the defenders of the land and environment (Greenfield & Watts, 2020).

Chapter 2

Pastures and Cash Crops: Biomass Flows in the Socio–metabolic Transition

Keywords: socio-ecological transition, biomass flows; net primary production; land-use change; cash crops

2.1 INTRODUCTION

Over the twentieth century, economic, and population growth led to unprecedented levels in the appropriation and use of energy and materials worldwide (Smil, 2013)[1]. Although resources such as fossil fuels and other minerals dominated this increase, the appropriation of biomass also continued to grow due to population growth and income rises affecting the diet's patterns (Smil, 2002; Tilman & Clark, 2014). This process has led the agroecosystems to massive use of fossil fuel-based inputs (Arizpe, Giampietro, & Ramos-Martin, 2011; Conforti & Giampietro, 1997; Giampietro, Cerretelli, & Pimentel, 1992) increasing the environmental pressures on nature. The amount of nitrogenous fertilizers used in agriculture around the world has moved from 11 million to 109 million in the last half-century, which is a ten–fold increase (FAOSTAT, 2021), and global biomass extraction has grown by 60% between 1980 and 2013 (WU, 2020), while the proportion of the world's area being harvested extended by 40% between 1990 and 2014 (FAOSTAT, 2021).

This process of intensification and extensification of agriculture has left among the main consequences and challenges to solve pollution, soil erosion, biodiversity losses, deforestation of tropical rainforests, and threatens to human health and its food security (Foley et al., 2005; Gibbs et al., 2010; Rodrigues et al., 2013).

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[1] Most of this chapter has been published as an article co-authored with J. Infante and E. Tello (Urrego-Mesa, Infante-Amate, & Tello, 2019). This version includes some changes in the introduction and more significant ones in the discussion.

These challenges summarized in the trilemma of the energy, environment, and food (Tilman et al., 2009), which rise the need to confront the environmental impacts of farming together with the projected rise in the demand for food, feed, biofuels, and other biomass-based resources. The proposals to meet these challenges include improvements in the efficiency of nutrients and water use, the reduction of wastes, and the changes of diets, policies, and agricultural practices (Foley et al., 2011; Smil, 2001; Tilman, Cassman, Matson, Naylor, & Polasky, 2002; Tilman & Clark, 2014).

In this vein, biomass becomes essential to the economy (Ayres, 2007), but it is also crucial to ecosystems restoration and the functioning of the landscapes. The cycling of biomass flows within agroecosystems plays a valuable role in promoting crop productivity, maintaining farm-associated biodiversity, and preserving underground life forms by restoring eroded soils and improving their organic matter content, fertility, and structure. Biomass is also a critical element in nutrient and carbon cycles (Bardgett, 2005; Smil, 1999, 2001). Therefore, the careful management of biomass flows is a key element along the path towards more sustainable forms of agriculture. Thus, a better understanding of the historical roots of the changes in biomass production, appropriation, and uses are essential to plan the management of the biomass chains and their role in the design of agroecosystems.

The most used approach when it comes to analysing biomass flows at national scales is the human appropriation of net primary production (HANPP) (Haberl, 1997; Haberl et al., 2007; Vitousek, Ehrlich, Ehrlich, & Matson, 1986) which is defined “as the aggregate human–based effect of land–use induced changes in productivity and biomass harvest on the energy availability in ecosystems” (Schandl et al., 2002, 48). Although HANPP provides an assessment of human intervention in the biosphere, even in the long run (Krausmann et al., 2013), it does not provide a detailed picture of the whole Net Primary Production (NPP) chain flows and the works using this methodology focus mostly on Europe(S. Gingrich et al., 2015).

In another way, material flow accounting (MFA) has become a standardized methodology for the study of the extraction and use of material flows, including biomass (Bringezu & Schütz, 2001; Eurostat, 2009; Fischer-Kowalski et al., 2011), but it is also not without problems. Biomass accounting in MFA does not always go into the details of biomass production and ignores the belowground flows of biomass as well as the biomass in circulation, which stands up useful for the studies at the national scale of the agrarian sector from an agroecological point of view. Biomass accounting has been directly or indirectly used in several case studies such as in Spain (Soto et al., 2016), Finland (Risku-Norja, 1999; Risku-Norja & Mäenpää, 2007), Czechoslovakia (Kovanda & Hak, 2011; Kuskova, Gingrich, & Krausmann, 2008), and even on a global scale (Krausmann, Erb, Gingrich, Lauk, & Haberl, 2008; Wirsenius, 2003). Although all of these studies have provided additional indicators on production, use, or input consumption, none of them focuses on developing economies, and just three provide a long term historical perspective. Thus, aggregate accounting, Eurocentrism, and short–term readings predominate when it comes to the understanding of the biomass flows of the agroecosystems.

Addressing this gap, this chapter presents a long-term estimation of the biomass flows in a developing and tropical country. We contribute with new data on NPP and biomass extraction from the cropland, pastureland, and forestland up to its final uses between 1915 and 2015 in Colombia. Our main goals is to provide a biophysical reading of the socio–metabolic transition carried out along the twentieth century by Colombian agriculture. We draw up a century-long annual series converting a wide set of indicators from net primary production (NPP) into the final socioeconomic uses of biomass, distinguishing around 200 different categories of crops, forests, and pastures. Our calculations draw on FAOSTAT (2021) and several corpuses of national statistics.

The results show a fall of 10% in total NPP related to land-use changes involving forest conversion. Throughout the twentieth century, pasture was the most relevant among domestic extraction. Besides, allocations of cash crops to industrial processing rose while the figure for staple crops for primary food consumption stagnated. The critical role of cattle throughout all periods and the higher yields of the industrial cash crops are behind this profile. Thus, we discuss these features in the light of, first, the changes in the contributions of extensification, intensification and cropland composition to the agricultural output; second, the institutional bias towards extensive cattle rearing and commercial agriculture from the agrarian policy; and third, the socio-ecological impacts of industrial agribusiness and deforestation.

Colombia represents a fascinating case study within Latin America for the socio-metabolic study of biomass flows because of its size and ecological relevance. The country is representative of a medium–sized economy in the region. GDP (at current US$) in the country in 2016 was around 282 billion, which is very close to Chile (247), twice bigger than Ecuador, Paraguay, Bolivia, and Uruguay, and half of the GDP of Argentina. Concerning the population, after Mexico, the country is the second largest with 48 million inhabitants. It is comparable to Argentina (43), Peru, and Venezuela (31) (WB, 2021b). Lastly, and more importantly, the country is the second largest biodiversity reservoir around the globe. Following the data from Biodiversity Information System in Colombia SiB, the country occupies the first place in birds and orchids, the second in plants, amphibians, butterflies, the third in reptiles and palms, and the fourth in mammals. Biological variety is the result of the differences among its ecosystems, including tropical forest in the Amazon and Chocó, mountain ecosystems in the Andes, or grasslands and meadows in the East of the country (Steinmann et al., 2017a), this is why biodiversity loss and its conservation in Colombia is a global issue.

The study of the biomass flows during the twentieth century in Colombia, therefore, helps to set the material bases of the tropical agriculture of an exporter and developing economy of Latin America into the framework of the socio–ecological transition of western agriculture, while also gives some clues on biomass management. This could be a starting benchmark for future research in these contexts.

The remainder of the article is structured as follows. The second section explains the methodological approach, sources, and treatment of data. In the third section, we present the main series on land uses, NPP by types of land cover, the extraction and the uses of biomass, livestock figures, and crop yields. Lastly, we discuss the results in light of the main phases of the socio-metabolic transition its contributing factors and offer an initial exploration of the institutional drivers of the process of transition.

2.2 METHODOLOGY AND DATA

2.2.1 Methodological approach

MFA provides a broad set of indicators, including domestic extraction (DE), the physical trade balance (PTB), and domestic material consumption (DMC), by identifying four major material categories: biomass, construction minerals, fossil energy carriers, and ores. MFA is considered a good proxy for environmental impacts (Heijungs, 2017; Steinmann et al., 2017a, 2017b), as it helps us understand the material bases of economic development and has proven useful in the study of socio–ecologically unequal exchange (Giljum & Eisenmenger, 2004; Muradian & Martinez-Alier, 2001a, 2001b, 2001c). The long-term analyses made so far cover the crucial change from solar–based to fossil–based systems throughout the twentieth century in the United Kingdom (Schandl & Schulz, 2002), Austria (Krausmann, Schandl, & Sieferle, 2008), Japan, the United States of America, Czechoslovakia (Kovanda & Hak, 2011), and Spain (Infante-Amate et al., 2015). The "medium–term" approach is the most common in the analysis of less developed countries (LDCs). Since 1960-–1970, socio–metabolic studies have been conducted for India (Singh et al., 2012), the Lao People's Democratic Republic (Vilaysouk, Schandl, & Murakami, 2017), Chile, Ecuador, Mexico, Peru (Russi et al., 2008), Brazil, Venezuela, Bolivia (Amann, Bruckner, Fischer-Kowalski, & Grünbühel, 2002), and Colombia (Pérez-Rincón, Vargas-Morales, & Crespo-Marín, 2018; Vallejo, Pérez Rincón, & Martinez-Alier, 2011).

These works offer a comparative view of the pressures associated with material extraction in the world regions examined. They stress the role of LDCs as exporters of materials and energy carriers from the 1970s onwards (Behrens, Giljum, Kovanda, & Niza, 2007), income growth as the main driver of the per capita increase in global material use, and the large gap in material living standards that exists between developed countries and the rest of the world (Schandl et al., 2016, 2017; Steinberger, Krausmann, & Eisenmenger, 2010). However, in the MFA framework, biomass is only an item in the aggregated flows of national extraction from natural systems. Aggregated MFA indicators may be dominated by just one material category like copper in Chile (Giljum, 2004) or fossil fuels in Saudi Arabia (Schandl et al., 2017). In these cases, the analysis fails to shed light on the role of other groups of materials or economic sectors and their environmental impacts. In consequence, the estimation of biomass flows within MFA approaches tend to be very narrow and simplified. Therefore, it does not capture the complexity of production, the extraction, and the final use of biomass flows.

We identify four items in which MFA accounting fails to provide a detailed picture of the biomass flows in a given economy where the changes in production and use of biomass may entail an environmental burden.

- MFA approach focuses on extraction, not in production, so it is no possible to assess the actual impact of extraction.
- MFA only considers aboveground flows and not the belowground ones despite its ecosystem functions (Guzmán et al., 2014; Smil, 2013).
- MFA does not provide a homogenized system to measure the biomass flows. Only in the case of pastures, the methodology suggests quantifying the flows in dry matter while the rest of biomass flows are accounted in fresh matter (Eurostat, 2013).
- MFA approach does not consider the biomass flows that recirculate nor the final uses of all the extracted biomass.

For the reasons above, we account for a set of biomass flows by drawing on recent methodological proposals for the study of energy and material flows in both present–day and historical agroecosystems (Galán et al., 2016; Guzmán et al., 2014; Guzmán & González de Molina, 2017; Tello et al., 2016). First, we estimate actual net primary production (NPPact), understood as "the sum of harvested NPP, as reported in statistics, and other fractions not recorded in agricultural statistics" (Haberl et al., 2007, 12946). The NPP of agro–ecosystems takes into account the share of NPP used for humans (food, feed, fibers, and fuel), and the fraction of NPP remaining and used in the reproduction of other species living in the agro–ecosystems (Guzmán & González de Molina, 2017). NPP accounting is the addition of the main plant product (P), usually labelled "gross agrarian production", the associated by–products or residues from crops (CR), i.e., the rest of the aboveground production of the plant, the NPP of weeds (W), the belowground NPP or roots (R), and, lastly, the accumulated biomass in aerial trunks and branches (A). It can be written as follows.

$$NPPact_{tj} = P_{tj} + CR_{tj} + R_{tj} + W_{tj} + A_{tj} \tag{2.1}$$

In Equation (2.1) t refers to the specific year adopted as the time frame and j to the land use, namely cropland (CL), pasture land (PL), and forest land (FL). The addition of the NPP coming from these land covers also corresponds to the NPPact accounted here and can be written as follows.

$$NPPact_{t} = CL_{ti} + PL_{ti} + FL_{ti} \tag{2.2}$$

The i in Equation (2.2) is the cover type of each land use e.g., maize, oil palm, or other crops, in the case of crops, pasture and shrubland for pasture land, and the types of forest detailed below.

Finally, we conduct an additive decomposition analysis based on B. W. Ang (2005) to understand the factor contribution of extensification (E), intensification (I), and crop composition (Cp) on the variations of the agricultural output (AO). Where E is the area devoted to crops in hectares (Ha), I correspond to the land yields of each group of crops $_i$ ($\frac{AO_i}{Ha_i}$), and Cp is the mix composition of the cropland ($\frac{Ha_i}{Ha}$).

Therefore, the changing variations in AO between year 0 and year t can be decomposed as:

$$\Delta AO = AO^t - AO^0 = \Delta E + \Delta I + \Delta Cp \tag{2.3}$$

Following B. Ang and Su (2016), the decomposition formula for each factor is.

$$\Delta E = \sum_i L(w_i^t - w_i^0) \cdot ln(\frac{E_i^t}{E_i^0}) \tag{2.4}$$

$$\Delta I = \sum_i L(w_i^t - w_i^0) \cdot ln(\frac{I_i^t}{I_i^0}) \tag{2.5}$$

$$\Delta Cp = \sum_i L(w_i^t - w_i^0) \cdot ln(\frac{Cp_i^t}{Cp_i^0}) \tag{2.6}$$

Being w:

$$w_i^t = \sum_i \frac{AO_i^t - AO_i^0}{ln(AO_i^t) - ln(AO_i^0)} \tag{2.7}$$

2.2.2 Sources

The data were gathered from official and secondary sources for the first half of the century and FAOSTAT (2021) for 1961 to 2015. The main categories covered were farming active population, total population, crop production, livestock numbers, and land use. From the population data, we used the decennial census and FAOSTAT (2021) to arrive at the shares of agricultural and urban population. However, for the total population, we used the corrections made by Flórez Nieto and Méndez (2000). Cropland, crop production, and livestock data were gathered from 1915, 1933, 1934, and 1937 Statistical Yearbooks (DGE, 1915, 1933, 1934, 1937), supplemented by reports to the US government that provide data for 1925–1928 (Wylie, 1942) and 1948–67 (Atkinson, 1969). For 1925, there is information on production from Sanchez Santamaria (1925), Diot (1976), the Revista , and Bejarano (2011). Between 1934 and 1946, the primary source is Varela Martínez (1949). The production series for twelve crops (1915–50) and cattle (1915–97) offered by Kalmanovitz, López, Romero, et al. (1999) were also used with the latter being supplemented after 1997 by figures from FEDEGAN (2021).

Data on the land-cover forest were derived from the figures on deforestation of Etter et al. (2008) and land-cover figures of the forest in 1990, 2000, 2005, and 2010–15 from IDEAM (2018) and Pizano and García (2014). In this way, we distinguish between tropical dry forest, Rainforest, Andean forest, and others forest covers. As example, in 1996, the other's category included the fragmented basal forest, the riparian forest, the planted forest, mangroves, and other minor covers (Leyva et al., 2001, 284). We gathered pastureland figures for 1915, 1950, 1960, and 1970 from the DGE (1915), Varela Martínez (1949), and the agrarian census (DANE, 1964, 1974), respectively. As of 1992 we used the addition of grassland and shrub-covered categories from the annual land cover maps (1992—2015) produced by the Université Catholique de Louvain (UCL)-Geomatics for the Climate Change Initiative (CCI) in FAOSTAT (2021) since the values for 2013 are very close to those for land covers obtained from the agrarian census for 2014. Series for the forest wood production are available in FAOSTAT (2021) "Forestry" from 1961 to 2017, and firewood series from 1975 to 2016 in UPME (2017). For the period before 1961, we relied on data on wood exports collected for 1916, 1922, 1923, 1938, 1945, and 1955 from the Statistical Trade Yearbooks (DANE, 1955a; DGE, 1916, 1923, 1938b, 1945).

2.2.3 Data processing

Between 1915 and 1960, the series covers 30 crops and one aggregate category for fruits other than bananas and plantains. The entirety of production in our assessment for 1960 reaches 87% of the production of the FAOSTAT database for 1961. It is from 6.1 Mt dm in 1960 to 7.1 Mt dm in 1961. After 1961, we rely on FAOSTAT (2021) “Crops Production” database. Annual area and crop production missing values between 1915 and 1955 were obtained using linear interpolation, per-capita variables or adjusts in the original data (see section A.2 in appendix A). The results were checked with the available yields obtained from sources for the years either side of the one being considered and with the yields of other Latin American countries during this period such as Argentina (1909, 1925–26) (MA, 1910, 1926), Costa Rica (1925, 1927) (DGEC, 1926), Cuba (1945) (MAC, 1951), Ecuador (1938–42) (DNE, 1944), Bolivia, Brazil, Chile, Peru, and Venezuela (1949) (UNECLA, 1953).

Using the scientific literature, we calculated the by-products or residues and the biomass roots of each crop, differentiating between traditional and conventional varieties when such information was available. We also differentiated between the biomass of weeds associated with crops depending on the type of farming management that prevailed throughout the century (traditional, low-input and conventional). All these flows were reduced to dry matter content and expressed in tons. The information on conversion factors was compiled from Guzmán et al. (2014) and Montero (2018), which is being expanded to achieve the aims of the study by going into depth in the literature review (see tables A.2 and A.3). Lastly, to match the two series (pre-FAOSTAT and FAOSTAT) and, to simplify our analysis, the crops were aggregated into 27 categories and then re-aggregated into 10 final categories: cereals, pulses, root & tubers, vegetables, fruits, oil crops, fiber crops, stimulants, sugar & sweeteners, and other plant products (see table A.5).

In the case of forest land, we break down the aggregation of “forest´´ data into the rainforest, the tropical dry forest, the Andean forest, and another forest cover. The latter was calculated by subtracting specific covers from the general forest. Given the lack of available data before 1961, forest cover was estimated by using the rates of change in the historical series of forest clearing in Colombia calculated by Etter et al. (2008) (see table A.6). This back projection uses, as its starting point, the series of forest covers made available from the 1990s onwards thanks to satellite images. The NPP of each type of forest was calculated by applying productivity factors and to the area by the type of forest (see table A.4). Domestic extraction figures are the result of matching the series for wood production (removals) and firewood FAOSTAT (2021); UPME (2017). For the period before 1961, we used the series resulting from the Statistical Trade Yearbooks (DANE, 1955a; DGE, 1916, 1923, 1938b, 1945), which have been matched with (FAOSTAT, 2021)[2]. We have also adjusted this series for the period before 1975 with the available data for per-capita firewood consumption

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[2] A reviewed version of the extraction from forest was conducted for the energy balances. See 5.2.2

in rural areas for that year, which was adjusted by comparing the proportion of the rural population with the figure for the total population between 1915 and 1975.

In the pastureland, we identify two main categories: pasture, understood as the amount of land allocated for grassing, and shrubland & others, which is known as a mixture of land for grassing and secondary vegetation resulting from the changes in the forest use. For the first category, we figured the cattle density for the years with available data from 1950, 1960, 1970, and 1992–2015 (table A.7). We got the missing years using the steady ratios by periods including 1915–50, 1951–60, 1961–70, and 1971–92. When figures for the areas of crops, fallow, forests, pastures, infrastructures, other lands, and land area were available, the residue was labelling "shrubland & others" We positively validated our estimations by reviewing other available sources: "permanent meadows and pastures" from FAOSTAT (2021) for 1961–2015, the values of the land-cover map for 20102012, and the agrarian census for 2014 (DANE, 2014) (see section A.5.2)
.

We obtained NPP for tropical and seeded (or improved) grasses using the NPP productivity factors in the literature (see table A.4). The extraction of grassland is equal to the total animal feed requirements minus animal feed from crops, imported feeding, and a fixed percentage of crop residues taken from Wirsenius (2003). To calculate animal feed intake, we employ nutritional requirements for cattle, pigs, sheep, goats, horses, mules, and donkeys in respect of their weights (Borda & Ramírez Nader, 2003; Mamoon, 2008; NRC, 1985, 1998, 2003). Where possible, we adjusted these weights historically (DANE, 1955a, 2018; DGE, 1916, 1923, 1938b, 1945; Hertford et al., 1982; Varela Martínez, Palacio del Valle, Cañón, & Ramírez, 1952; Wylie, 1942) (see table A.8 and A.9). We additionally test the results by performing a sensitive analysis of our series and a comparison with the existing series on biomass extraction (see section A.6.3). Seed, feed, and imported feeding were retrieved from FAOSTAT "commodity balances" as of 1961. Since we do not have data on seeds and animal feeding before 1961, we assume the same percentage as the one retrieved from FAOSTAT from 1961 to 1963.

Regarding the final uses, we distinguish five categories, namely: animal feeding, wood and fuelwood, recycled biomass, cash crops, and staple crops. Animal feeding is the addition of the residues use as feed, the feed from crops, and the extraction from pasture. Wood and fuelwood include the removal of wood, firewood, and charcoal. Recycled biomass is composed by the piece of crops allocated to seeds and the crop residues not included in the animal feeding. Crop production is split in cash and staple crops. The former includes fibers, oil crops, the piece of sugarcane allocated to the industry to be processed, and the production of the stimulants category. The latter is the addition of cereals, pulses, tubers, vegetables, fruits, and the piece of sugarcane used directly as food.

2.3 RESULTS

2.3.1 Land use changes

Colombia's land area is 110 Mha, the main cover being forests with an average proportion of 54% between 2005 and 2015 (60.1 Mha average). However, at the beginning of the twentieth century this figure was 68% (76.2 Mha), and it was consistently higher than 65% (72 Mha) until 1964 (see Figure 2.1). The area under the forest fell from 76 to 59 Mha during the twentieth century. This average loss of 22% was more profound in the case of the Andean forest than in any other forest cover, especially since the 1970s, due to the historically higher population densities in this region (Etter et al., 2008; Etter & van Wyngaarden, 2000). The share of the Andean forest over the total land area fell more than half, from 19% to 8%, during that period. The tropical dry forest has represented a tiny part of the whole forest area and, although its deforestation has slowed since the 1970s (Etter et al., 2008), it is at risk of disappearing entirely (Pizano & García, 2014). The rest of forest covers have stayed almost constant at around 12 Mha.

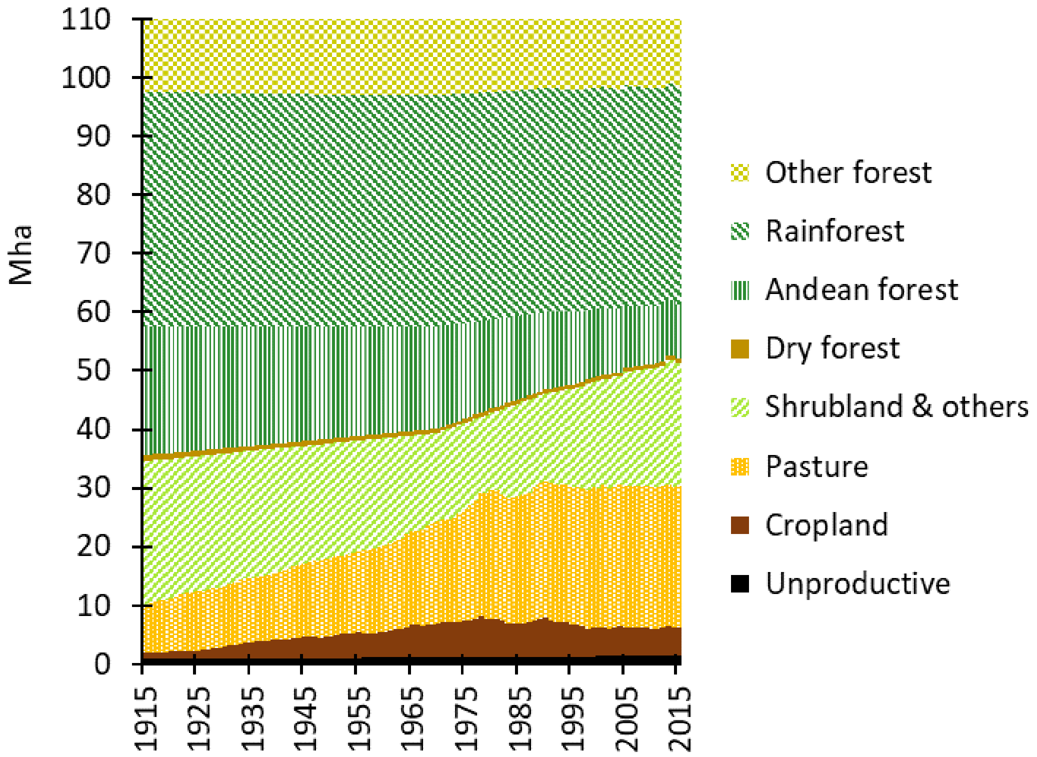

Figure 2.1: Land uses by groups in millions of hectares from 1915 to 2015. Source: own calculations from the sources given in the text.

The categories of pasture and shrubland & others combined represent the second largest type of cover, which accounts, on average, for a third of the land area during the 1915 to 1984 period, but, by the mid-1970s, this figure rose and presently represents more than 40% of the total land area. Pasture and shrubland increased the area from 32.6 Mha in 1970 to 45 Mhas in 2015, but it is worth remembering that, in our series, the shrubland & others land use is a residual category whose fluctuations reflect the dynamics of the other types of land cover. However, it has some interesting features. Between 1915 and 1980, it fell from 21% (24.5 Mha) to 12% (13.2 Mha) due to the expansion of cropland and pastureland. After the 1980s, shrubland and others recovered and reached 19% (21 Mha) in 2014 while cropland stagnated and the growth in grass pasture slowed. At the beginning of the period, the pastureland represented only 8% (17.3 Mha) of total land area. It doubled during the 1970s and since the early 1990s covers more than 20% (24 Mha in 2015) of the total land area.

Lastly, although the area under cropping is only a small part of the total land area, its change is even more significant than that of pasture. The cropland experienced a four-fold increase between 1915 and 2015, which moved up from 0.9 Mha (1% of land area) to 5 Mha (4%) and reached its highest point in 1978, 6.9 Mha (6%). The process of cropland expansion was more intense during the first half of the century (1915—64), with an annual rate of growth of 3.6% than during the second half (1965–2015), when the growth stagnated. The intensification of agrarian production under industrial management and increases in imports of staple food items are the main factors behind the stagnation of the agricultural frontier, which we will discuss below.

Regarding the area harvested by crops (Figure 2.2a), we can divide the frontier expansion into three sub-periods. In the first two periods, intensive ploughing is observed. From 1915 to 1944, the cropland annual growth was 4.5% and, from 1945 to 1974, it was 1.5%. However, after 1975, the agricultural frontier stagnated, with an average annual rate of growth of only 0.3%.

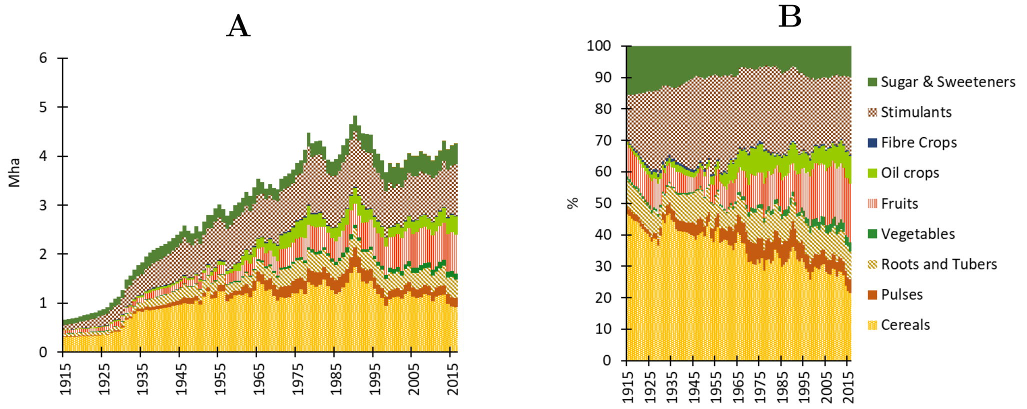

Figure 2.2: (a) Area harvested by groups of crops in millions of hectares and (b) as a percentage between 1915 and 2015. *Source*: own calculations from the sources given in the text.

By looking at crop compositions, we observe that staples have traditionally been the largest crop group. Their percentage over total cropland area has barely changed during the analysed period, which moved from 55% to 43%. However, if we focus on cereals, we observe a sharper drop (Figure 2.2b). Between 1915 and 1954, cereal crops occupied more than 40% of the area harvested. Afterwards, their share lost importance by up to 27%. From 1915 to 1960, the reduction in the proportion of arable land devoted to cereals was offset by the increase in the production of stimulants, especially coffee, which moved from 11% to 29%. However, the share of land under coffee plantations fell after that date and reached 20% of the cropland area in 2015. Fruit crops (both traditional and new ones) and oilseed crops have filled the gap left by the contraction in the cropland areas of coffee and cereals. Among oilseeds, the oil-palm fruit stands out and has expanded since the late 1980s with a share of 8% of the total area harvested at present.

2.3.2 The Long-term trend of the NPP

During the whole period, the NPP experienced a 10% reduction from 2 Gt in 1915 to 1.8 Gt in 2015 (Figure 2.3a). Between 1915 and 1994, the annual rate of change was, on average, -0.13%. However, after that year, it fell to -0.04%. In other words, although we observe a long-term pattern of decline in NPP, as of the 1990s it stagnated. Nevertheless, the volatility of the short-term variation of the NPP increased during the second half of the century. The standard deviation of the annual rates from 1915 to 1964 was 0.07%, but it more than doubled from 1965 to 2015 (Figure 2.3b).

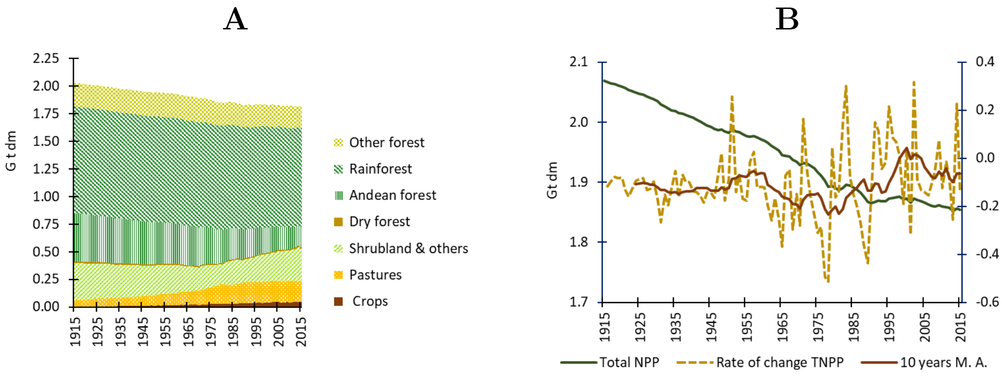

Figure 2.3: (a) NPP by groups in giga-tons of dry matter, 1915–2015. (b) Total NPP in giga-tons of dry matter, rates of change, and 10-year moving average in percentage (right axis), 1915–2015. *Source*: own calculations from the sources given in the text.

The weight of the NPP in forest lands dominates the composition of the NPP. It comprised 80% of the whole NPP until 1974, but from 1975 to 2015 its share fell from 78% to 71%. However, there have been sharp disparities in the trend and composition of the different types of forest. The main component of the whole NPP in forest lands is rainforest, which is the most productive and the primary land cover in most of the country. Although its area has been reduced, its NPP contribution to the total has stayed almost constant at near 50% of total. Conversely, the Andean forest reduced its NPP share by half, from 21% to 11%, which is in absolute numbers a drop from 434 to 184 Mt during the period.

The NPP of pastureland and shrubland, where there is also secondary vegetation, fell from 19% to 18% between 1915 and 1974. This slight reduction corresponds to the shrubland NPP falling from 22% to 13%, or from 487 to 298 Mt in absolute figures, and a rise in the pasture NPP from 3% to 7%. After 1975, these figures recovered somewhat from 11% to 15% of the total share of the NPP up to the end of the period. This trend was different to the one of forest, especially the 10% reduction in the Andean forest NPP. Although pasture and shrubland NPPs rose by 0.75% during this last period, the gains were driven by increasing shrubland. Then, pasture NPP mainly took place during the first period, while the recovery of shrubland and secondary vegetation occurred during the second period.

The increase of the extraction from the cropland as share of the NPP was smaller, this rose from 0.2% in 1915 to 2% in 2015. However, the growth of the NPP of crops was the most dynamic 3% for the whole period, even more than pasture, which means a nearly fifteen-fold increase throughout the century (from 3 to 44 Mt). By grouping this increase in 10-year periods we can distinguish three different sub-periods of growth: firsts, the most exceptional period at 4.5% average annual rates (1915–44); second, from 1945 to 1974, when there was a slight reduction to 3%, and finally, a period of lower growth of around 2% average annual rates between 1975 and 2015, and the downtrend at the beginning of the 21st century (Figure 2.4a).

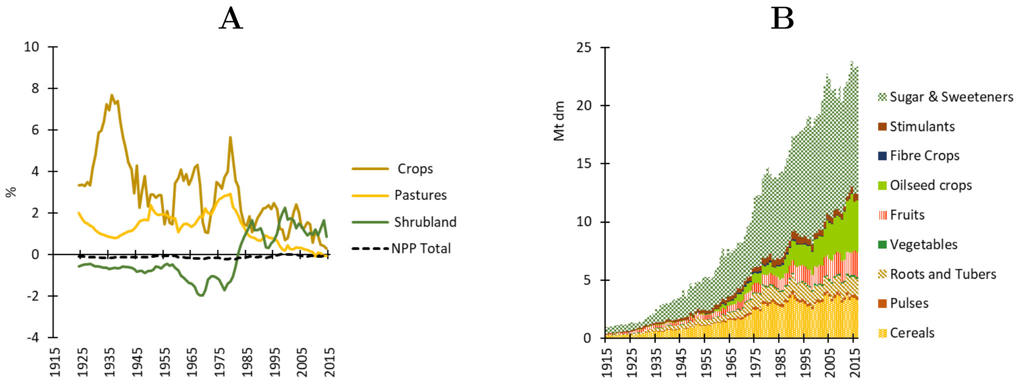

Figure 2.4: (a) Rates of change in NPP for cropland, pastureland, shrubland, and total NPP. Mobile 10–year average. (b) Crop production by groups in millions of tons of dry matter, 1915–2015. *Source*: own calculations from the sources given in the text.

By groups of crops, the most basic division into temporal and permanent crop production initially seems favourable to the second group. Staple food crops such as cereals, pulses, tubers, and vegetables shared on average 30% of NPP production in cropland during the whole century while cash crops like fruits, oilseed crops, fibers, stimulants, and sugar were the other 70% (sd. 4.5). Although the first feature that stands out is the importance of sugar and sweeteners with an average share of 50% and no so much changes (s.d 5), in the long term stands up the reduction of basic grain production which fell from 22% in 1915–24 up to 16% in 2005–15 and the rose of permanent crops such as the palm oil which increased from 7% in 1965 to 17% at the end of the period.

2.3.3 Final uses of the NPP extraction

Domestic extraction (DE) of biomass nearly three-folded during the period. Meanwhile, total NPP fell by 10%. Consequently, the DE share of total produced phytomass increased from 1% to 6%. Of this total, the grassland experienced the most significant degree of extraction with a share of 70% on average throughout the whole 1915–2015 period. However, the share of grassland fell from 80/70% before the 1960s to 60% in the 2010s (Figure 2.5a and 2.7). The second largest extraction was of crops, which is a third of total DE in the last several years. In the long run, the categories in the second position of DE components experienced a switch. From 1915 to 1960, this position was occupied by forest extraction, but from 1970 onwards, the increasing trend in crop extraction surpassed the share of forestry. After this tipping point, forest extraction fell from 17% to 7% in 2015. This process was driven by the reduction in fuelwood consumption and the transition to “modern” energy carriers, which are mainly fossil fuels Pérez-Rincón et al. (2018).

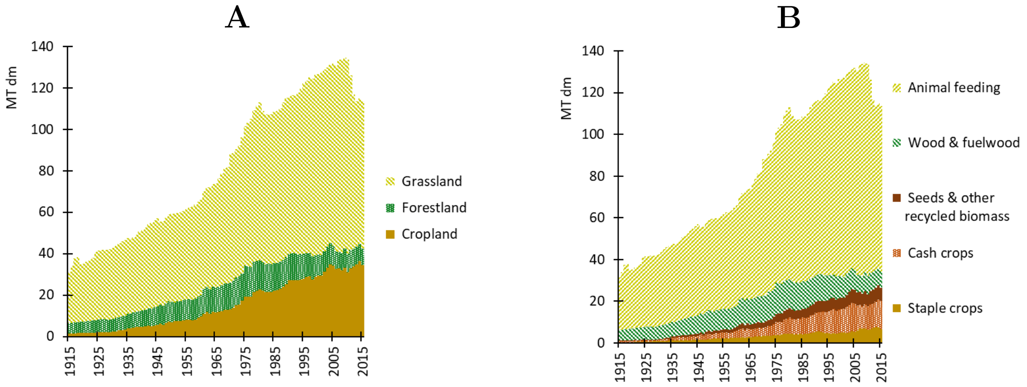

Figure 2.5: (a) Domestic extraction and (b) final uses of biomass in millions of tons of dry matter, 1915–2015. *Source*: own calculations from the sources given in the text.

The uses of biomass extracted from Colombian agriculture also reveal the importance of the biomass devoted to animal feed (Figure 2.5b and 2.6a), especially that from pastureland grazed by cattle. Although the composition of the livestock intake included significant amounts of crop production, residues, and even imports as contributions to the supply of animal feed, pasture dominated the nutrition of herds by far, particularly cattle, the central element in livestock composition (see 2.3.4). The pasture was nearly the only source of feed until 1970. After this date, its share fell from 99% to 88% in 2015, since the increase in crop yields also reported on more residues to feed the livestock. In a lesser extend, feed imported also began to rise, but this represented only 5% of the biomass used extracted from domestic agroecosystem (see section 5.3.1 for details on imported feed).

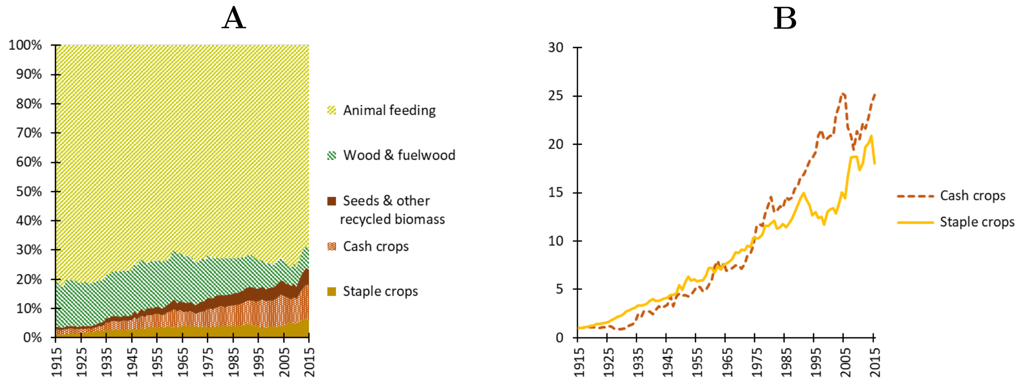

Figure 2.6: (a) Final uses of biomass extraction in percentage and the (b) index of the biomass devoted to primary food and processing industries, 1915=1 (1915–2015). Source: own calculations from the sources given in the text.

If we go more deeply into the uses of cropland extraction, the most relevant feature is that primary foodstuffs like cereals, pulses, tubers, or vegetables represent a smaller component than the biomass flows from the cash crops such as fibres, sugarcane, or oil-palm fruit (Figure 2.6a and 2.7). Only after the food crisis at the end of the 1920s did the amount of primary food for human consumption exceed the amounts of biomass produced in cash crops. At that time, biomass flows of both primary foodstuffs and for market purposes were 3% to 4% of the whole DE, respectively. In 2015, the biomass flows extracted from cash crops shared 13% of the total DE, while primary food remained at around 6%.

The primary staple food rose in absolute terms from 0.3 to 2.3 Mt until 1950–1960, when it achieved a share of 4% of DE. Subsequently, this share remained almost flat, at 4–5% up to 2010, when experienced a slight increase. The biomass devoted to the processing industries through the markets ran almost parallel to that used for primary food until 1970. Yet, with a slightly lower index, until 2015, its share rose from 5% to 13% at a higher rate than staple food (Figure 4.5b).

2.3.4 Livestock and cropland intensification

The two main long-term features in the flow metabolic pattern of Colombian agriculture have been the dominance of animal feeding extracted from grassland, especially for cattle, and the dynamism of the cash crops through the industrial

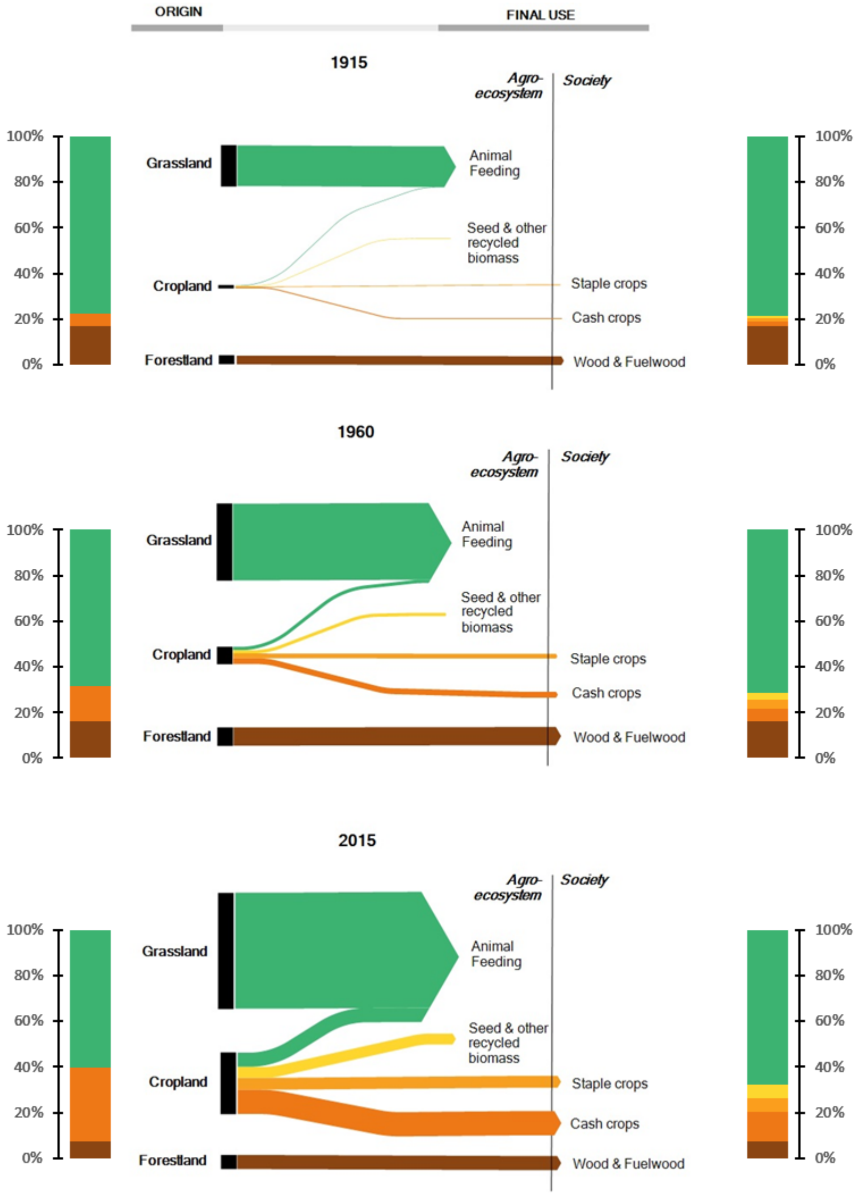

Figure 2.7: Biomass flows from domestic extraction to final uses. Millions of tons of dry matter, and its share for 1915, 1960, and 2015. Source: own calculations from the sources given in the text.

intensification of farming. Measured in live units of 500 kg (LU), the national livestock herd rose two and a half times from 5 to 17.5 LU between 1915 and 2015 (2.8) moving from a density of 0.15 LU/ha of grassland to 0.39 LU/ha in 2015. This increase is due practically entirely to the growth in cattle numbers, which accounted for more than 80% of total livestock throughout the period (from 4 to 14 LU).

Compared to other regions, the livestock per capita (LU/cap) in Colombia between 1915 and 1943 remained higher than the average of Latin America (the second largest in the world) in 2000 (0.82 LU/cap), but thereafter this portion dropped up to 0.37 LU/cap, which is a bit higher than the global average (0.34 LU/cap). In terms of land, however, the livestock density (measured as the LU on the area of the country) stands up the increase of the livestock which moved from 0.04 LU/ha in 1915 to 0.16 LU/ha in 2015. such a difference is comparable to the difference in the year 2000 between North or West Africa and the global average, and compare with the Latin American region in 2000 (0.21 LU/ha), livestock system looks like more extensive, especially since the beginning of the 21_{st} century when began a slight reduction.

The reasons for this reduction of national herd are related to the increasing prices of meat since 1991 (FAOSTAT, 2021), which led to a fast reduction of cattle stock as well as the increase of violence that rose from the kidnapping of breeders and from cattle thefts (Kalmanovitz & López, 2006). The number of kidnappings in Colombia increased from 442 to 3,456 during 1995–2000 and remained at 1,356 kidnappings a year on average from 2004 to 2010 (CNMH, 2018). Lastly, the main long-term changes in livestock composition have occurred with the fall in the number of mules and donkeys, and the increase in pigs and poultry in both absolute and relative terms.

Regarding crop intensification, the indices of domestic crop extraction and area harvested show a close relationship between 1915 and 1945/55 (Figure 2.9a), which means that land productivity remained relatively stable. During this period, the increase in production was very land (and labour) dependent. However, after 1955, and especially from 1970 onwards, production growth decoupled from the land. Since then, increases in yield have driven the DE trend for crops since the 1990s when the area harvested fell. The average yield of the total biomass extracted per unit of cropland more than doubled between 1915 and 2015 and rose from 1.4 to 5.5 tons of dry matter per hectare. Although there had been some increases in these average yields during the 1930s, the actual change in the trend in yields took place from about 1950 onwards and accelerated until 2000, after which the average yield stagnated (Figure 2.9b).

Yield trends differed between staple crops and cash crops. The yields of cereals not only remained under average, but they also grew less than those of cash crops such as sugar and oilseeds. Although there was a take off in the yields of cereals

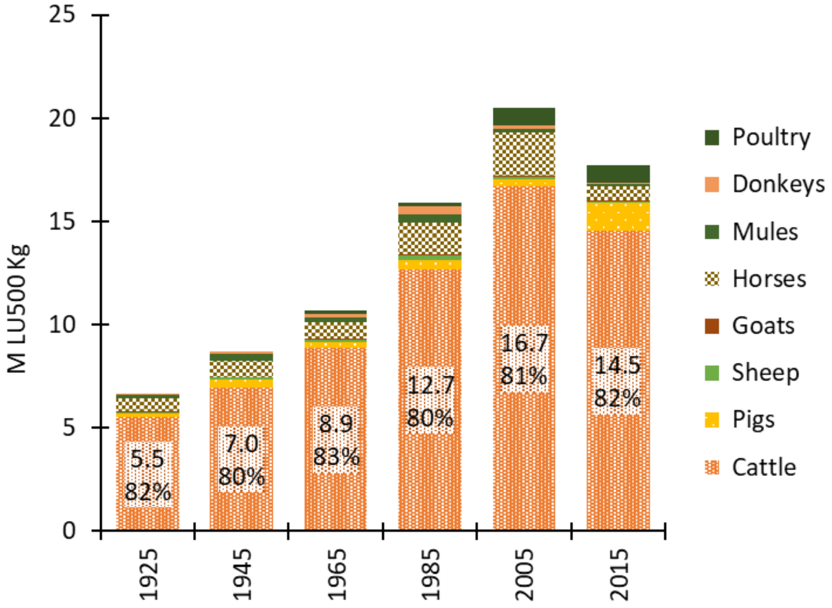

Figure 2.8: Livestock in millions of LU 500kg in benchmark years (1925-2015). *Source*: own calculations from the sources given in the text.

between 1960–75, this growth was suddenly interrupted thereafter around 2.1 t/dm/ha between 1975 and 1995. In the case of sugar crops its yields rose since the 1930s, moving from 3 to 26 tons of dry matter per hectare between 1930 and 2015.Sugarcane became by far the most intensive crop, but its yields have remained at that ceiling since 1979. Intensification of oilseed crops, however, occurred later; after 1950, the yields of this group of crops passed from 0.6 to 11.6 tons of dry matter per hectare in 2015, being the major change during the 1990s due to the arise of oil palm.

2.4 THE SOCIO-METABOLIC PROFILE OF COLOMBIAN AGRICULTURE

Land availability, productivity, livestock, trade, population density, and increases in incomes are among the main drivers of the changing patterns of biomass use (Krausmann, Erb, et al., 2008) and HANPP (Krausmann et al., 2013) identified both globally and nationally. Studies of land use and cover change (LUCC) carried out both nationally and regionally in Colombia have identified similar socioeconomic variables to explain the expansion of the agricultural frontier and its impacts on deforestation. In older settlement areas of the Andean mountains, high population densities and intensive forms of agriculture have transformed Andean ecosystems. Moreover, cattle-grazing appears to have been associated with extensive forms of land use, low population densities, and impacts on tropical lowland forest, especially since the 1970s (Etter & van Wyngaarden, 2000). After clearing, the introduction of pasture is the most common type of

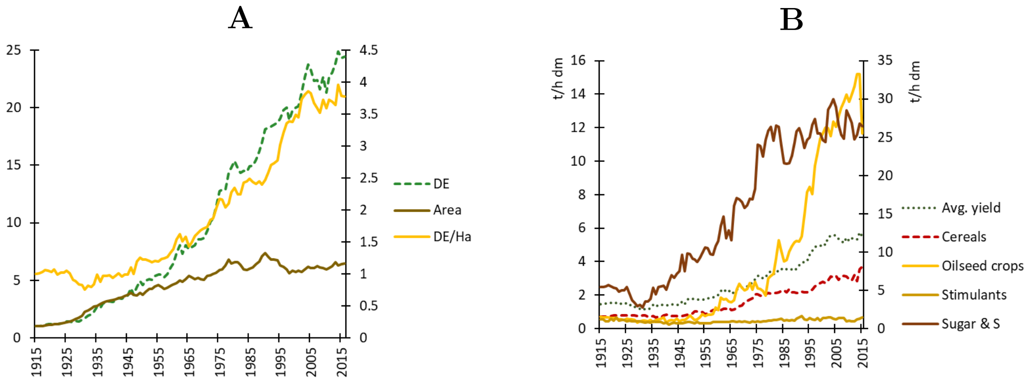

Figure 2.9: (a) The index of biomass extracted from crops and area harvested. DE: domestic extraction from crops and area (left axis) 1915=1. Yields of DE (DE/ha) (right axis). (b) Average yields of the biomass extracted from crops and yields by groups of crops. Sugar and sweeteners at the right axis (1915–2015). Tons per hectare in dry matter. *Source*: own calculations from the sources given in the text.

cover replacement in the lowlands (Etter, McAlpine, Pullar, & Possingham, 2006; Etter & van Wyngaarden, 2000),and, in the long term, extensive cattle-rearing has been responsible for the major transformations in land use country-wide (see Figures 1.7 and 1.1). Together with the extensive amounts of livestock, agrarian intensification and tropical crop production in these lowlands have also become relevant factors in land-use change affecting biomass production.

In the following section, I discuss the socio-ecological changes of biomass production in Colombia, already presented in Section 2.3, by arguing that the predominance of pasture and cash crops in the extraction of biomass and its changes are the result of the institutional bias towards the economic interests of the rural elites. I first propose a periodisation of the socio-ecological transition of biomass extraction based on a decomposition analysis of agricultural output to depict the main factors contributing to its variation. I then focus on the historical roots of the relationships between agrarian policy, cattle-ranching, and commercial agriculture throughout the twentieth century. Finally, I describe the socio-ecological impacts of extensive cattle-ranching and the predominance of cash crops based on the recent literature.

2.4.1 Three phases of biomass extraction

Socio–ecological transitions are historical changes in the appropriation and use of natural resources by societies, including that which took place two hundred years ago and involved the massive use of fossil fuels (Fischer-Kowalski & Haberl, 2007; Steffen, Broadgate, Deutsch, Gaffney, & Ludwig, 2015). However, there are differences in these transitions at the regional (Kander, Malanima, & Warde, 2014) and sectoral levels (González de Molina & Toledo, 2014).In the case of the appropriation of biomass crops in Colombia, we can identify three major

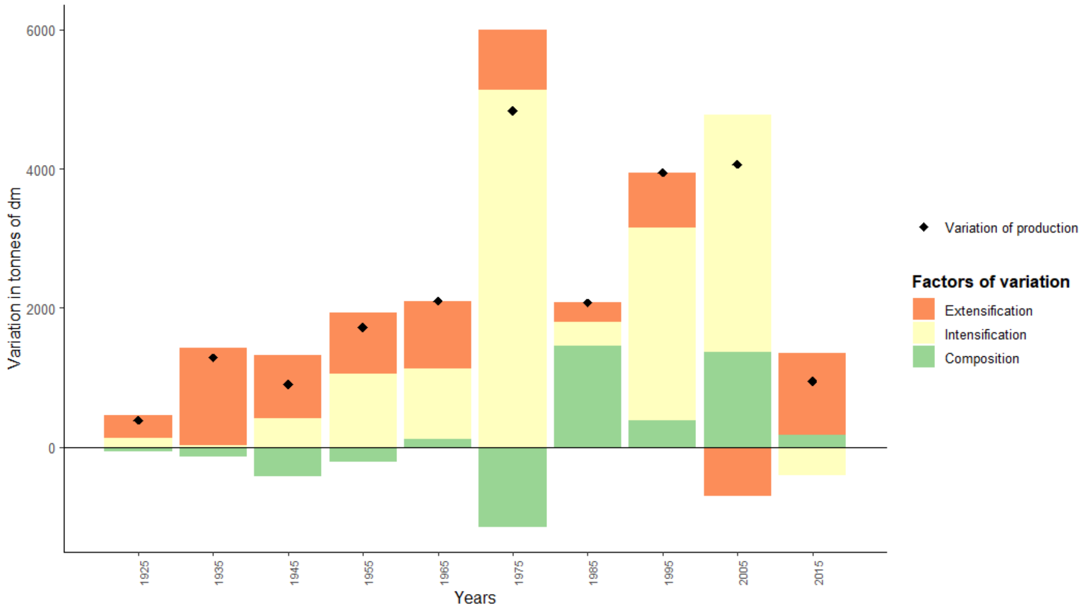

Figure 2.10: Decomposition analysis of the factors of variation of agricultural output by decade (1915–2015). Source: own calculations from the sources given in the text

factors in changing agricultural output, namely the expansion of the agrarian frontier, the increase in yields, and the composition of the cropland. In a decomposition analysis, we identify the contribution of each of these factors to agricultural output throughout the twentieth century. As shown in Figure 2.10, there are three main phases characterized respectively by extensification (1915–45), intensification (1945–75), and change in cropland composition (1975–2005), these being the main sources of the variation of output.

Until about 1945, the profile of the production and appropriation of biomass is that of the pre-industrial organic economies. The main characteristic of these economies is that production was mainly dependent on land (Fischer-Kowalski & Haberl, 2007; Kander et al., 2014).). Most consumption goods came from biomass flows like fuelwood for houses and industries, animal feed to provide power for transport and traction, and food for humans. The severe energy restrictions on long-distance terrestrial transport reinforced the need for close spatial relationships between land use, livestock feeding, and human consumption. Production and consumption were tightly linked geographically (Erb et al., 2009; Sieferle et al., 2001).

In Colombia before this date, grains and roots dominated the production and appropriation of biomass from crops. The area under these crops amounted to 1.2 Mha, which is more than half the harvested area. However, the constraints in agriculture entailed a trade-off between staple crops and cash crops, especially coffee and cereals, which caused a severe food crisis at the end of the 1920s and required the state to intervene actively in agriculture in the 1930s (see Chapter 4).Although there was some room for improving yields,as in the case of highly intensified cash crops like sugarcane and bananas (Bejarano, 2011; Bucheli, 2005, 279–81), the increase in agricultural output during this phase was mainly achieved by taking more land into cultivation. This enlargement of the agricultural frontier deeply affected the Andean forest (Etter et al., 2008; Etter, McAlpine, Wilson, Phinn, & Possingham, 2006),while cattle-ranching gained ground at lower altitudes in order to supply the increasing demand from the cities (Carbó, 1998).

During the second phase, from about 1945 to c. 1975, the expansion of the area under staple crops, especially cereals, stagnated, while the area under cash crops continued to expand. However, the main source of agricultural growth was the wide spread of the yields of cash crops like coffee, oilseeds, and cereals, which intensified as intended by the Rockefeller Foundation (Kalmanovitz & López, 2006). The promotion of the Green Revolution helped the introduction of fertilizers and pesticides (see Chapter 5), but the role of the state was also relevant. Spending by the Instituto Colombiano Agropecuario on agrarian research grew from 0.1% to 0.7% of agricultural GDP between 1965 and 1990 (Kalmanovitz & López, 2006). The result was the decoupling of domestic extraction from the area harvested and the increasing production of biomass in the form of cash crops, as clearly shown in our series. The expansion of the agricultural frontier did not come to an end, but its contribution as the main sources of agricultural growth did. Meanwhile deforestation had already taken half of the NPP from the Andean forests, which was beginning to expand over the lowland rainforests.

After 1975 the changing composition of the cropland became positive to the variations of agricultural output, which relates to the rise of more land devoted to export-led crops like sugarcane, oil palm, and tropical fruits (see Chapter 4) with higher densities of biomass content and energy (see Chapter 5). In parallel, an overall reduction in cropland took place for the first time over the century being analysed. The area harvested was reduced from 4.8 to 4 Mha between 1990 and 2005, intensification being the main source of growth between 1985 and 2005.

Many pieces of research indicate that gains in yields, and even some recent energy-efficiency improvements in the production and use of industrial inputs for farming (Pellegrini & Fernández, 2018), are leading to a new trend in land use involving forest transition (Rudel et al., 2005). However, the Colombian case looks more complex. The last decade of this third phase (2005–15) exhibits negative contributions from intensification and a renewed process of extensification. There was a slight reduction in average yields since the 2000s (see Figure 2.9), while the new cash crops like oil palm and other tropical fruits continued to expand the cropland area, to which the illegal cultivation of coca must be added.

In contrast, the simultaneous reduction of the requirements of cattle on grassland and the increasing shrubland offered an opportunity to reduce or even halt deforestation rates from 2010 to 2015 (IDEAM, 2018). However, these are only the main national trends, and they differ strongly when the actual regional and local trajectories are examined. Despite apparently being opposed, more biomass from tropical crops and the intensification of cattle-rearing represents the same processes of specialization, which is closely linked to the same institutional bias privileging access to land, trade, and technology by the already privileged of rural elites.

2.4.2 Institutional bias towards extensive cattle rearing and commercial agriculture

The predominance of the biomass flows of pasture and cash crops into the agroecosystem reflect the development of agrarian and trade policies that have been biased towards land concentration and extensive livestock rearing on the one hand, and the promotion of commercial agriculture in both the international and domestic markets on the other. This bias can be linked to the institutional support of the state in the economic interests of the agrarian elites throughout the twentieth century.

The origins of Colombia's modern economic development are rooted in the establishment of the coffee economy (Bejarano, 2011; Cárdenas et al., 2000b; J. A. Ocampo, 2015).After years of civil war between the regional elites, the country embraced the last opportunity offered by international trade top make growing coffee the nation's main economic project (Safford et al., 2002).Export promotion and protection policies were introduced by the government of Rafael Reyes (1904–09), while public land distribution and labour relations favoured large property and cheap labour in the form of the hacienda system up to around 1934 (Bejarano, 2011).

The policies that were implemented to transfer public land between 1910 and the 1930s were mainly favourable to the concentration of landed property and the development of sharecropping labour relations under the hacienda system. In exchange for a piece of land, the sharecropper had to work preparing the land for pasture, especially in the Atlantic region. Most of the time, the restrictions on growing cash crops aided the landowner in acquiring the land sown by the sharecropper (Richani, 2012). Social relations worked similarly in taking the first steps to introducing coffee colonization in the Andean mountains in the west-centre of the country (Bejarano, 2011). However, this same success of the coffee economy and the expansion of the public sector drove the demand for land and labour higher, contributing to food scarcity, the growing bargaining power of the peasants, and the collapse of the hacienda (Bejarano, 2011; Kalmanovitz & López, 2006).

The expansion of the agricultural frontier to grow coffee was the main stimulus of agricultural production, but the capacity to produce primary food was not as successful as it was for cash crops. Despite the state's promotion of experimental stations and schools of agriculture and agronomy, the technical developments actively promoted during the first half of the twentieth century were, at first, only adopted in some regions and for some cash crops like banana plantations in Magdalena (Bucheli, 2004, 2005; F. Ellis, 1983), sugarcane in the Cauca Valley (Delgadillo-Vargas, 2014),and cotton in Tolima (Cárdenas et al., 2000a). The use of land and labour in the coffee economy and the technical backwardness of agriculture resulted in significant food shortages between 1927 and 1945 (see Chapter 4). The pressure from coffee growers finally led the state to reduce cereal tariffs in 1927 to solve the food crisis with the consequent increase of the share of agricultural products in imports up to 1934 (Kalmanovitz & López, 2006, 137). This policy did not contribute to the development of domestic agriculture, though it favoured the sectors joined to international trade, as was the case of the coffee elites of Manizales, who earned fortunes by hoarding commodities during the food shortages of the 1940s (Safford et al., 2002, 320).

As the boom in the coffee and public sectors helped to modernize the domestic economy, the socioeconomic relations of the hacienda system broken down, and the role of the state became more relevant both as regulator and economic agent. During the Liberal Republic, Law 200/1936 was passed as a tool to solve two main problems derived from the hacienda system: the growing bargaining power of the peasants and their claims for land on the one hand, and the need to make agriculture more productive on the other (Bejarano, 2011). The peasants received some support in securing their property rights (Cárdenas et al., 2000b; LeGrand, 1986)and even the average size of public land in the coffee zone was reduced (Villaveces N. & Sánchez, 2014), but redistribution was not a feature of the final reform, nor was the under-utilization of land attacked. The 0059 decree of Law 200/1936 protected the land under extensive cattle-ranching and provided incentives to the substitution of cropland by pasture (Bejarano, 2011; Villaveces N. & Sánchez, 2014). Finally, the opposition of the rural elites hit the attempts at agrarian reform a decade later with Law 100 of 1944. This time, the landowners safeguarded the property rights of their underused land and received subsidies for livestock and commercial agriculture (Richani, 2012) at the expense of a new period of conflict and claims for land during the second term of La Violencia (1948–58).

The land policy was clearly aimed at guaranteeing the property rights of the larger owners (Arango Restrepo, 1987; LeGrand, 1986; J. A. Ocampo, 1994; Villaveces N. & Sánchez, 2014), but the increasing need to supply raw materials to the growing industry made the dilemma of under-utilization of land more relevant. At mid-century, the World Bank's Currie mission concluded that land use in the country was irrational: while the most fertile and best connected land was used for extensive livestock rearing and cash crops, domestic food supply relied on small family farming on the slopes of the mountains (Bejarano, 2011, 216). Two approaches dominated the way to face the problem of the underutilization of land and increasing production: first, the development of a capitalist and industrial model of agriculture promoted by the World Bank throughout the Currie mission; and second, a new attempt at land reform and redistribution to guarantee agrarian production on the bases of the small-scale farming. In any case, the role of the state in agriculture and the role of agriculture in industrialization became primary.

State intervention evolved from merely expanding the transport infrastructure before 1930 and tackling the effects of the 1930s crisis to redirecting financial credit to strategic sectors, intervening in coffee production and markets, and transferring public resources to commercial agriculture. The emergence of the Federación Nacional de Cafeteros (National Federations of Coffee Growers –FNC) (1927) as a kind of state structure, though in private hands, helped to centralize the domestic and foreign policy of coffee to take the profits of the export sector. The FNC participated in setting quotas in the International Coffee Agreement (ICA), acquired the space of the North American trading companies, and controlled the domestic market for coffee in the country. To achieve this capacity in regulating coffee, the institutional support of the FNC was accompanied by the foundation of the Fondo Nacional del Café (National Coffee Fund) (1940), the creation of the Banco Cafetero (Coffee Bank) (1953), and its participation as a partner in the public merchant float of Gran Colombia.

Trade policies helped to protect the agricultural sector, especially the promotion of coffee and the capitalization of domestic agriculture. State support of coffee exports served as the main tool to capture foreign exchange and increasing the purchasing capacity to import agricultural implements and machinery. The main tools of this policy were tariffs, currency devaluations, and trade controls on imports of agricultural products, together with support for imports of farming inputs up until the 1950s (Kalmanovitz & López, 2006; Thorp, 2000). New institutional support was also implemented by founding sectoral banks, public agricultural research, and experimental stations, as well as promoting tobacco, cotton, barley, and cattle as alternative agricultural products and backing private federations of farmers and cattle-ranchers (Cárdenas et al., 2000b). This biased support clearly helps explain the differences in the adoption of the technologies of mechanization and the Green Revolution package by commercial agriculture or cash crops and subsistence-oriented family farming. Ultimately, these smallholder peasants were affected by the shortage of suitable land, as well as a lack of the business capacities and capital to “modernize” their crop production (Cárdenas et al., 2000a, 269).

After La Violencia (1948–58), and in the context of the Frente Nacional (National Front) (1958–74), new attempts to redistribute land and give support to small-scale farming were made by the Liberal governments of A. Lleras Camargo (1958–62) and C. Lleras Restrepo (1966–70). Law 135 of 1961 promoted the creation of the Instituto Colombiano de Reforma Agraria (Colombian Institute of Agrarian Reform –INCORA) which, between 1962 and 1971, gave support to small-scale farming production through the creation of a fund of lands to be redistributed and through titling among the peasants, the construction of infrastructure, and overviewing the issuing of credit to small farmers.

This time the agrarian policy was supported by the industrial elites, who proclaimed the need to guarantee the supply of raw materials for the expansion of the domestic industry (Bejarano, 2011, 198),), but it also encountered opposition again from the rural elites represented by the SAC and the Federación Nacional de Ganaderos (National Federation of Cattle Ranchers –FEDEGAN), founded in 1963. As a result, in 1967 the “Estatuto de Control de Cambios” was passed, which defined the development of agrarian exports as the new priority of agrarian policy (Bejarano, 2011). The increasing tilting of the INCORA and the land invasions led by the Asociaci´on Nacional de Usuarios Campesinos (National Association of Peasants –ANUC), founded in 1968, was another demonstration of power by the peasant movement.

The struggle and the influential opposition of the rural elites in Congress, however, led President R. Lleras to negotiate the reform and proclaim “modernization” and productivity as the route to agrarian development, thus ending the aims of the agrarian reform. The conservative government of M. Pastrana (1970–74) made the change towards the model proposed by the World Bank mission more clearly by focusing on urban employment and housing policies. This support for structural change put an end to agrarian reform during the 1970s. Law 4 of 1973 (which endorsed the Chicoral Agreement of 1972) aimed to transfer public resources to capitalize the agrarian sector (Bejarano, 2011, 203) through infrastructure and credit, which finally favoured cattle -ranchers and commercial agriculture (Callejas, 2002). The smallholders’ protests and land invasions increased during the 1970s (Kalmanovitz, 2003), but new laws restricted the access to land that became the property of the sharecroppers through land improvements (Law 5/1975) (Cárdenas et al., 2000a) and prohibited the legalization of occupied lands by the INCORA (Law 30/1988) (Richani, 2012).

A new opportunity for peasants escaping violence in the Andean region came in the form of the colonization of some marginal regions in the lowlands of Caquetá and Putumayo. In the first case, the colonization, which was led by the state, did not provide enough support for the peasants to keep the land under the plough, and ultimately it was larger properties and pastures that took over the cleared forest (Castellanos Sierra, 2018). In the second case, colonization by the small farmers was only maintained because of the expansion of the illegal coca economy (Urueña B., 2018). In any case, deforestation of the rainforest was a common result.

From the 1980s to the present, four million peasants have suffered land grab-induced displacements violently perpetrated by paramilitaries with the consent and help of many Colombian politicians and public institutions (Ballvé, 2013; Richani, 2012). Additionally, tax exemptions and public subsidies from the Colombian state (Giugale, Lafourcade, & Luff, 2003; Kalmanovitz, 2003) in support of the extensive cattle ranching have also became a way for coca-drug traffickers to launder their quick profits. In 1998, narco-traffickers possessed 6 Mha or 11% of all Colombian farmland (Richani, 2012, 60–61). The socioeconomic and political rationale behind this nexus between land and cattle has gone far beyond the simple business of ranching (Richani, 2012) expanding the agro-export business. All sectors of the Colombian elite, as well as many foreign investors, have played a role in this nexus to develop either agribusiness growth and the exportation of legal cash crops such as sugarcane, coffee, banana, and palm oil (Maher, 2015) or the illegal trafficking of drugs (Borón, Payán, MacMillan, & Tzanopoulos, 2016; Rincón-Ruiz, Pascual, & Romero, 2013). Trade openness and support to the export sector have fostered tropical agriculture, while make the country increasingly dependent on imports and endangering its food security (Fajardo et al., 2002), as I shall explore in Chapter 4.

This second wave of violence (1980–2012) (Gutiérrez-Sanín, 2019) was accompanied by the institutional support of the use of market mechanisms to access land and to ease the emergence of the agribusiness projects. In Law 30 of 1988, together with the technical support to agricultural production, public lands from 450 to 1500 hectares were transferred to agricultural societies, creating incentives for the rise of agribusiness (Villaveces N. & Sánchez, 2014). Additionally, Law 160 of 1994 changed land allocations by INCORA through market mechanisms and unique subsidies to buy land. Joined to decentralization, these mechanisms were captured by the local elites, who selected the beneficiaries, the lands, and its prices (Botella-Rodríguez & González-Esteban, 2021).

The foundation of the Instituto Colombiano de Desarrollo Rural (Colombian Institute for Rural Development –INCODER) in 2003 put an end to agrarian reform in the hands of the INCORA. INCODER helped to ease foreign and local investment in agribusiness and land by focussing on abolishing the collective titles of indigenous and afro-descendants communities (Richani, 2012). After two decades of violence and peasant displacement, attempts were made to legalize title to the occupied land (Law 1152/2007), while the “Agro Ingreso Seguro” public program would have granted cheap credit to the narco-bourgeoisie and landowner families (Espectador, 2009). Although the land policy turned to the restitution of abandoned land (Law 1448/2011), which was reinforced by the aims of the integral rural reform in the peace agreements between the guerrilla group FARC–EP (Fuerzas Armadas Revolucionarias de Colombia–Ej´ercito del Pueblo) and the state (2012–2016), the window for a new rural reform was blocked once again by the agribusiness interest and the rural elites involved with the state (Trujillo, 2020), starting a new wave of social repression.

The institutional arrangements that were developed throughout the twentieth century to avoid any attempt to increase small farmers' access to land ownership has given Colombian elites an easy way to grab a large share of land from the advance of the colonizing frontier, which mainly ends up in the hands of the larger cattle-ranchers (Richani, 2012) and is eventually introduced into agribusiness projects. An important outcome of these public policies, which fostered increasingly unequal land distribution, has been the huge share of fertile land taken over for pasture compared to that devoted to crops, and the extraordinarily high proportion of the total extracted biomass that is represented by cattle-ranching (Figures 2.5b, 2.6a, and 2.7) throughout the period, while at the same time there has been an increase in the participation of cash crops since the 1980s.

2.4.3 Socio-ecological impacts: monoculture and deforestation

The different socio-ecological impacts of the fund-flow of metabolic changes generated through biomass extraction by Colombian agriculture can be categorized into two main groups.

1 The impacts of monocultures and industrial cash crops.

2 The impacts of deforestation.

The export-led growth of industrial crops through monocultures such as sugarcane or palm oil in Colombia has been led increasingly by large-scale agribusinesses in the absence of either environmental regulations or their actual enforcement. This has caused substantial degradation to natural resources and agricultural landscapes. The impact on bodies of water has been significant in some regions, such as the Cauca Valley, where actual "water-grabbing" activities have deprived many communities of this vital resource (Vélez Torres, 2012). Industrial cropping of sugarcane has also undermined the landscape and the ecosystem protection formerly provided by the traditional organic mixed farming carried out by small peasants from indigenous and African-descended communities (Marull, Delgadillo, Cattaneo, La Rota, & Krausmann, 2018).

Although oil-palm expansion and its projections, being supported by government policies, are concentrated in pastureland, this process indirectly contributes to changing the land cover in natural areas by farmers and ranchers adding pressure on the land (Castiblanco, Etter, & Aide, 2013). Biofuels made from oil palm have created even more competition for water and land

(Fraiture, Giordano, & Liao, 2008),with negative effects on species diversity, such as communities of mammalians (Pardo et al., 2018). Finally, oil-palm expansion threatens local food prices and, as explored in Chapter 4, is also associated with food insecurity, violence and the concentration of land and wealth (Castiblanco, Etter, & Ramirez, 2015; CNHM, 2013; PNUD, 2011).

Although related to cash crop expansion, deforestation in Colombia has its own long- term pattern. This process has been moved from the Andean mountains, where the population has been concentrated since colonial times, to the lowlands through the expansion of pastures and tropical crops. Dry tropical forests and Andean forests were the first to experience a steady trend toward fragmentation and decline, while rainforest deforestation occurred later. Sub-humid tropical forests suffered their sharpest decline since the second half of the twentieth century, while in the humid lowlands, tropical forests have remained relatively well preserved until recently (Etter et al., 2008; Etter, McAlpine, Wilson, et al., 2006).

Under this general picture, regional and local trends have differed spatially and temporally. In the highlands, deforestation has been linked to the first steps in extending the agricultural frontier and higher levels of economic development, as occurred with the expansion of coffee. In these zones, however, the presence of small farmers was negatively correlated with the increase in deforestation between 1985 and 2005 (Armenteras, Rodríguez, Retana, & Morales, 2011). These findings are in accordance with the capacity for ecological restoration associated with the maintenance of the heterogeneity of the landscapes and the connectivity of the intermediate levels of disturbance from small family farm management (Castellanos-Castro & Newton, 2015; Marull et al., 2018)

In the lowlands, deforestation is linked to the extending of the agrarian frontier in sub-humid and humid tropical forests. By contrast to the Andean zones, and despite the greater number of protected natural areas, the growth of pastures, oil palm, and illegal coca cultivation in these areas has become the main driver of the process (Borón et al., 2016; Chadid, Dávalos, Molina, & Armenteras, 2015; Dávalos et al., 2011; Rincón-Ruiz et al., 2013). These changes in land cover are causing increases in shrubland and other successional types of land cover with significant consequences for the biotic homogenization of bacterial communities in the soil (Rodrigues et al., 2013),alterations in the carbon cycle (Dymond, Spittlehouse, et al., 2009), and biodiversity loss (Vélez Torres, 2012). This is especially true in Amazonas, though the dry-shrub vegetation of the Llanos may also be in danger if this area becomes a new open agricultural frontier (Castellanos-Castro & Newton, 2015).

Since the colonization of the rainforest is correlated positively with forced migration, unsatisfied basic needs, and inequality of land access, the fate of nature conservation and human development in rural Colombia depends on the peace agreement being implemented, as well as on an agrarian reform that gives peasant, indigenous, and African-descended communities greater access to the land and more secure land titles to reduce the historical roots of the institutional bias towards the rural elites while taking advantage of the biocultural heritage and knowledge in the forest management of the rural communities (Yoamara, Vélez, Calle, & Roa, 2020). Regrettably, the prospects for the peace agreement, and even more for the agrarian reform, are not very encouraging presently.

Capítulo 3

Las venas abiertas de América Latina en la era del Antropoceno: un estudio biofísico del comercio exterior (1900–2016)

Keywords: Metabolismo Social; Intercambio Ecológico Desigual, Globalización, Contabilidad del Fujos de Materiales, América Latina

3.1 INTRODUCCIÓN

América Latina ha desempeñado históricamente un papel clave en el suministro global de recursos naturales[1]. Con discontinuidades históricas y geográficas, la mayoría de sus economías han sido exportadoras netas de productos primarios con poco valor añadido mientras que han tendido a importar bienes manufacturados a precios más elevados (Russi et al., 2008; West & Schandl, 2013; J. G. Williamson, 2011). Aunque los debates sobre la naturaleza y el impacto de la inserción de América Latina en el comercio mundial siguen abiertos (p.ej. ver Topik, Marichal, Frank, Joseph, and Rosenberg (2020)), existe un consenso generalizado entre investigadores de diferentes disciplinas en señalar que este patrón de especialización comercial tiene implicaciones negativas para el desarrollo económico, el medio ambiente y, en general, para el bienestar de los habitantes de la región (Bértola & Ocampo, 2012; Hornborg, 2012; Prebisch, 1981; J. G. Williamson, 2011)[2].

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[1] This chapter has been published as Infante-Amate, Urrego Mesa, and Tello Aragay (2020). I have contributed to set the unequal exchange theoretical frame, gather and prepare the historical data (1900–60), and re-write the drafts of the document.

[2] En efecto, hay excepciones a esta regla. Muchos autores de la ortodoxia liberal han considerado que la especialización en productos primarios responde a las ventajas comparativas de la región y que la proliferación de este modelo de especialización es, en consecuencia, beneficioso para todas las partes. Un resumen en Cardoso et al. (1977)

Uno de los textos que caracterizó con más éxito (aunque no necesariamente con más rigor) el carácter extractivista de las economías latinoamericanas dentro del sistema económico global fue *Las venas abiertas de América Latina* de Eduardo Galeano, que rescatamos para dar título a este trabajo. Aunque se publicó hace ya casi medio siglo (en 1971), y sus tesis principales han sido cuestionadas desde diferentes ámbitos, su legado es inmenso y sigue siendo un texto referencial dentro y fuera de la academia. El trabajo, más divulgativo que académico, era representativo de las inquietudes de la izquierda académica del momento, fascinada por los análisis *dependentistas* de la CEPAL y por las incipientes teorías del "sistema mundo". Con base en una extensa revisión de literatura el autor recogía evidencias fragmentarias del carácter extractivo de las diferentes realidades latinoamericanas, desde Potosí hasta la explotación de petróleo en el siglo XX. Sin embargo, la base empírico-cuantitativa que sostenía este trabajo (la disponible en aquel momento) era muy limitada. Aunque documentaba sobradamente el carácter periférico de las economías latinoamericanas, así como los impactos asociados a este tipo de especialización, quedaban abiertas muchas preguntas que hoy, con los desarrollos metodológicos actuales, podemos responder de manera más robusta: ¿hasta qué punto estaban realmente "abiertas"las venas de América Latina? ¿cómo ha cambiado la hemorragia a lo largo del tiempo? ¿existen diferencias intrarregionales tanto en el nivel extractivo como en el tipo de especialización? Y, no menos importante, ¿hacia dónde fluyen los recursos naturales de América Latina?

Es importante dejar claro que en las últimas décadas numerosos investigadores se han ocupado de estos temas, principalmente desde perspectivas histórico-económicas e histórico-ambientales[3], realizando contribuciones sobresalientes. Sin embargo, a pesar de los enormes avances que han tenido lugar, aún seguimos sin contar con ningún trabajo que ofrezcan una visión de conjunto sobre el papel de América Latina en el suministro global de recursos y sobre su impacto en la región. La mayoría de los estudios publicados tienen a centrarse en los estudios de caso, tanto a nivel geográfico como a nivel de producto o sector.

Responder a estas preguntas resulta de interés en un momento como el actual, en el que tanto la agenda política como la agenda académica están focalizadas en estudiar los orígenes, la evolución, el impacto, las causas y las responsabilidades del cambio global. Buena parte de los impactos ambientales a escala planetaria tienen lugar en América Latina: desde la deforestación, a la pérdida de biodiversidad, la alteración de los flujos bioquímicos o las emisiones asociadas a los cambios de uso del suelo (Houghton, Skole, & Lefkowitz, 1991;

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[3] En este sentido es obligado mencionar las decenas de trabajos publicados en el marco de la Sociedad Latinoamericana y Caribeña de Historia Ambiental y en su revista HALAC. A modo de ejemplo: los impactos de la expansión azucarera en Cuba (Monzote, 2005); el cambio forestal en Argentina (Zarrilli, 2004), el Amazonas (Pádua, 2010) o Costa Rica (Goebel McDermott, 2013); o la expansión del café en Centroamérica (Gallini & Murga, 2009; Infante-Amate & Picado, 2018)

Hurtt et al., 2011; Lassaletta et al., 2014). Todos estos impactos se incluyen entre los conocidos “límites planetarios”que, de ser sobrepasados, podrían poner en cuestión nuestra supervivencia como especie. En otras palabras, profundizar en la dimensión material y económica del comercio de América Latina no solo nos sirve para contribuir a debates clásicos como los relativos al impacto del comercio internacional en la región o su carácter *dependensdista* que siguen contando con buena salud, sino también para arrojar luz sobre sobre uno de los grandes temas de nuestros días: el surgimiento del Antropoceno, la nueva era geológica dominada por los humanos (Steffen et al., 2015).

Por fortuna, en los últimos años se han llevado a cabo avances metodológicos muy importantes, sobre todo relativos a la capacidad de computación de datos y a la digitalización de fuente históricas que nos permiten analizar estos fenómenos a gran escala. Las principales contribuciones en esta dirección han surgido desde la Economía Ecológica, la rama biofísica de la economía[4], donde se han desarrollado diferentes metodologías ad hoc para dimensionar la extracción, la circulación y el consumo de recursos. Una de las más extendidas es la Contabilidad del Flujo de Materiales (en adelante MFA, por sus siglas en inglés), que hoy en día forma parte de la contabilidad ambiental de muchos países del mundo, así como de importantes organismos internacionales como la OCDE, Naciones Unidas o Eurostat (Fischer-Kowalski et al., 2011; Schandl et al., 2017). En la actualidad, se han publicado estimaciones MFA para la mayoría de las economías nacionales, incluyendo las latinoamericanas, entre 1970 y la actualidad. De hecho, existen numerosos análisis monográficos sobre América Latina a nivel regional (West & Schandl, 2013) por grupos de países (Crespo-Marín & Pérez-Rincón, 2019; Dorninger & Eisenmenger, 2016; Russi et al., 2008; Samaniego, Vallejo, & Martínez-Alier, 2017) o para estudios nacionales específicos como Colombia (Pérez-Rincón, 2006b; Vallejo et al., 2011), Chile (Giljum, 2004), Ecuador (Vallejo, 2010), Argentina (Manrique, Brun, González-Martínez, Walter, & Martínez-Alier, 2013) y México (Gonzalez-Martinez & Schandl, 2008)[5].

Los resultados derivados de estas recientes investigaciones han sido decisivos para arrojar luz sobre el debate de las “venas abiertasz para caracterizar el papel de América Latina en el ascenso del Antropoceno. Sus principales contribuciones pueden resumirse así:

1 A nivel global, América Latina (junto a Asia Central) es la región del mundo

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[4] La teoría económica convencional se basa en lenguajes de valoración monetarios que no captan adecuadamente los impactos sobre el medio ambiente: el valor de mercado de un bien, sugieren los economistas ecológicos, no es indicativo del impacto ambiental que genera, es más, ni siquiera informa bien sobre su grado de escasez (Daly, 2019; Hornborg, 2012; Martinez-Alier & Muradian, 2015). La Economía Ecológica, por el contrario, utiliza métricas de valoración biofísicas, más ajustadas al “lenguaje de la naturaleza”. En este sentido, una de sus principales contribuciones ha sido el desarrollo de metodologías estandarizadas para caracterizar la base material de los sistemas económicos.

[5] Igualmente, existen estudios de carácter global en los que se analiza América Latina como una entidad territorial (p.ej., Schandl and Eisenmenger (2006) y Schaffartzik et al. (2014)

con mayores exportaciones netas de materiales por habitante, superando la tonelada por habitante y año. Aunque existen otras regiones que son exportadoras netas de materiales, como Oriente Próximo o África, ninguna de ellas aporta tantos recursos per cápita al resto del mundo (Schaffartzik et al., 2014).

2 Entre las regiones exportadoras netas, América Latina es la principal suministradora de biomasa y de minerales metálicos. En el resto de las economías periféricas los combustibles fósiles dominan en el conjunto de los materiales exportados. El perfil exportador de América Latina es mucho más diversificado y, por tanto, asume impactos ambientales mucho más variados, incluyendo tanto los rela-cionados con el extractivismo mineral como con el extractivismo agrario (Schaffartzik et al., 2014; West & Schandl, 2013).

3 Desde la década de 1970 la extracción de materiales se ha multiplicado por cuatro, pasando de c. 2000 millones de toneladas (Mt) a más de 8000 Mt. Alrededor de un 10 % de esa extracción se destina al comercio internacional (West & Schandl, 2013). El crecimiento en la extracción es muy superior a la media global, por lo que el papel de América Latina en la apropiación global de recursos es cada vez mayor (Krausmann et al., 2009). En otras palabras, después de la publicación de “las venas abiertas”, el carácter extractivo de América Latina ha seguido creciendo en términos absolutos y relativos (a la media global).

4 Solo los estudios de caso nacionales ofrecen información sobre la intensidad material de las exportaciones o sobre la relación de intercambio, esto es, sobre la relación entre el comercio físico y el comercio monetario (p.ej., Pérez-Rincón (2006a)). Aunque existen importantes divergencias regionales y las tendencias han cambiado a lo largo de la historia, la mayoría de las economías de América Latina importan a mayor precio del que exportan. Dicho de otra forma, su descapitalización material no siempre genera retornos económicos positivos. De hecho, en muchos países de la región coexisten déficits tanto en los balances comerciales físicos como en los monetarios: a pesar de exportar más recursos de los que se importan, no se generan suficientes ingresos para pagar las importaciones (Fischer-Kowalski & Amann, 2001; Hall, Van Laake, Perez, & Leclerc, 2000; Russi et al., 2008).

5 Todas estas evidencias han servido para nutrir una de las principales teorías dentro de la Economía Ecológica, la del Intercambio Ecológico Desigual (Dorninger & Hornborg, 2015; Hornborg, 2012; Rice, 2007). Esta teoría, que supuso una relectura ambiental de las tradicionales interpretaciones del intercambio económico desigual, ha sido nutrida por estudios MFA que

evidencian el papel del Sur global como provisor neto de materiales a bajos precios (Common & Stagl, 2005; Giljum & Eisenmenger, 2004).

Esta literatura no obstante tiene importantes limitaciones más allá de su sesgo económico-ecológico y la consecuente desatención de algunos debates centrales en otras disciplinas como la historia o la sociología. En primer lugar, presenta un marco temporal estrecho. En el mejor de los casos se ofrece información desde 1970 (West & Schandl, 2013; WU, 2020). Las “venas”de América Latina han estado abiertas durante mucho más tiempo. Para comprender un fenómeno histórico es imprescindible dotar de historicidad las bases empíricas con las que construimos nuestras narrativas.

En segundo lugar, las bases de datos sobre comercio de materiales en América Latina, salvo contadas excepciones (Ricaurte Greene, 2012), no distinguen el comercio bilateral. Dicho de otra forma, aunque se asume que la contribución material de América Latina nutre a los países más desarrollados, lo cierto es que no se cuenta con evidencias que corroboren a nivel agregado esta hipótesis[6]. En este sentido, se suele señalar que hubo una transición hegemónica en las potencias que han controlado el extractivismo latinoamericano: del dominio colonial europeo a la influencia de los EE.UU. (y parcialmente de la URSS). Sin embargo, se desconoce el peso material que ha tenido el norte global en la sustracción de recursos procedentes de América Latina. Esta laguna es tanto más inquietante cuando existen evidencias que apuntan a que, con el cambio de siglo, el eje Asia-Pacífico, liderado por China, está jugando un nuevo papel hegemónico en el extractivismo de América Latina (R. E. Ellis, 2009; Walter & Martínez-Alier, 2012) ¿Hasta qué punto es así? ¿Es comparable la influencia oriental en el subcontinente con la tradicional influencia occidental?

La tercera laguna tiene que ver con la pobre relación entre extractivismo e impacto económico. La mayoría de los trabajos que usan la metodología MFA documentan con eficacia la descapitalización material de un país a través de sus balances comerciales físicos, sin embargo, no suelen ofrecer análisis que vinculen el comercio físico con el comercio monetario, por lo que es difícil testar la aseveración de que el continente exporta materiales a un precio más bajo, o con menor valor añadido, del que los importa. Desde la economía sí existe una gran tradición en el estudio de las relaciones de intercambio entre países. En el caso de América Latina este debate, que es de gran importancia, ha girado en torno a la teoría cepalina de la dependencia, que sugería la existencia estructural de una relación de intercambio lesiva (Blattman et al., 2003, 2004, 2007; Cardoso et al., 1977; Hadass & Williamson, 2003; J. A. Ocampo & Parra, 2010, 2003a; J. Williamson, 2008; J. G. Williamson, 2011). Sin embargo, la teoría económica se ciñe, al decir de Naredo and Naredo (2010), a la esfera crematística, esto es, a los

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[6] Obviamente esta hipótesis es totalmente plausible dada la gran cantidad de evidencias locales existentes.

flujos monetarios asociados al comercio, los cuales no son indicativos del impacto ambiental. La literatura de la relación real de intercambio es poco informativa sobre la degradación ambiental en los países estudiados.

El objetivo de este trabajo es arrojar luz sobre las tres limitaciones que se acaban de señalar. Para ello, siguiendo la metodología MFA, se plantea un estudio de las balanzas comerciales físicas y monetarias para una amplia muestra de países de América Latina (un total de 16), entre 1900 y 2016. La base de datos resultante permitirá responder a las siguientes preguntas de investigación:

i ¿Cuánto ha contribuido América Latina a la construcción material del mundo moderno en el siglo XX? O, dicho de otra forma, ¿cuál ha sido su papel en el desarrollo del Antropoceno?

ii ¿Cuáles son los patrones de especialización extractiva y comercial en los diferentes países de la región?

iii ¿Cuál es el diferencial de retribución por unidad comerciada y cómo ha evolucionado a lo largo del tiempo y entre socios comerciales?

iv ¿Cómo ha evolucionado la relación entre el crecimiento económico y la descapitalización material?

Tras esta introducción, el texto se organiza de la siguiente forma. Primero, se detallan la metodología y las fuentes utilizadas. Después se presentan y analizan los principales resultados en una sección que se divide en seis bloques: i) la contribución de América Latina a la economía biofísica global; ii) los diferentes patrones regionales de especialización comercial; iii) las relaciones bilaterales del comercio en unidades físicas; iv) las relaciones de intercambio y el intercambio ecológico desigual; y v) la relación entre comercio físico y crecimiento económico.

3.2 NOTAS METODOLÓGICAS

3.2.1 La contabilidad de flujos de materiales

La contabilidad del flujo de materiales (MFA) es una herramienta metodológica, harmonizada internacionalmente, que data de finales de la década de 1990 y que hoy está incorporada por las principales agencias estadísticas del mundo. Fue diseñada para suplir las carencias de la Contabilidad Nacional clásica a la hora de informar sobre la presión de la economía en el medio ambiente (Fischer-Kowalski et al., 2011). A pesar de sus reconocidas limitaciones (ver, por ejemplo, Giampietro (2006)), constituye una herramienta útil y didáctica para monitorear el perfil productivo, la especialización comercial y los niveles de consumo de las economías nacionales en términos biofísicos (ver Infante-Amate, de Molina, and Toledo (2017) y Haberl et al. (2019)).

En la Figura 3.1 se recoge una síntesis de los principales indicadores propuestos por la metodología MFA. Por un lado, se contabiliza la "Extracción Doméstica"(en delante DE, por sus siglas en inglés), que es la cantidad de recursos materiales que son extraídos dentro de la unidad político-territorial analizada. La DE actúa como proxy de la presión doméstica sobre el medio ambiente (Giljum, Dittrich, Lieber, & Lutter, 2014). Por otro lado, se contabiliza el comercio de materiales. La diferencia entre los materiales importados y los materiales exportados se denomina "Balance Comercial Físico"(en delante PTB, por sus siglas en inglés). Este indicador es un buen proxy de la externalización de los impactos a terceros países (Giljum & Eisenmenger, 2004). Un PTB positivo indica que una economía importa más bienes materiales de los que exporta, por lo que es demandante neta de recursos. Y viceversa. Finalmente, se contabiliza el "Consumo Doméstico de Materiales"(en delante DMC, por sus siglas en inglés), que es estimado como la ED más las importaciones menos las exportaciones de materiales, esto es, la ED menos el PTB. El DMC recoge el consumo de materiales de los habitantes del territorio analizado, independientemente de donde sean extraídos.

Estos indicadores están disponibles para la mayoría de los países del mundo desde 1970 y han permitido arrojar luz sobre debates muy relevantes como: 1) los puntos calientes globales en la extracción de materiales por tipo de productos; 2) identificar el nivel de consumo de materiales a nivel nacional y la desigualdad del consumo material entre países; 3) identificar los territorios que son suministradores netos de materiales y los que son demandantes netos, lo que ha permitido arrojar luz en debates como los del Intercambio Ecológico Desigual y 4); relacionar el consumo de materiales con otros indicadores como el PIB o en IDH, lo que ha permitido analizar hasta qué punto nuestro desarrollo económico y nuestro bienestar material son dependientes del consumo de materiales (Haberl et al., 2019; Infante-Amate et al., 2017).

3.2.2 Límites del estudio

Este trabajo se centra exclusivamente en los indicadores de comercio. En particular, se cuantifican las importaciones, las exportaciones y el balance de materiales (PTB) para un total de 16 economías de América Latina para las que ha sido posible compilar información fiable de largo plazo.

Siguiendo la metodología MFA, los flujos de materiales analizados se agregan en Biomasa, Combustibles Fósiles, Minerales Metálicos y Minerales no Metálicos (Eurostat, 2018). Así, el PTB de cada país ($_i$) se estima como la sumatoria de las importaciones (M) menos las exportaciones (X) de cada grupo de productos ($_j$):

$$PTB_i = \sum_j M_j - X_j \tag{3.1}$$

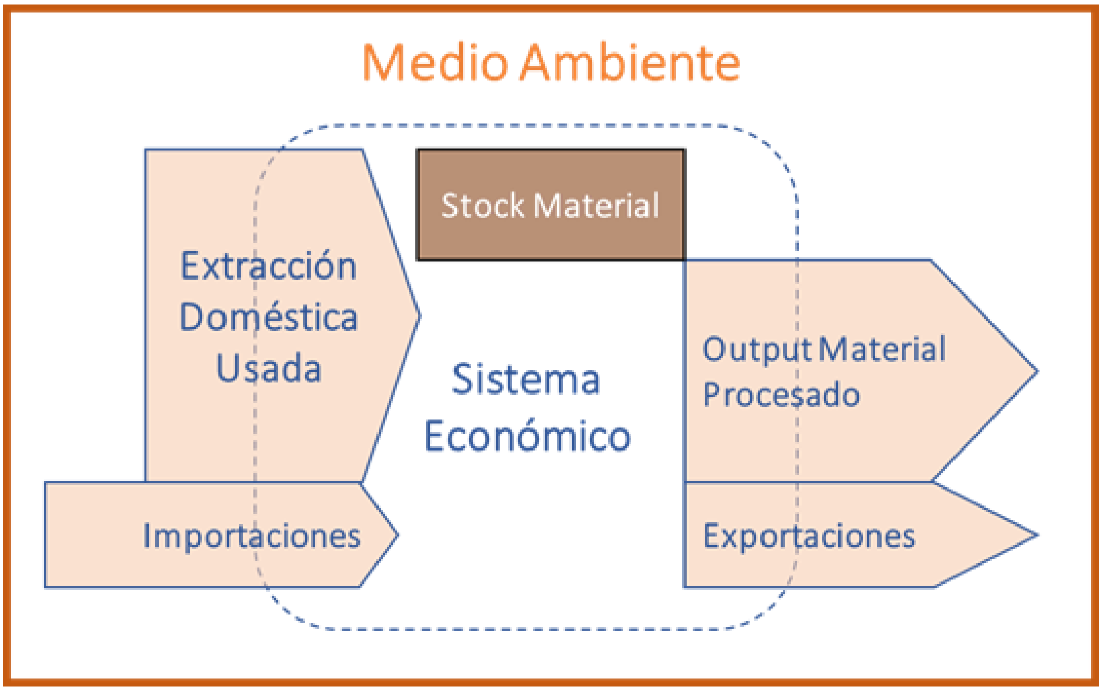

Figura 3.1: Esquema simplificado de la contabilidad del flujo de materiales. Fuente: adaptado de Eurostat (2018)

Entre 1966 y 2016 se han podido reconstruir las relaciones comerciales bilaterales en cada país distinguiendo un total de 268 socios. Para facilitar el análisis de los resultados se agregan los países estudiados en grupos regionales (ver Tablas B.1 y B.2 del Anexo Metodológico). En el caso de los países de América Latina se distinguen: México, Centro, Andinos, Brasil y Sur. En el caso de los socios comerciales distinguimos entre: América Latina y Caribe; América del Norte; Europa; África; Asia Central y Occidental; y Asia-Pacífico. Esta última división permite deducir el comercio intrarregional y, por lo tanto, cuantificar el PTB neto de América Latina. Nótese que sin los datos de comercio bilateral no es posible estimar el comercio de América Latina como un todo, ya que si simplemente se agregan las exportaciones y las importaciones de cada país se estaría estimando la suma total de sus exportaciones e importaciones, incluyendo aquellas que se destinan a países de la propia región. Así, excluyendo los países (i) de América Latina y el Caribe, se estima el PTB neto de toda la región de la siguiente forma:

$$PTB = \sum_{ij} M_{ij} - X_{ij} \tag{3.2}$$

También se estiman los balances comerciales monetarios a precios corrientes. Con esta información, se analiza cómo han evolucionado el precio de las importaciones y el precio de las exportaciones por unidad material. La ratio entre estos dos indicadores permite analizar la evolución de las relaciones de intercambio tal como han sido planteadas en otros trabajos desde la Economía Ecológica (Infante-Amate & Krausmann, 2019; Pérez-Rincón, 2006a; Samaniego et al., 2017). Tal relación puede notarse así:

$$RI_{ij} = \sum_{j} \frac{m_{ij}}{x_{ij}} \tag{3.3}$$

Siendo m_i el valor monetario de cada unidad material importada y x_i el valor monetario de cada unidad material exportada (en ambos casos, medida en US$/kg). Si el resultado es mayor que la unidad significa que el precio de las importaciones es mayor que el precio de las exportaciones. La lectura económico-ecológica que se hace de este fenómeno es que para mantener equilibrada la balanza comercial es necesario vender más materiales de los que se importan y, por lo tanto, descapitalizarse materialmente.

3.2.3 Fuentes y procedimiento de cálculo

Para la reconstrucción del comercio físico y monetario de las economías latinoamericanas seleccionadas para un período tan amplio de tiempo, se han combinado diferentes fuentes documentales. En la Tabla B.3 del Anexo Metodológico recogemos un resumen de las mismas para cada caso. Entre 1962 y 2016 la información proviene de la base de datos de comercio de Naciones Unidas (UNCT, desde aquí). UNCT es la única base de datos global que ofrece información del comercio bilateral tanto en unidades físicas como monetarias entre 1962 y la actualidad para la mayoría de los países del mundo. Otras fuentes, como FAOSTAT, solo ofrecen información para los productos agrarios y únicamente distingue el comercio bilateral a partir de 1986, mientras que la de la Organización Mundial del Comercio, con información desde 1948, solo proporciona valores monetarios.

El uso de UNCT, sin embargo, no está exento de problemas. El más relevante es que presenta importantes vacíos de información en, al menos, dos ámbitos: no todos los países aportan información para todos los años y no siempre se ofrece información en unidades físicas (más información en Dittrich and Bringezu (2010)). En el caso de los años sin información la cobertura en las 16 economías seleccionadas es casi total. De hecho, los países que se han descartado en este estudio (muchos de ellos caribeños) son aquéllos en los que la información era más limitada, tanto en cantidad como en calidad. En 10 de las economías estudiadas, entre las que se incluyen las de mayor tamaño (Brasil y Argentina), hay información para todos los años. En las 6 economías restantes existen ciertas lagunas que nunca superan los 3 años (de un total de 54 años), exceptuando Uruguay, donde no hay información para 8 años.

Para cubrir la información no disponible, se ha operado de la siguiente forma: (1) si la falta de información es un año suelto que cae en medio de la serie, la estimación se realiza mediante interpolación lineal y; (2) si la información que no está disponible corresponde a varios años al inicio o al final de la serie, se estima tomando como referencia la variación de otras variables. En el caso de la serie en unidades monetarias, se toma la variación de las importaciones y de las exportaciones en cada país recogidas en la base de datos de la Organización Mundial de Comercio (WTO, 2020). En el caso del comercio físico se utiliza el índice de “volumen de las exportacionesz las “importaciones”disponible en la base de datos MoxLAD (2020) para cada uno de los países analizados. Finalmente, para los productos que no registraban información en unidades físicas, se calculó el valor por unidad física (US$/kg) en los países en los que sí hay información disponible y se aplica la media regional del precio por kilogramo a los datos monetarios.

UNCT ofrece varios niveles de desagregación de la información en la descarga de datos. En este estudio se utiliza el sistema SICT-1 con “3 dígitos”, ya que es el único que posibilita obtener información entre 1962 y 2016 en una descarga única, permitiendo una desagregación de 182 productos de exportación e importación. Solo para el período 1962-2016, en el que se utiliza UNCT, la base de datos resultante supera los 20 millones de observaciones.

Para el período 1900-1961 la información está dispersa en diferentes fuentes. En este período solo se estima el comercio físico. LN (1926) ofrece información del comercio físico total para los años de 1913 y de 1920 a 1934 para todos los países excepto Uruguay. Los datos restantes se complementaron con la información de los Anuarios Estadísticos de Comercio Exterior de Argentina, Bolivia, Brasil, Chile, Colombia, Costa Rica, México, Paraguay, El Salvador y Venezuela (ver Tabla B.3 en los Anexos) y, cuando no fue posible, se usó el índice de volumen de MoxLAD (2020).

De esta forma obtenemos una serie anual entre 1900 y 2016 del comercio físico total por país. Para distinguir los diferentes tipos de materiales utilizamos las series del IIA (1909) entre 1909–47 y de FAO (1948-1961), para el caso de la biomasa; y las estadísticas históricas de Mitchell (2013), que ofrecen información sobre el comercio de combustibles fósiles y minerales para los principales productos y países de la región. En los casos en que no se obtuvo información se asumió la proporción del año más próximo. Para limitar el impacto de los *outliers* y para suavizar la tendencia, las series se estiman tomando las medianas móviles quinquenales.

3.3 RESULTADOS Y DISCUSIÓN

3.3.1 La contribución Latinoaméricana a la economía biofísica global

La Figura 3.2 muestra el PTB de América Latina entre 1900 y 2016 por tipo de producto. La primera evidencia es que, durante el período analizado, América

Latina aparece, sin excepción, como suministradora neta de materiales hacia el resto del mundo, esto es, sus exportaciones son siempre mayores que sus importaciones. El segundo mensaje que sobresale es que el nivel de déficit material no ha dejado de crecer hasta la actualidad. El suministro neto es hoy en día mayor que nunca. En 1900 las exportaciones netas eran 4 millones de toneladas métricas (Mt) y en 2016 ascendieron a 610 Mt. El crecimiento, no obstante, no ha sido lineal, lo que nos conduce a la tercera observación: la "gran aceleración.en el comercio de materiales, tanto en la importación como la exportación, tuvo lugar en la segunda mitad del siglo XX, especialmente desde la década de 1980. La conocida "gran aceleración.en el consumo de recursos a nivel planetario tuvo lugar tras la Segunda Guerra Mundial y se concentró en los países más ricos (Steffen et al., 2015). No obstante, la contribución de América Latina a este proceso empezó a ser más relevante desde la década de 1980. Hasta esa fecha el aumento en el consumo de materiales en los países más ricos se completó con recursos domésticos o con materiales provenientes de otros países periféricos (Schaffartzik et al., 2014). Durante el período c. 1930–80 las economías latinoamericanas desarrollaron políticas de "sustitución de importaciones".

Sin embargo, tras la crisis de la deuda externa y el giro neoliberal de la década de 1980 la mayor parte del continente abandonó estas políticas y puso en práctica, o le fueron impuestas por planes de ajuste de las entidades financieras internacionales (FMI, Banco Mundial y otras), medidas de desregulación y de apertura al comercio internacional, lo que generó un incremento acelerado en las exportaciones globales (Bértola & Ocampo, 2012; Hall et al., 2000).. En términos materiales, según nuestros datos, las exportaciones totales de materiales pasaron de 7 Mt a 115 Mt entre 1900 y 1980. El gran crecimiento fue posterior: en 2016 las exportaciones ascendían a 1.035 Mt.

Entre 1980 y 2016 las exportaciones de América Latina han representado de manera más o menos estable un 10 % de las exportaciones totales globales. Esta cifra es mucho mayor en el caso de la minería metálica. Durante buena parte de las décadas de 1980 y 1990 una de cada tres toneladas exportadas en el mundo provenía de América Latina. En el caso de la biomasa la cifra tambíen supera la media y ha crecido en los últimos años: en la actualidad una de cada cinco toneladas exportadas proviene de la región. Dicho de otra forma, América Latina ha jugado un papel central en la segunda fase de la "gran aceleración", en consecuencia, en el aumento dramático del uso de recursos a nivel global que nos ha conducido a una nueva era geológica: el Antropoceno. No todos los países tienen, sin embargo, la misma responsabilidad en este proceso: mientras que unos son grandes consumidores y demandantes netos, otros, como los latinoamericanos, soportan la carga de la transición con beneficios limitados. Esta carga, además, es cada vez mayor: la exportación de materiales de las últimas tres o cuatro décadas puede haber sido mayor que la que ha tenido lugar en toda la historia antes de

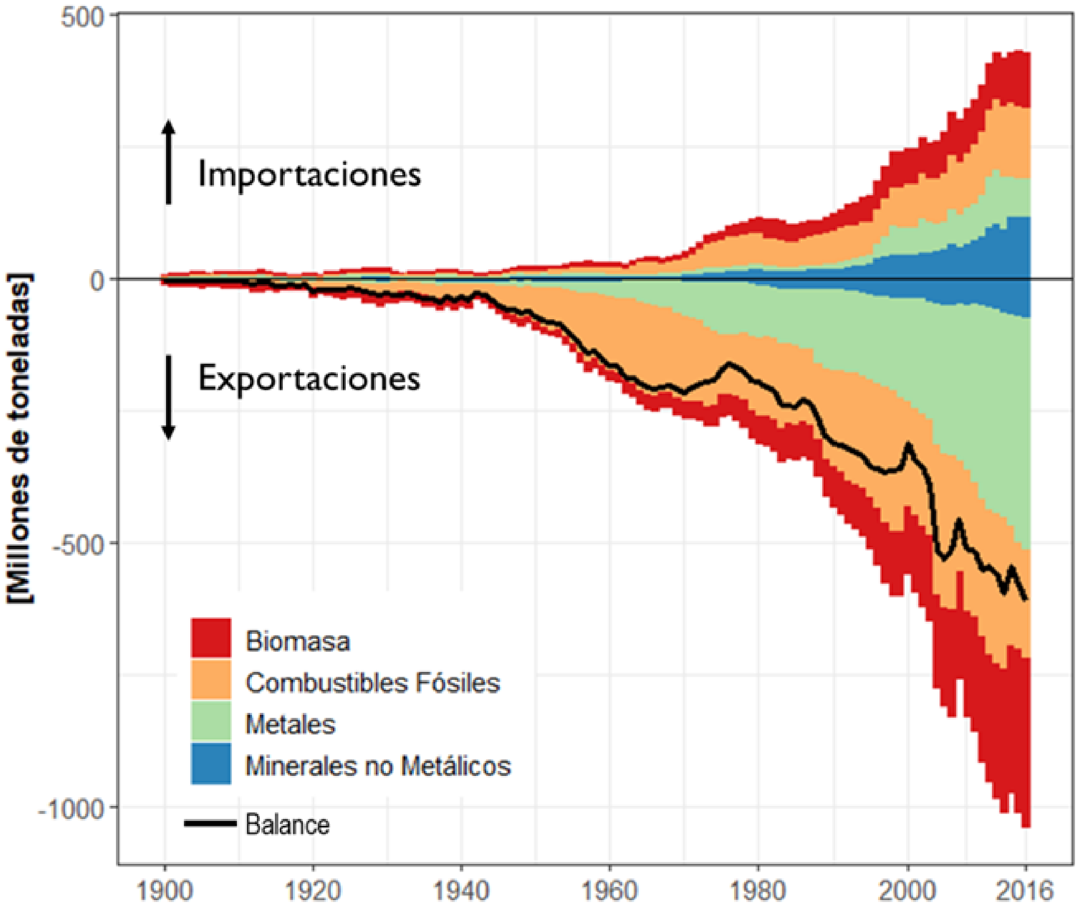

Figura 3.2: Balance comercial físico (PTB) de América Latina (1900–2016). Las importaciones son las barras con valor positivo y las exportaciones las barras con valor negativo. La línea negra es el balance. Fuente: elaboración propia (ver apartado 3.2.3).

esa fecha, y, solo las exportaciones de 2015 y 2016, pueden haber superado las que tuvieron lugar durante más de tres siglos de colonialismo[7].

Una cuarta evidencia que extraemos de la Figura 2 es que la especialización comercial ha cambiado a lo largo de la historia. A principios del siglo XX la biomasa, esto es, los productos agrarios, pecuarios y forestales, eran los principales bienes de exportación. A media que avanzó el siglo XX los combustibles fósiles se convirtieron, con diferencia, en el principal material exportado. En 1952 llegaron a representar tres cuartas partes de todos los materiales exportados. A partir de esa fecha su peso cayó significativamente por dos motivos: primero, por la caída de las exportaciones debido a la aparición de nuevas zonas productoras como Oriente Próximo y, segundo, por la rápida expansión de la minería metálica. Con la llegada del siglo XXI se ha consolidado la exportación de minerales metálicos, principalmente provenientes de Chile y Brasil, pero también de biomasa, que hoy supone un 30 % del total de las exportaciones de la región y ya superan en cantidad a las de los combustibles fósiles.

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[7] Suponiendo, con un ejercicio muy simplista pero prudente, que las exportaciones previas a 1900 se mantuvieron relativamente estables a lo largo del tiempo.

En la Figura 3.3 ofrecemos un detalle más pormenorizado de la evolución de los balances físicos por tipo de producto. En todos los casos las exportaciones y las importaciones han crecido durante el período estudiado, especialmente tras la segunda mitad del siglo XX. Observamos que la región es exportadora neta de todo tipo de materiales salvo de minerales no metálicos, con unas importaciones netas acumuladas de 334 Mt entre 1900 y 2016. Esta cifra contrasta con las exportaciones netas acumuladas de los combustibles fósiles (8.795 Mt), los minerales metálicos (7.839 Mt) y la biomasa (4.045 Mt). Como se anunciaba en la introducción, el perfil exportador difiere del de otras regiones periféricas del mundo como Asia Central u Oriente Próximo, donde la mayor parte de las exportaciones son combustibles fósiles. La diversidad en el tipo de materiales exportados hace que el subcontinente albergue múltiples problemáticas y conflictos de tipo ambiental. En el caso de los combustibles fósiles se combinan problemas asociados al desarrollo de instituciones disfuncionales y luchas por el control de los beneficios en Venezuela, México o Bolivia (Ross, 1999; Wenar, 2015), al tiempo que se destruyen zonas con gran valor ecológico como en el reciente caso de Yasunni ITT (Larrea & Warnars, 2009). La extracción minera a gran escala también implica la alteración de ecosistemas de gran valor, como ocurre en las zonas mineras de Brasil, Chile o Perú, pero principalmente contaminación a gran escala de suelos y agua (p.ej, Castro and Sánchez (2003); Li (2015); Malm, Pfeiffer, Souza, and Reuther (1990)).

Por su parte, el auge del comercio de la biomasa ha estado acompañado de severos procesos de deforestación en algunos de los bosques con más densidad de carbono y más biodiversos del mundo como los de Centro América o de la Amazonía (p.ej., (Houghton et al., 1991; Malhi et al., 2008). El carácter intensivo que caracteriza la agricultura de exportación de América Latina genera importantes problemas de contaminación de los recursos naturales y de intoxicaciones humanas. A modo de ejemplo, Costa Rica conocido por sus fuertes medidas de protección ambiental es el país del mundo con mayor uso de pesticidas por superficie cultivada debido a su especialización agroexportadora en productos que se manejan de manera muy intensiva (según datos de FAOSTAT, ver también Hall et al. (2000); Galt (2008)). La diversidad en la exportación de materiales en la región se correlaciona bien con la diversidad de conflictos ambientales recogidos por el proyecto EJOLT (2019), en el que se puede corroborar que en América Latina no solo se concentra un volumen muy importante de conflictos ambientales sino que también alberga una amplia diversidad tipológica (Scheidel et al., 2020).

3.3.2 Patrones regionales de especialización

Siguiendo la metáfora de las “venas abiertas”, la hemorragia de recursos naturales presenta cuadros muy diferentes en cada uno los países de América Latina. En

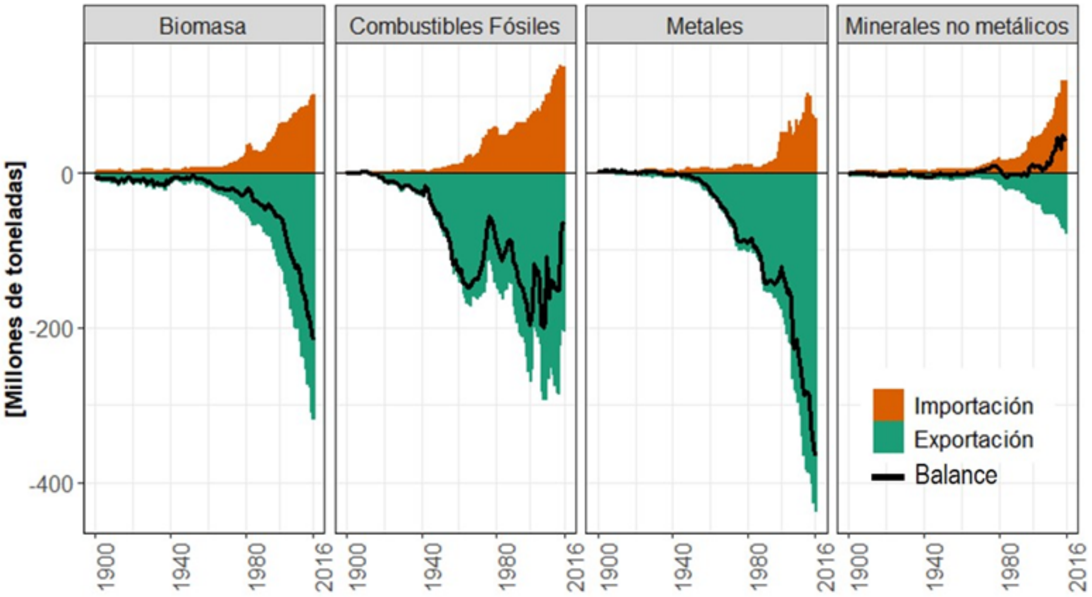

Figura 3.3: Balance comercial físico (PTB) de América Latina por tipo de material (1900-2016). Fuente: Elaboración propia 3.2.3.

la Figura 3.4 (en valores absolutos) y la Figura 3.5 (en valores per capita) se recopilan los PTB de las 16 economías analizadas. En todas ellas es perceptible una aceleración dramática del comercio en la segunda mitad del siglo XX, especialmente a partir de la década de 1980, aunque se pueden identificar diferentes ritmos de crecimiento así como diferentes patrones de especialización.

Lo primero que se observa es que no todas las economías analizadas son exportadoras netas. De hecho, un total de 5 economías (las centroamericanas) reportan importaciones netas acumuladas para el periodo 1900-2016. El Salvador es la economía más dependiente, con unas importaciones netas de 0,4 toneladas por habitante y año (t hab-1 año-1) en el período estudiado. Además, este país es el único que es importador neto de todo tipo de materiales. Los otros países centroamericanos también son importadores netos, aunque “solo.^{en} el caso de los minerales y los combustibles fósiles. El resto de economías observadas son, al igual que el conjunto de la región, exportadoras netas, aunque con rangos muy variables que van desde una situación casi balanceada en Uruguay, hasta desequilibrios extremos como el observado en Venezuela con 6,7 t hab-1 año-1.

Igualmente, se encuentran patrones de especialización muy diferenciados. En la Figura 3.6 se muestra el tipo de especialización comercial en todos los países analizados. En concreto, se evalúa el nivel de importación o exportación neta en los productos extraídos del manto superficial del suelo (biomasa) frente a los productos extraídos del subsuelo (minerales y combustibles fósiles). En esta figura, el perfil exportador se evidencia en valores superiores a la unidad y valores inferiores son indicativos de un perfil importador. Así, se identifican tres grandes grupos subregionales: 1) Países centroamericanos que son importadores netos en general, pero exportadores netos de biomasa. Esto se debe a que, a pesar de

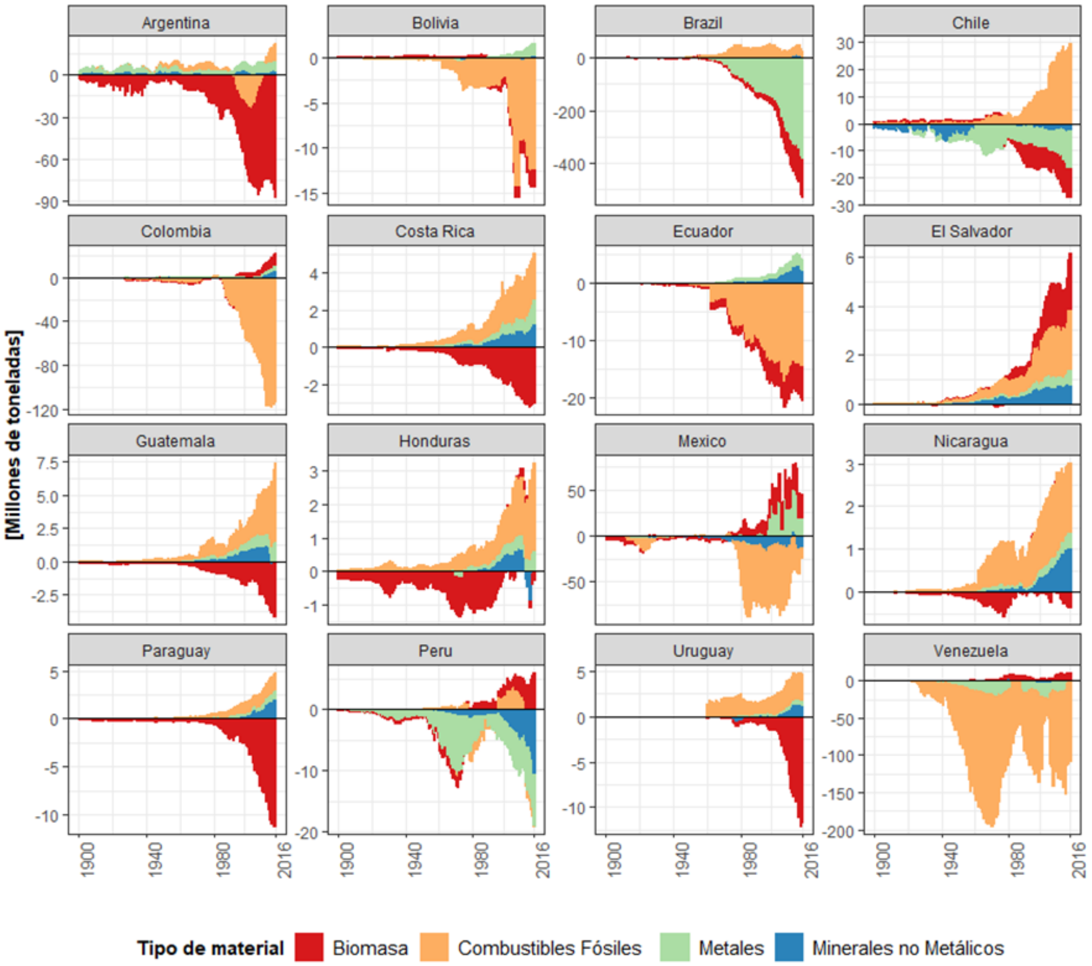

Figura 3.4: Balance comercial físico (PTB) a nivel nacional por tipo de material (1900–2016). Fuente: Elaboración propia (ver apartado 3.2.3). Nota: hemos eliminado la información de Uruguay entre 1900 y 1970 debido a la baja fiabilidad de la estimación.

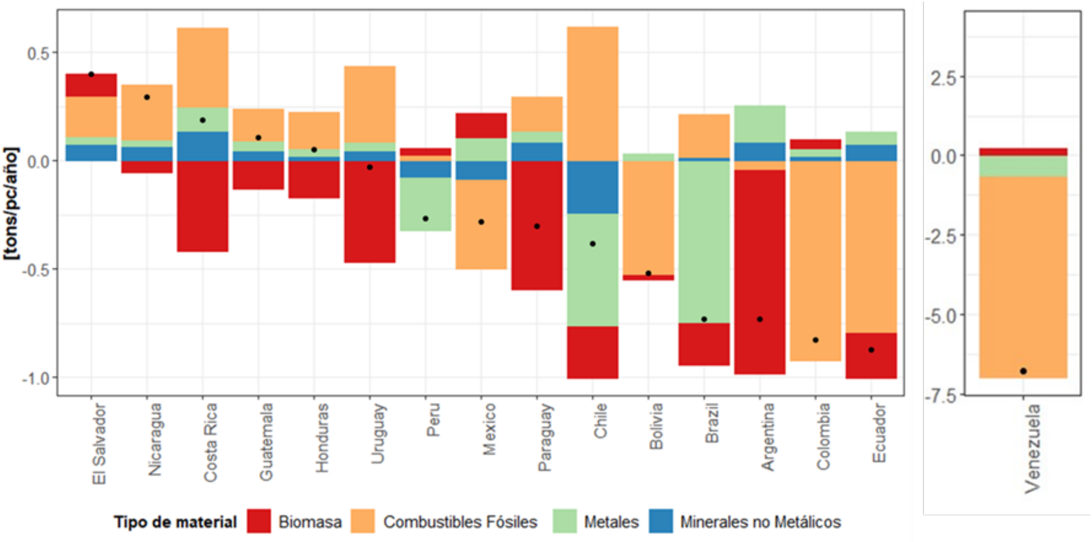

Figura 3.5: Balance comercial (importaciones menos exportaciones) por habitante y año. Datos del período 1900-2016. Fuente: Elaboración propia (ver apartado 3.2.3). Nota: los datos de Uruguay solo recogen el período 1970-2016.

ser exportadores netos de biomasa por su especialización en productos tropicales como el café, el cacao o el banano, y de productos ganaderos, son dependientes de combustibles fósiles. 2) Países del Cono Sur, que al igual que el grupo anterior son demandantes netos de subsuelo y exportadores netos de suelo. A diferencia de Centro América, la especialización comercial en productos derivados del suelo, como granos y productos pecuarios, responde adecuadamente a la abundancia relativa del factor tierra sobre el factor trabajo que define la tradición exportadora de los países del Cono Sur (O'Rourke & Williamson, 1999). La mayor disponibilidad por habitante de superficies aptas para la agricultura hace que el nivel de tierra exportada per cápita también sea superior. 3) Países andinos, principalmente exportadores netos de subsuelo. En Colombia y Venezuela las principales exportaciones son los combustibles fósiles mientras que en Chile y Perú destacan los metales. Este grupo es, no obstante, más heterogéneo. Por un lado, Colombia, Perú y Venezuela son importadores netos de biomasa. México tiene un patrón similar a estos tres países. Por otro lado, Chile, Bolivia y Ecuador, además de ser exportadores de subsuelo, también lo son de suelo. Brasil también entraría en este grupo. Estos últimos cuatro países son "exportadores totales", tanto de productos del subsuelo como de tierra. Destaca Brasil, que es el principal exportador en la región, concentrando casi el 60 % de las exportaciones totales de materiales.

3.3.3 Los actores globales

Tal vez uno de los aspectos menos conocidos del comercio de materiales es el de las relaciones bilaterales entre países ¿Hacia dónde fluyen los recursos que exporta América Latina? ¿Han cambiado los países receptores a lo largo de la historia? Es un canon señalar la transición de la influencia colonial europea hacia el dominio norteamericano en el control de las actividades extractivas en la región. Aunque este proceso es bien conocido en el comercio monetario, no se cuenta con estimaciones desde un punto de vista físico a nivel agregado nacional y regional. Lamentablemente, en el caso de las relaciones bilaterales del comercio de materiales la información solo está disponible a partir de 1966.

Las Figuras 3.7 y 3.8 muestran el destino de las exportaciones y el origen de las importaciones de América Latina como región en términos netos. En efecto, Europa y Norte América han acaparado hasta el cambio de siglo casi tres cuartas partes de las exportaciones de América Latina. El flujo de recursos que sale de la región tiene como destino principal un pequeño grupo de países del Norte global que concentran menos del 10 % de la población mundial, pero que suman casi la mitad del PIB mundial (WB, 2021b). Esta influencia, que solo se documenta desde la década de 1960 es, con toda seguridad, una continuación de la dominación de las potencias hegemónicas en el subcontinente

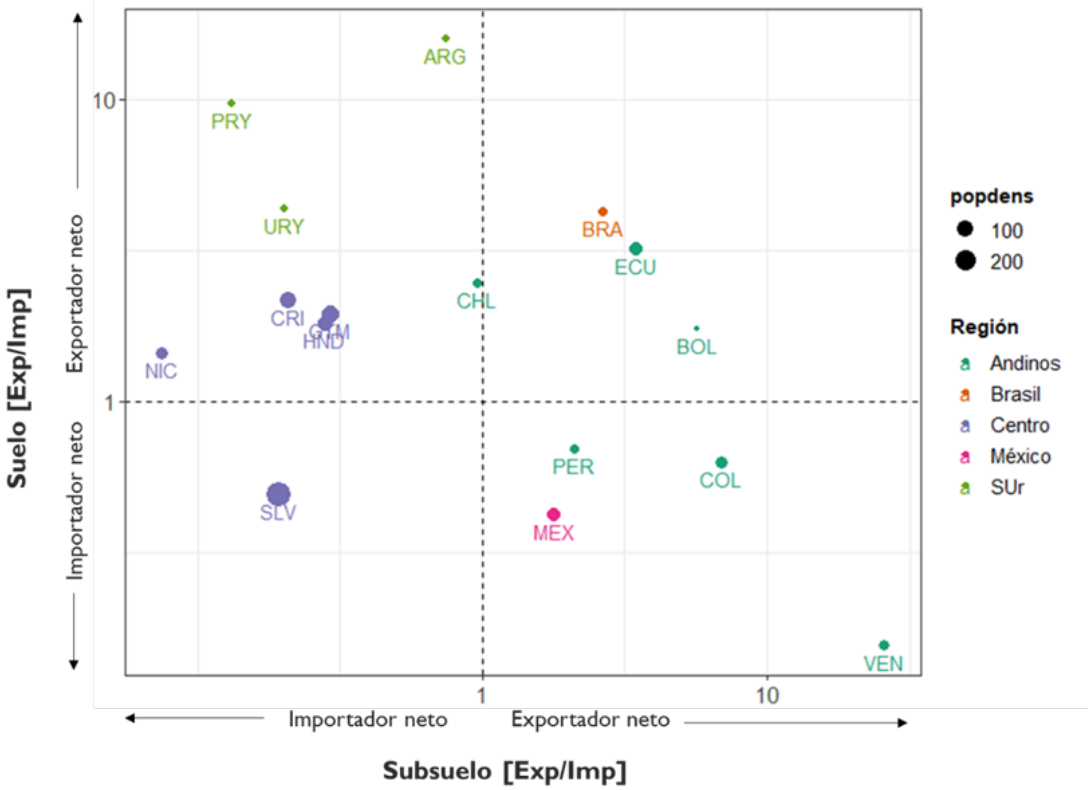

Figura 3.6: Perfil exportador de los países de América Latina. Los ejes miden las exportaciones dividido por las importaciones. Los ejes miden las exportaciones dividido por las importaciones. Fuente: Elaboración propia (ver apartado 3.2.3). Nota: Valores superiores a 1 indican un perfil exportador. Menos de uno corresponde a un perfil importador. Suelo incluye la biomasa y subsuelo el resto de los materiales.

desde hace siglos: primero, bajo la dominación colonial formal y después, bajo la dominación colonial informal (Ferguson, 2005; Pérez Brignoli, 2018). Los procesos de independencia no trajeron consigo una autonomía plena. Durante la primera globalización la región estuvo dominada por “un imperio informal basado en el libre comercio, el control de rutas navieras, la exportación de capitales y una poderosa ideología de superioridad”(Pérez Brignoli, 2018). En el período de entreguerras y tras la Segunda Guerra Mundial, el comercio de América Latina estuvo nuevamente condicionada por las injerencias de EE.UU. que desde principios del siglo XX multiplicó sus inversiones y sus intereses en la región (Ferguson, 2005; Fontana, 2012). Así, hasta bien entrado el siglo XX, la mayor parte de los recursos materiales fluyeron hacia un grupo pequeño de países industrializados que requerían de materias primas baratas para mantener activas las industrias locales.

En la actualidad, y al contrario de lo que cabría esperar, la relación con Norteamérica ha tendido a balancearse. Esto se debe a que las importaciones desde Estados Unidos han crecido aceleradamente con la llegada del siglo XXI: en 1966 las exportaciones netas de América Latina a Norteamérica eran de 99 Mt, en el año 2000 habían bajado a 82 Mt y en la actualidad solo son 2 Mt. Este h

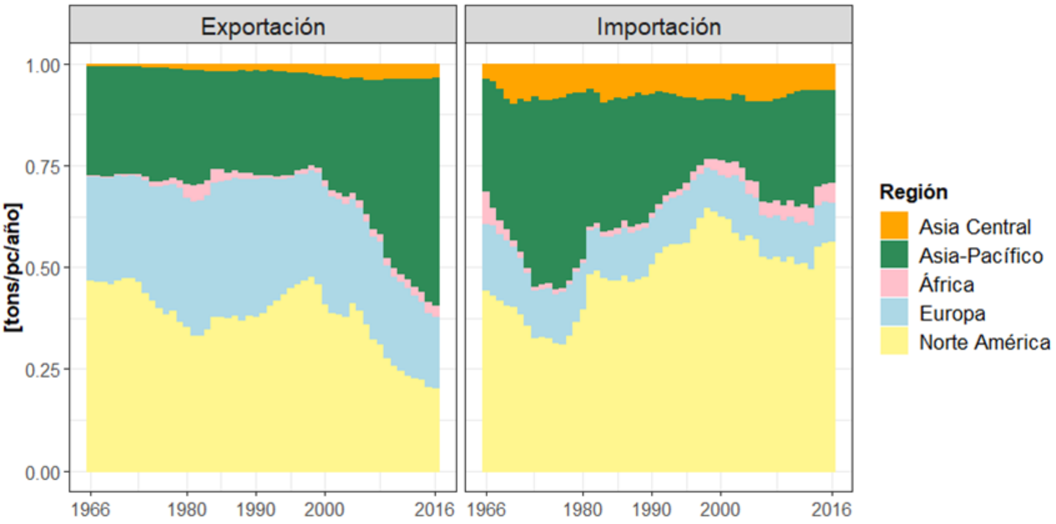

Figura 3.7: Exportaciones e importaciones de materiales en América Latina distinguiendo el socio comercial. Fuente: Elaboración propia (ver apartado 3.2.3).

cambio tiene mucho que ver con la pérdida de autosuficiencia alimentaria en un número cada vez mayor de países de América Latina debido a que la creciente expansión de cultivos de exportación desplaza el cultivo local de alimentos básicos e incluso madera que deben importar de Estados Unidos y Canadá, un rasgo particularmente agudo en América Central (Hall et al., 2000). Esta evolución contrasta con el caso de Europa, en el que las exportaciones netas no han dejado de crecer, pasando de 57 Mt en 1966 a 155 Mt en 2016.

Con el cambio de siglo se observan dos transformaciones disruptivas en el comercio de materiales latinoamericano. Por un lado, en las relaciones Sur-Sur. Hasta finales del siglo XX, las relaciones con África y Asia Central habían sido balanceadas e incluso hasta negativas, esto es, con importaciones netas. Sin embargo, desde el año 2000, América Latina se ha convertido en exportadora neta de materiales a estas regiones, suministrándole 11 Mt y 12 Mt respectivamente en 2016.

El cambio más dramático, no obstante, tiene que ver con el eje Asia-Pacífico. Si bien es cierto que la relación comercial ya era notable en la década de 1960, su peso era menor en comparación con Norteamérica y con Europa. Sin embargo, a partir del año 2000 los flujos de materiales hacia la región Asia-Pacífico, principalmente por la demanda de China, creció de manera acelerada. Solo en 2016 las exportaciones netas superaron los 527 Mt, un valor sin precedentes históricos. El resurgir del eje asiático con China a la cabeza, supone un punto de inflexión en la historia de la economía biofísica global. China y algunos países del entorno se han convertido en los “nuevos talleres del mundoz, en consecuencia, demandan enormes cantidades de energía y materiales. Hoy en día, China concentra el 21 % de las importaciones totales de materiales, mientras que en 1970 apenas alcanzaba el 0,3 %. El renacer oriental, como proceso histórico, está aún en una fase muy

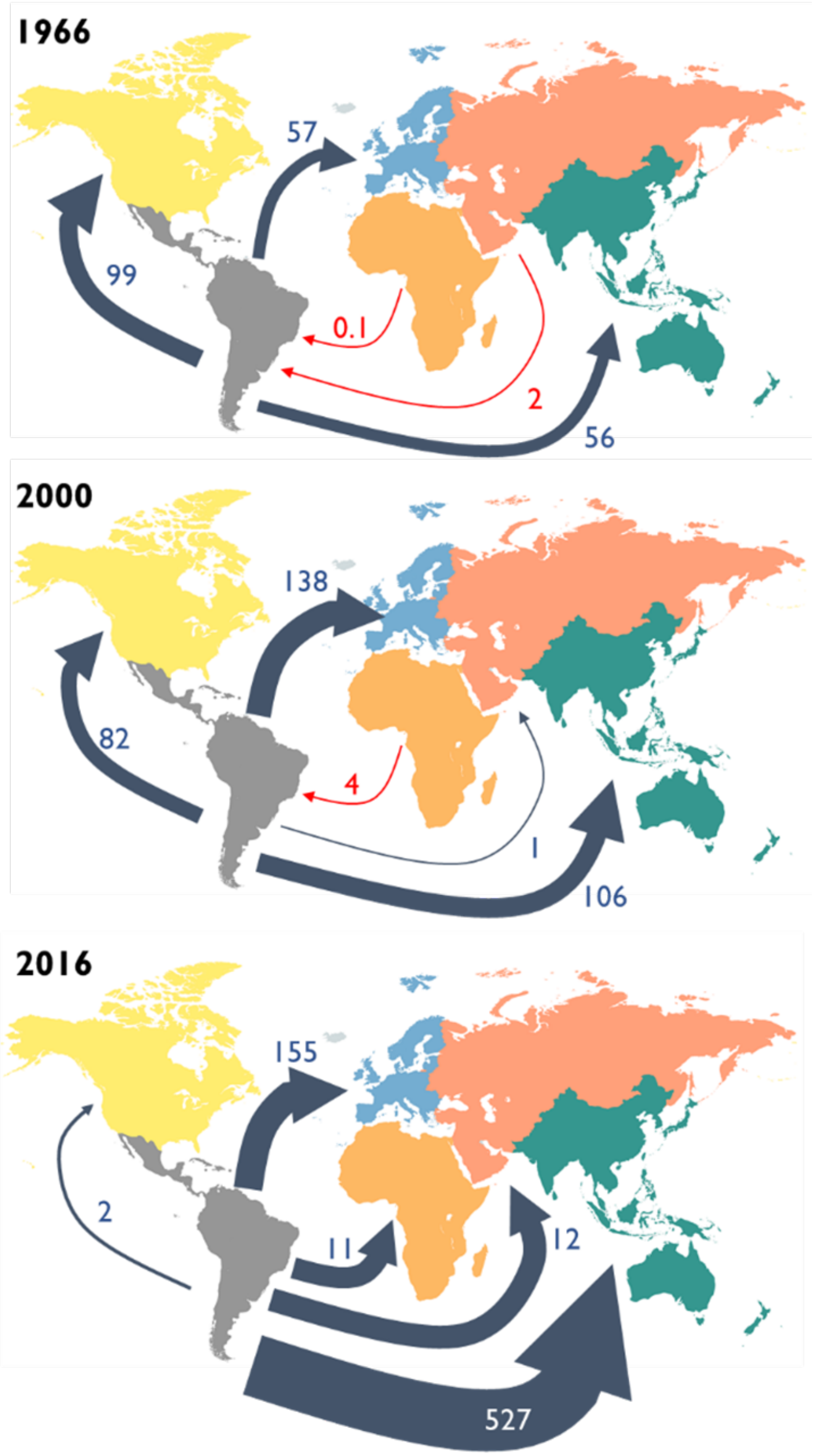

Figura 3.8: Comercio físico de América Latina. Exportaciones netas (azul) e importaciones netas (rojo), 1966, 2000, 2016. Fuente: Elaboración propia (ver apartado 3.2.3).

prematura y es difícil aventurar conclusiones sólidas sobre su impacto en general y en el Sur global en particular. Por un lado, se interpreta que el auge de China solo supone un desplazamiento geográfico del poder hegemónico global sin que suponga ninguna oportunidad en los países periféricos. En este sentido algunos autores están documentando cómo este país reproduce las mismas prácticas de dominación que sus predecesores en los países del Sur global: acaparamiento de tierras, explotación laboral o generación de relaciones de intercambio desiguales que perpetúan la especialización en productos básicos (p. ej., R. E. Ellis (2009).

Por otro lado, existen indicios para pensar que la influencia de China en la economía física global es mucho más limitada y se restringe a la de mero intermediario entre los tradicionales centros de poder global (Norte América y Europa) y las economías periféricas. Los trabajos sobre “huella material”sugieren que buena parte de los productos primarios que recibe China son transformados y luego vendidos, en su mayoría, a países ricos (algunos indicios en Bruckner, Giljum, Lutz, and Wiebe (2012); T. O. Wiedmann et al. (2015). Los países de ingresos más altos siguen, a fin de cuentas, apropiándose de los recursos primarios de América Latina, solo que ahora lo hacen a través de la explotación del trabajo en China, en donde han externalizado las fases de procesamiento.

3.3.4 Notas sobre las relaciones de intercambio y el Intercambio Ecológico Desigual

La relación de intercambio entre dos países expresa hasta qué punto el comercio es beneficioso para cada parte. Desde la Economía Ecológica, una manera recurrente de estudiar este fenómeno es comparar el precio medio por material exportado con el precio medio por material importado. En el caso de América Latina, se observa que durante todo el período analizado el precio por unidad de peso de las importaciones siempre ha sido muy superior al de las exportaciones. De hecho, a lo largo del tiempo esta brecha (en términos absolutos) ha crecido: en 1966 la región pagaba 0,5 $ por cada kg importado mientras que vendía a 0,1 $; en 2016, pagaba 1,6 $ y vendía a 0,6 $. En otras palabras, América Latina tiene que vender muchos más recursos para poder pagar sus importaciones. En la Figura 3.9 se muestra la relación de intercambio distinguiendo las regiones del mundo con las que comercian los países de América Latina. La relación con Europa es la más lesiva: por unidad de peso, las importaciones europeas se pagan entre 6 y 8 veces más caras que las exportaciones. La relación también ha sido desventajosa con la mayoría de las regiones del mundo salvo con África y con Asia Central hasta la década de 1980. Desde entonces la relación con estas regiones también se ha balanceado. Dicho de otra forma, hoy en día América Latina no comercia de manera “ventajosaçon ninguna región del mundo, lo que nos indica una profundización del patrón de especialización basado en la explotación

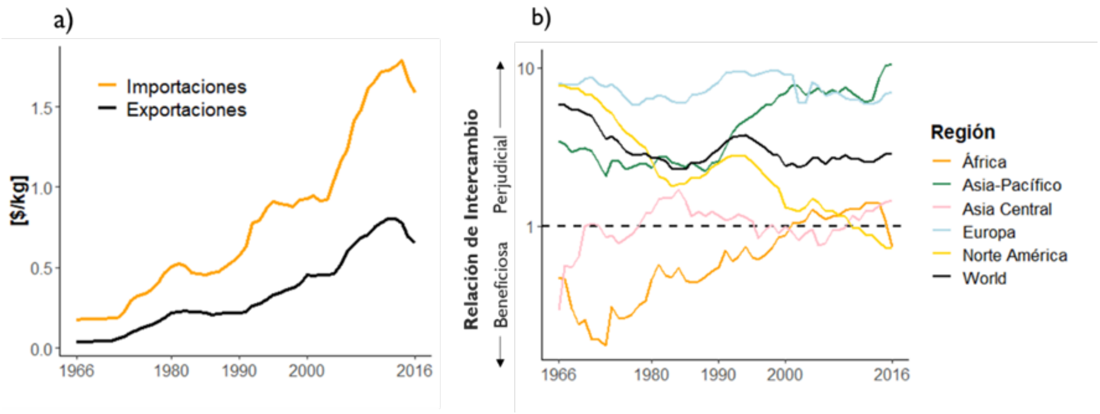

Figura 3.9: (a) Precio de las importaciones y las exportaciones por unidad material ($ constantes por kg). (b) Relación de intercambio con las diferentes regiones del mundo. Fuente: elaboración propia (ver apartado 3.2.3). Nota: Un valor superior a uno indica una relación desfavorable y viceversa.

y exportación de recursos naturales, como se mostró más arriba.

La relación de intercambio de América Latina con el resto del mundo se ha mantenido relativamente estable, fruto de la combinación de comportamientos regionales diferentes: mientras que la relación con África y Asia ha empeorado, la relación con América del Norte ha mejorado. No obstante, se observa que la relación de intercambio mejoró ligeramente hasta bien entrada la década de 1980. En el largo plazo, J. A. Ocampo and Parra (2003a) encontraron un deterioro escalado de los términos de Intercambio de las *commodities* desde 1920, aunque menos claro entre 1920 y 1970, y una tendencia evidente de deterioro a partir de 1980. Sin embargo, al analizar el comercio agroalimentario de la región, Pinilla and Aparicio (2015) confirman el deterioro de los precios relativos entre 1920 y 1950. No obstante, lo que está claro, es que durante el periodo de “Industrialización Dirigida por el Estado”(c. 1930-1975) la dependencia de la región de los mercados internacionales fue mucho menor que durante la Primera Globalización y durante el periodo de apertura económica forzada por la crisis de la deuda externa de 1980 en adelante

A partir de las décadas de 1970–80, no solo se hace evidente el deterioro de los precios relativos de las materias primas (J. A. Ocampo & Parra, 2003a), sino que, además, el colapso de la política de “industrialización dirigida”, abrió la puerta a una nueva etapa de “reorientación hacia los mercados internacionales”(Bértola & Ocampo, 2012). Durante la Segunda Globalización, la reprimerización extractivista y el creciente deterioro de las relaciones de intercambio han marcado la pauta de las relaciones comerciales de la región con el mundo.

A principios del siglo XXI se inició una nueva etapa caracterizada por un alza en el precio de los productos básicos y una gran demanda por parte de los mercados asiáticos. En este período se consolidó la reprimarización del comercio en América Latina junto con una fuerte subida de las importaciones de productos manufacturados. El incremento en el precio de los productos básicos hizo que, no obstante, el balance comercial monetario fuese favorable. La nueva transición hacia los mercados asiáticos ha derivado en una gran descapitalización material, pero, eso sí, con balances comerciales monetarios saneados. Sin embargo, según nuestros resultados, y como han mostrado otros trabajos (Samaniego et al., 2017), esta tendencia parece que se está revirtiendo en los últimos años. Se anuncia una nueva caída en los precios de los productos primarios que potencialmente puede llevar a una situación *lose–lose* ya vivida en la década de 1980: aumento en las exportaciones netas de materiales con balances monetarios negativos.

La situación de desventaja secular se explica principalmente por nivel de procesamiento de los bienes comerciados. América Latina tradicionalmente ha sido importadora neta de manufacturas y exportadora neta de productos primarios, y esta tendencia se ha acentuado con el tiempo y a nivel geográfico: en la segunda mitad del siglo XX ha pasado de ser importadora neta a ser exportadora neta de productos primarios hacia el resto de las regiones periféricas del mundo, incluyendo África.

3.3.5 Comercio y desarrollo económico

Existe un consenso casi generalizado entre los economistas sobre el impacto positivo del comercio internacional en el desarrollo económico. Desde David Ricardo hasta las modernas teorías del comercio internacional se asume que el comercio es un juego de suma positiva en el que todas las partes ganan al sacar provecho de sus ventajas comparativas (Krugman & Obstfeld, 2009). Las ventajas de la especialización no obstante han sido disputadas cuando se analizan casos como el de América Latina. La crítica más profunda y temprana, que hoy ha sido vinculada a la Economía Ecológica, es la que se encuentra en la formulación de la tesis Prebish–Singer. Esta tesis sostiene que la relación de intercambio de los países periféricos, especializados en la exportación de productos primarios, tiende a empeorar a lo largo del tiempo, limitando la capacidad de estos países para desarrollarse[8]. Por otro lado, las teorías de la "maldición de los recursos"también abundan en esta idea, mostrando una fuerte asociación en los países de perfil extractivista con problemas sociales y políticos (Collier & Hoeffler, 2005; Ross, 2013; Wenar, 2015). Con el tiempo, la tesis Prebish–Singer ha sido matizada

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[8] Esta lectura fue la base para el desarrollo de teorías mucho más radicales, como las "teorías de la dependencia.º del "sistema mundo"que no solo corroboraban la existencia de intercambios desiguales, sino que sostenían que éstos se producían por la existencia de relaciones de poder desiguales que perpetuaban el desarrollo del Sur global (Emmanuel, 1972; Frank, 1967). En estudios recientes, otros autores, sin entrar en el impacto económico de este patrón de especialización, cuestionan el papel dependiente de América Latina. Sostienen que la región no fue una "víctima pasiva.º una "simple marioneta"de poderes exteriores, sino que sus actores internos tuvieron un papel muy relevante en las relaciones con otros países y que incluso llegaron a influir decisivamente en las economías exteriores (Topik et al., 2020).

por algunos autores que han documentado que los términos de intercambio no siempre han sido desfavorables para los países periféricos o las *commodities* que exportaban (Hadass & Williamson, 2003; J. A. Ocampo & Parra, 2003a). Sin embargo, estas mejoras no siempre han sido beneficiosas para el desarrollo económico de las economías latinoamericanas. J. G. Williamson (2011) sostiene que la mejoría en las relaciones de intercambio durante la Primera Globalización generó un fuerte incentivo para sostener la especialización primario-exportadora y, por lo tanto, un desincentivo a la industrialización. El crecimiento económico producido durante este periodo fue menor que el experimentado por los líderes industrializados, lo que aceleró la divergencia económica de América Latina con el resto del mundo.

En la Figura 3.10, observamos una clara correlación positiva entre las exportaciones físicas y la renta por habitante a lo largo del siglo XX. Esto es, la descapitalización material que se ha documentado ha coexistido con aumentos en la renta por habitante. Sin embargo, hay dos matices importantes a esta afirmación.

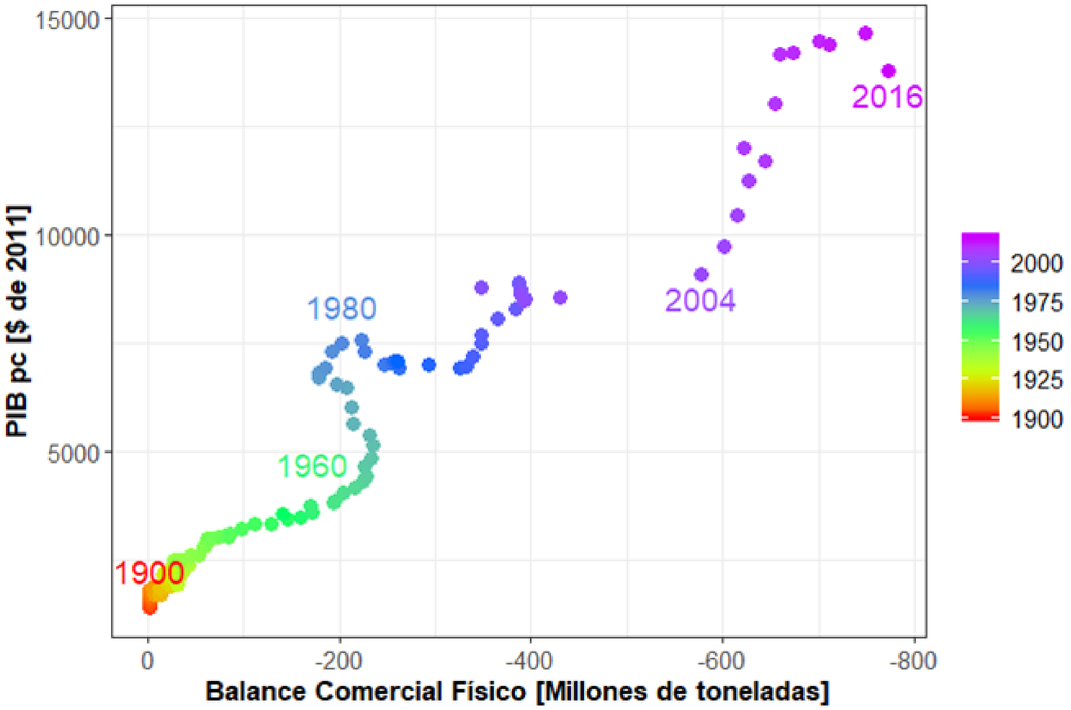

Figura 3.10: Relación entre el balance comercial físico y renta per cápita (dólares constantes de 2010). Fuente: Los datos de PIB han sido tomados del WB (2019), los de comercio son de elaboración propia (ver apartado3.2.3).

En primer lugar, el crecimiento no siempre ha generado convergencia económica con otras regiones del mundo. En la primera mitad del siglo XX la renta por habitante en América Latina pasó de representar un 70 % de la renta mundial a representar casi un 90 %. Sin embargo, en la década de 1980 la renta de América Latina cayó 16 puntos con respecto a la renta global. Aunque hubo crecimiento, también hubo divergencia económica con el resto de los países del mundo.

En segundo lugar, se observa que la correlación entre el aumento de las exportaciones netas y el desarrollo económico no es completamente lineal, sino que muestra discontinuidades históricas en las que es posible distinguir cuatro grandes fases:

1) Entre c. 1900 y 1950, aumentaron paralelamente el crecimiento económico, la convergencia con el resto del mundo y los déficit comerciales en términos materiales. Tras los procesos de independencia la región protagonizó un profundo proceso de cambio en sus estructuras económicas: se liberalizaron los factores productivos y tuvo lugar una rápida apertura al resto de economías. En términos históricos este período se enmarca en la Primera Globalización (1870-1930) y la primera etapa de las políticas de Crecimiento Liderado por el Estado (1930-1950), y se caracteriza por la presencia destacada de la región en los mercados internacionales como exportador de bienes agropecuarios. Aunque la evolución de los precios relativos de estos productos fue positiva durante esa etapa (Pinilla & Aparicio, 2015), su volatilidad limitó el desarrollo de la región aumentando la divergencia con los países industrializados (Blattman et al., 2003, 2004, 2007; Hadass & Williamson, 2003; J. Williamson, 2008).

2) Entre c. 1950–1980 tuvo lugar un crecimiento económico acelerado sin que aumentasen sustancialmente las exportaciones netas de materiales. De hecho, en 1981, justo antes de la crisis de la deuda, la renta media de América Latina superó por primera vez la renta media global. Durante este período tuvo lugar la consolidación de la política de desarrollo hacia dentro en el contexto de la “Edad de Oro”del crecimiento económico (c. 1950–1972). Sin embargo, este modelo de desarrollo entró en crisis. Por un lado, debido a factores externos como la crisis del petróleo. Por otro lado, por un fracaso en ciertas políticas desarrollistas. Las industrias de la región se volvieron adictas a subsidios originalmente diseñados para ayudar temporalmente al despegue de ciertos sectores. Con el aumento del precio de algunos recursos y la competencia de nuevos países asiáticos la producción industrial se volvió cada vez menos competitiva (Fajnzylber, 2017).

3) Tras la crisis del modelo desarrollista se abrió un período de aperturismo comercial y desregulación económica en el contexto de las reformas estructurales impuestas por organizaciones financieras internacionales. En perspectiva, observamos que la década de 1980, la de la “utopía neoliberal”, usando la expresión de Pérez Brignoli (2018), fue especialmente trágica: la convergencia con el resto del mundo se desplomó a niveles de principios de siglo, las tasas de crecimiento se ralentizaron y, sin embargo, las exportaciones netas siguieron creciendo. El continente se empobreció a la vez que se descapitalizaba ambientalmente.

4) Desde el año 2003 se inició una fase similar a la de principios del siglo XX: crecimiento económico y convergencia con fuerte descapitalización

material. Durante este período, gobiernos de izquierdas, en muchos casos de corte indigenista, ascendieron al poder criticando el modelo extrativista y la reprimarizacion de la región. Sin embargo, la evolución positiva coyuntural de los precios relativos les permitió beneficiarse de las rentas generadas por las exportaciones de productos básicos con precios al alza (Gudynas, 2009). Por otro lado, como se apuntaba antes, el flujo de recursos se destina ahora mayoritariamente al eje Asia-Pacífico, hoy convertido en taller del mundo. Existen dudas de si la tendencia de aumento de los precios de los productos de exportación y de las tendencias generalizadas de crecimiento económico sigan creciendo en los próximos años (Samaniego et al., 2017).

3.4 REFLEXIONES FINALES

Existe un amplio consenso a la hora de caracterizar a América Latina como una región del Sur global especializada en la provisión de energía y materiales a las metrópolis globales. Sin embargo, la base empírica que sostenía este dibujo era aún muy limitada. En este trabajo se ha cuantificado el flujo total de materiales exportados e importados por la región desde 1900 hasta la actualidad, el valor monetario de esos intercambios y se han analizado las principales características de su modelo de especialización.

Los resultados obtenidos corroboran el “saber convencional”: América Latina siempre ha sido exportadora neta de materiales y la retribución que recibe por los bienes que vende son menores de los que recibe por los bienes que compra. Sin embargo, este trabajo aporta nueva evidencia empírica que ayuda a comprender mejor el papel de América Latina en la economía biofísica global. Destacan seis grandes ideas:

1) La contribución material de América Latina no ha dejado de crecer en todo el período analizado, aunque la mayor aceleración tuvo lugar desde la década de 1980. La región ha jugado un papel determinante en la segunda fase de la conocida “gran aceleración”, sustentando el gran crecimiento del consumo de materiales a nivel global. El nivel extractivo reciente ha alcanzado niveles sin precedentes: es posible que en las últimas cuatro décadas se hayan extraído más materiales para la exportación que en toda la historia previa de la región.

2) Una particularidad de América Latina entre las regiones periféricas del mundo es su alta diversificación en la exportación de materiales: a lo largo de la historia ha sido el principal suministrador, de productos agrarios, metálicos y petrolíferos. El peso de los diferentes tipos de recursos ha variado a lo largo de la historia: a principios del siglo XX los productos agrarios y ganaderos fueron el principal rubro de exportación; entre c. 1930 y 1950 lo fue el petróleo; después de la Segunda Guerra Mundial tuvo lugar un auge sin precedentes de la exportación de metales; y con el cambio de siglo la biomasa, con manejos agrícolas

muy intensivos, volvió a cobrar importancia. En cualquier caso, en todos los períodos ha persistido una fuerte diversificación extractiva que hace de la región un escenario de conflictos ambientales de todo tipo a nivel global.

3) La geografía del flujo de recursos que sale de América Latina ha cambiado sustancialmente a lo largo de la historia. Hasta finales del siglo XX, el principal flujo exportador iba dirigido a Europa y EE.UU., y existía una relación balanceada con el resto de periferias. La dirección de los flujos de exportación ha estado dominada durante la mayor parte del siglo XX por una suerte de “colonialismo informal”que dominó el subcontinente desde el siglo XIX. En los últimos 20 años el eje Asia-Pa-cífico, liderado por China, se ha convertido en el principal importador de materiales. Aunque es pronto para evaluar la naturaleza de esta transformación, se vislumbran dos posibles interpretaciones: por un lado, que esté teniendo lugar un cambio en la geografía del poder global en el que China está desplazando el papel hegemónico de Estados Unidos y Europa; por otro lado, es posible que China simplemente sea un mero intermediario entre las tradicionales potencias del norte, y la periferia global. Por último, con el cambio de siglo, también se observa un cambio en las relaciones Sur-Sur. Por primera vez en la historia, América Latina es también exportadora neta a gran escala al resto de regiones periféricas del mundo.

4) Como era previsible, América Latina muestra una relación de intercambio desfavorable con el resto del mundo fruto de ser exportador neto de productos primario e importador neto de productos manufacturados. Esta relación ha sido más gravosa con Europa y EE.UU. A partir de la década de 1980 también se ha deteriorado con África y Asia Central.

5) A lo largo del siglo XX han aumentado tanto las exportaciones físicas netas como la renta por habitante. Sin embargo, esta relación no es exactamente lineal: durante la primera mitad del siglo y desde el año 2003, la región combinó descapitalización natural con aumento precario de la renta y la convergencia. En ambos períodos, la biomasa jugó un papel muy relevante. Entre mediados del siglo XX y la crisis de la década de 1980, coincidiendo con las políticas de “sustitución de importaciones”, se vivió una situación óptima: aumentó la renta y la convergencia económica sin tanta descapitalización natural; sin embargo, esta política pudo ser parte (no exclusiva) de la crisis que se desencadenó en 1982.

6) Los teóricos del Intercambio Ecológico Desigual argumentan que los países más pobres del mundo son suministradores netos de materiales al resto del mundo. En efecto, lo países de América Latina, entre los más pobres del mundo, son mayoritariamente exportadores netos de materiales. No obstante, dentro de la región no se observa esta relación de un modo lineal: países muy pobres como los de Centroamérica son los principales importadores de materiales. En este sentido, la densidad poblacional parece jugar un papel clave, aunque son necesarios estudios adicionales para testar esta hipótesis.

Aunque este trabajo aporta nuevas evidencias en el debate de las “venas abiertas”de América Latina, es solo un primer paso para comprender adecuadamente el papel de la región en la economía biofísica global y, en consecuencia, en el desarrollo del Antropoceno. Existen varias preguntas abiertas que se deberán resolver en futuras investigaciones. En primer lugar, como se acaba de apuntar, es necesario estudiar con más detalle cuáles son los determinantes de la descapitalización material a nivel nacional, en los que la densidad poblacional, la dotación de recursos o factores sociopolíticos específicos seguramente jueguen un papel clave. En segundo lugar, es preciso estimar el nivel de extracción y de consumo para diferenciar no solo el suministro neto al resto del mundo sino la presión real sobre los ecosistemas de cada territorio (a través de la extracción doméstica) así como la responsabilidad de sus habitantes (a través del consumo). Esto es, es preciso estimar el resto de indicadores MFA para comprender el funcionamiento de las economías biofísicas de los países analizados. De esta forma podremos evaluar la divergencia entre los niveles de consumo y extracción de América Latina con resto del mundo.

Por último, este trabajo solo se ha centrado en los flujos de materiales directos. La cuantificación en unidades materiales permite agregar la mayor parte de bienes consumidos por un país, pero agrega bienes con diferentes características y pondera su impacto teniendo en cuenta únicamente su peso. En trabajos sucesivos es preciso cuantificar los flujos de recursos con métricas que informen mejor de problemas ambientales específicos como la tierra y el trabajo incorporados en el comercio, los flujos de energía o los flujos de nutrientes.

Chapter 4

Food Security, Trade Specialization, and Violence in Colombia (1916–2016)

Keywords: Food Security, Food Availability, Self-sufficiency, Agricultural Trade, Conflict in Colombia, Twentieth century

4.1 INTRODUCTION

The sustainable development goal of zero hunger and assuring access to food as a main human right are among the major challenges of our contemporary societies, especially in developing countries where more than 800 million people still go hungry today (FAO, 2019a)[1]. Food-security issues in developing countries, such as shortfalls, under-nutrition, food availability, and a lack of access to food of minimum quality are at the core of debates over economic development and international trade, since ensuring the availability of enough quality food is critical to human capital formation, individual productivity, and ultimately economic development, as it has been throughout human history (Fogel, 2004). Therefore, the multi-criteria evaluations of socioeconomic and historical approaches can contribute to the understanding of food insecurity (Porkka, Kummu, Siebert, & Varis, 2013; UNHRC, 2020). This work aims to integrate historical and empirical analysis of food security, agricultural trade, and violence in Colombia to shed some light on the relationship between food security and agrarian trade between 1916 and 2016 on the one hand, and to establish the role of armed conflict and international markets as drivers of the tropical trade specialization since the Second Globalization (c. 1980) on the other.

Market and non-market advocates stress the negative and positive effects of trade on food security. From a market-based perspective, trade is a useful

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way to maintain food security nationally. International trade can allocate food from countries with abundant food supplies to countries where the supply of food is scarce (Runge, Senauer, Pardey, & Rosegrant, 2003). Trade openness has a positive impact on dietary energy consumption, as well as improving diet diversity (Dithmer & Abdulai, 2017), and short-term food security (Dorosh, 2001). Although imports of food can also alleviate food shortages in favourable policy environments, exports can negatively affect food security (Shettima, Zakaree, Sa'ad, & Shettima, 2019).

Focussing on self-sufficiency, some research suggests that trade liberalization and specialization in agro-exports threaten domestic food security in developing countries (Kumar Sharma, 2016; UNHRC, 2020). After the second World War and up to the 1970s, the promotion of national self-sufficiency became a worldwide political response, but since the 1980s the promotion of agricultural exports and trade liberalization in developing countries has changed this policy (O'Hagan, 1976). Since this moment, the food regimen literature emphasizes that international corporations connected fresh food production and cereal imports in developing countries with agricultural offshoring and the supermarket revolution in developed ones. The main mechanism for creating food dependence and agro-export specialization across the developing world would have been the need to face the foreign debt crisis with relatively well-paid tropical and fresh products (McMichael, 2013).

Food security can be defined as food availability or self-sufficiency, given the greater relevance of the role of trade or the capacity to produce domestically. In this vein, Clapp (2017) argues that this debate between trade and self-sufficiency has been held under a false dichotomy. Following the author, self-sufficiency depends on the political orientations and indicators that are used. However, this is not only a debate but a fact. The decoupling of consumption and production is the current (and future) picture of the global dynamics of agriculture . While more than half of the food availability in Latin America relied on imports during the 2010s, 70% in the case of Colombia (Fader et al., 2013), specialization in high-value agricultural exports has been created through favourable policies promoting the agro-export sector (Norberg, 2019; Patel-Campillo, 2010). Therefore, it seems clear that the food dependency on imports and trade export specialization compound the contemporaneous picture of agriculture across the developing world.

Beyond international explanations, agrarian change towards food dependency and agrarian specialization – for example, in the case of soya in Paraguay, Argentina, and Uruguay – have been linked to the long-term economic interests of the agrarian elites in international markets and state support of these interests (Norberg, 2019). In the case of Colombia, however, this agribusiness development of tropical agriculture has also been linked to the intensification of the armed conflict. Competition over land and territorial control to maintain cattle-ranching and the illegal economy (Richani, 2002) are closely related to the agrarian elites' direct participation in conflict (Gutiérrez-Sanín & Vargas, 2017) by legal (Peña-Huertas, Ruiz, Parada, Zuleta, & Álvarez, 2017) and illegal means, and together with the active role of the state (Ballvé, 2012; Grajales, 2011, 2013). The elites linked to commodity crops such as coffee, banana, or oil palm, who paid for security and fought peasant claims (Gutiérrez-Sanín, 2019), were the direct beneficiaries of land dispossession and the public policies to promote their agribusinesses (Maher, 2015; Vargas & Uribe, 2017). Therefore, in the case of Colombia, agrarian change towards tropical specialization and food dependence can be linked to international market forces, as well as to domestic and non-market forces such as the use of violence.

However, in contexts of a high risk of conflict farmers tend to produce more annual than permanent crops since they require less investment of time and capital, then increases the risks of food insecurity (Arias, Ibáñez, & Zambrano, 2019). According to this approach, conflict would promote the increase in production of annual crops such as grains, while creating no incentives for permanent cropping such as tropical fruits, which is just the opposite of the argument for the use of violence in promoting tropical export specialization and food dependency on international markets of cereals. As a complement, armed conflict would hamper economic and trade development (Collier et al., 2003).

I use a case study of Colombia between the First and the Second Globalizations as a remarkable example to analyse the relationship between food security and agricultural trade, and the role of armed conflict in the agro-export specialization. During the First Globalization (1910–30), the country entered international trade with a progressive crop like coffee. Despite favouring the economic interest of the commercial classes, coffee expansion depended on the intensive use of labour and was rooted in medium-sized family farming (J. A. Ocampo, 1989; Palacios, 1983) due to the difficulties of increasing economies of scale on the slopes of Antioquia. In contrast, during the Second Globalization, increasing conflicts, land-grabbing, and expansions of regressive monocultures such as banana, sugarcane, and oil palm took place in the lowlands. These crops, which are intensive in their use of capital and easy to mechanise in large plots, contributed to land concentration and the displacement of family farming by both market and non-market mechanisms Grajales (2013, 2021); Maher (2015); Peña-Huertas et al. (2017); Vargas and Uribe (2017).

Does the dichotomy between trade and self-sufficiency hold during the Colombian twentieth century? Did armed conflict in Colombia contribute to the specialization in agro-exports during the Second Globalization? To answer the first question, I build on time series from the early twentieth century to the present day on food availability, agricultural trade, self-sufficiency, and land-use changes.

I analyse the evolution of these time series considering the policies from the First to the Second Globalization passing through the state-led growth period. To answer the second question, I test the long- and short-term relationships between tropical agro-export specialization, armed conflict, and relative international prices using a Vector Error Correction Model (VECM) for the period between 1961 and 2016.

The results tell a story of success in improving per capita consumption of calories in the long-term and an impoverishment of diet that parallels the shift in agricultural trade. Colombia moved from being an exporter of tropical foodstuffs to becoming a food-dependent importer of cereals from the 1990s. This transformation did not mean reducing or ending tropical exports but increasing imports of staple foodstuffs. The growth in regular imports allowed some gains in per capita consumption, while also eroding the self-sufficiency capacity of the domestic agricultural system to provide staple foods. Regarding the empirical testing, there is a positive long-term relationship going from violence and international prices towards tropical specialization, which is in line with the argument that the use of violence as a tool of agribusiness development is more than just an obstacle. However, in the short-term the lagged values of specialization and the relative prices are positively associated with the rise in violence. These results open a window to exploring the role of commodity crops as a cause of violence in the short-term.

The chapter discusses some of the implications for food security that can be drawn from the historical evidence beyond the dichotomic debate and also draws some lines of the framework of the long- and short-term interactions between the international and domestic actors involved in tropical specialization based on the literature on the political economy of violence.

The following section deals with the sources, data, and methodology used. Section three presents the main results, namely the evolution of the time series on food security and agricultural trade on the one hand, and the dynamics between tropical specialization, armed conflict, and international prices in the VECM on the other. The discussion in section four is split between the historical lessons of the relationship between food security and agricultural trade, and a sketch of the framework to understand the relationship between tropical specialization and violence. Finally, some concluding remarks are provided.

4.2 DATA AND METHODOLOGICAL APPROACH

I propose two methodological approaches: the historical description of the relationship between food security and agricultural trade from 1916 to 2016, and the empirical testing of the long- and short-term interactions between tropical specialization, violence, and relative prices.

4.2.1 Food security and agricultural trade time series (1916–2016)

The data before 1960 is from official records available in the historical archives of the statistical bureau of Colombia (DANE) and the archive of statistics of Latin America in Casa-América at Barcelona University (Urrego & Fuentes, 2016). I harmonized these historical data with the series of production and trade of crops and livestock products available in FAOSTAT (2021) for the period 1961–2016. These series are grouped in eight vegetal food products (Urrego-Mesa et al., 2019, Table S3) and three animal food products.

I use technical coefficients of gross energy for more than five hundred items in trade and production from Guzmán et al. (2014) and Urrego-Mesa et al. (2019, Table S2), and convert into kilocalories. Standardization of trade data before 1961 is based on the composition in 1961, 1962 and 1963 (FAOSTAT, 2021) and the average coefficient by groups of products (Appendix C, Table C.4). Trade information before 1961 was collected from the International Trade Yearbooks (DANE, 1955a; DGE, 1916, 1923, 1929, 1938b, 1945, 1950) and FAOSTAT (2021) since then. The database contains data on all the agricultural trade filtered to collect food products and excluding seeds or animal feeding. The use of kilocalories in agricultural trade makes possible to relate the trade patterns with the indicators of food security, which tends to be mostly in units of matter rather than in value (FAO, 2012) (FAO, 2012). This strategy allows to compute the per capita intake and diet composition. Moreover, the energy analysis of the trade balance highlights the role of export specialization as way of extraction and unequal exchange (Givens et al., 2019), which is helpful for the understanding of agriculture as an extractive activity

To track the trends in the food calories involved in international trade, I compute the trade balance (TB) (Eurostat, 2013; Soto et al., 2016), which provides the net imports by subtracting the calories exported (X) to those imported (I):

$$TB_{ti} = I_{ti} - X_{ti} \tag{4.1}$$

In eq. 4.1 and onwards, the t refers to the specific year adopted as the time frame, and i represents the different products coming from each sub-sector of the agricultural system, e.g. the amount of production of maize, plantains, and livestock products. The TB is in deficit when the country exports more food than it imports. This difference is the final trade balance.

The classic definition of food security is based on three dimensions: availability, access, and utilization (Barrett, 2010). In accordance with this definition, this work focuses on the first dimension since it looks at the supply of food nationally. Therefore: the variables to assess food security are the domestic supply (DS) and the self-sufficiency index (SS).

The DS of food also excludes uses such as seed or feed and accounts for agricultural and livestock food products from domestic production (DP) and the TB (eq. 4.2).

$$DS_{ti} = DP_{ti} + TB_{ti} \tag{4.2}$$

Data on domestic production of primary crops before 1960 is from Urrego-Mesa et al. (2019), but I figure sugar, molasses, and non-refined sugar by using the yields of production in the 1940s (Varela Martínez, 1949, 85). Vegetal data were completed by livestock production of meat, milk, fat, and tallow. In the case of meat, the estimation draws on the information of the number of slaughter cattle (male and female) between 1915 and 1950 (Kalmanovitz et al., 1999). The slaughter for small livestock (i. e. pigs, goats, and sheep) during 1915–60 and the years lacking for cattle (1951–60) were collected directly from the Statistical Yearbooks (DGE, 1918, 1928, 1935, 1936, 1937, 1938a, 1949). When carcass weight was not available, I computed the average living weight and applied the yields of 1950 (Varela Martínez et al., 1952) to obtain the average yields of carcass (see Appendix C Tables A.8 and C.1). It must be borne in mind that higher yields in 1950 than 1916 can conduct to overestimation and misinterpretations. Finally, tallow and animal fat are proportional to the number of animals slaughtered.

In the case of milk, and given the fact that Colombia's dairy industry developed around the 1980s (Kalmanovitz & López, 2006), I took the data for cows older than two years (Kalmanovitz et al., 1999) and computed the yields with the amounts of milk recorded for 1961–65 (FAOSTAT, 2021), thus obtaining a yield of 288 kg of milk per cow annually, which is lower than the yields in 1950 (Varela Martínez et al., 1952) and 1961 (FAOSTAT, 2021). I used this lower value to avoid overestimates.

Food availability is the portion allocated for human food in the balance sheets (FAOSTAT, 2021) and the global average of household wastages of food (12%) (Porkka et al., 2013) subtracted from the DS in eq. 4.2. Before 1961, I assumed that this portion was the same as the average percentage of 1961–63 and apply this figure per categories of products (see Appendix C Table C.3). In the case of the TB, the portion of food was obtained with the same coefficients. Finally, the apparent daily per capita consumption is this availability divided by population and 365 days. The population between 1916 and 1949 is given by Flórez Nieto and Méndez (2000) and from 1950 by FAOSTAT (2021).

I compare the evolution of the daily per capita consumption with the minimum requirement of calories (1800 kcal/pc/d) given by Porkka et al. (2013). Note that the amount of food wastage may change across time, increasing with rising household income. Thus, I may underestimate the availability of calories consumed in the past and overestimate the contemporaneous calorific intake, but these changes do not primarily affect interpretation of the long-term. Conversely, the use of this threshold provides information on the quality of the sources and the role of non-market or subsistence agriculture as a source of food, especially before 1961.

The second variable of food security is self-sufficiency (SS). This index allows weighting the role of trade on domestic supply. I figure a self-sufficiency index of calories in a similar way to Falconí, Ramos-Martin, and Cango (2017), but instead of imports in the numerator, I use the net imports. In this way, the index is also informative on the role of exports. The SS indexes for each of the groups of food (eq. 4.3) and for the whole agri-food system (eq. 4.4) are presented:

$$SS_{ti} = 1 - (\frac{TB_{ti}}{DS_{ti}}) \tag{4.3}$$

$$SS_t = 1 - (\frac{\sum_i TB_t}{\sum_i DS_t}) \tag{4.4}$$

The index reports on the full capacity of the agricultural system to provide the domestic supply when it is equal to one. If it is less than one this capacity deteriorates, which means that the availability of food relies on imports, and when the index is higher than one, it indicates that the agrarian system is not only capable of supplying the demand of the country, but it is also an international food supplier, giving some clues to the country's role in internationally traded of food.

Finally, I analyse land-use changes (LUC) as the share of the tropical products involved in the basket of agricultural exports (CC) on the total area harvested, which includes the area allocated to staple crops (SC). In eq.4.5,CC is the addition of fruits, oil crops, stimulants, and sugarcane represented with j and SC is composed by cereals, pulses, vegetables, roots, and tubers represented with k.

$$LUC_t = \frac{\sum_{jt} CC}{\sum_{jkt} SC + CC} \times 100 \tag{4.5}$$

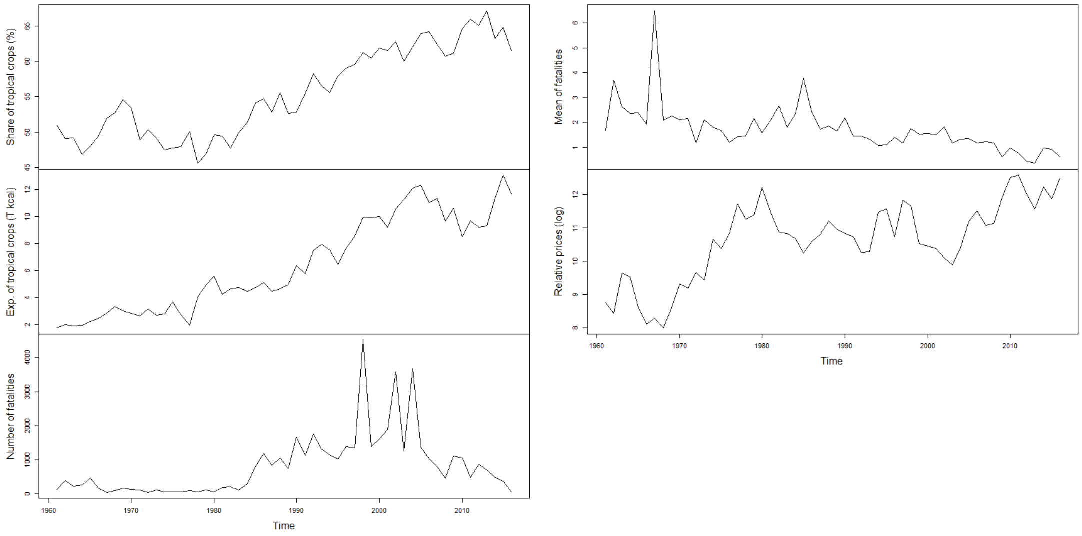

Figure 4.1: Time series for the VECM. Top to down and left to right: 1) the share of tropical crops on the total area harvested; 2) the export of tropical crops in trillion of kilocalories (T kcal); 3) the raw number of deads from the armed conflict; 3) the mean of fatalities; and 4) the relative prices for tropical commodities to cereals in logarithms. *Source:* see Section 4.2.

4.2.2 Vector Error Correction Model (1961–2016)

The second approach of the methodology is the empirical testing of the interactions between tropical export specialization (SP), violence (V), and relative prices (P). The role of relative prices as incentive to specialization is a common place in economics (Feenstra & Taylor, 2017) and economic history (O'Rourke & Williamson, 1999), but this is not the case of conflict (Collier et al., 2003). The political economy literature of war on the second wave of violence in Colombia (c. 1980) has pointed out the use of violence by the agrarian elites and the state as a tool of land dispossession which has favoured the development of agribusiness rather than being a hindrance (Ballvé, 2020; Grajales, 2021; Gutiérrez-Sanín, 2019; Gutiérrez-Sanín & Vargas, 2017; Richani, 2002; Vargas & Uribe, 2017). Therefore, I propose to explore this idea by testing for the long-term co-integration of those three variables and modelling its short-term relationships in a VECM from 1961 to 2016.

SP is the interaction between the LUC (eq.4.5) and the amount of tropical products involved in agricultural exports given above as CC (Figure 4.1 and Table 4.1). I use its interaction due to the LUC and the supply of exports does not necessary occur at the same speed. LUC use to be slower than the supply of markets, especially when the commodity can be stored as in the case of coffee for example. In this sense, the interaction of these two variables will capture better the phenomenon of specialization and its direct links with international markets. The sources for this variable are the same as for the time series of agricultural trade and food security.

In the case of violence, the limits of the temporal coverage of massacres and displacement prevent the use of this information for the model proposed. Therefore, to capture the phenomenon of violence I use the number of deaths derivate from the fighting between the state forces, paramilitaries, and guerrillas during 1961–2016 (CNMH, 2018). I measure the dimension of conflict by the total number per year (V) and approximate the intensity of the conflict as the mean of victims in each case per year ($\overline{V}$). Although these two measures perform so different, the expected outcome is the positive relationship with specialization.

To explore these two measures of violence, I build model 1 and model 2 for V and $\overline{V}$, respectively[2]. The underlying idea is that violence does not act through direct murdering but rather by the fear of the armed fighting and its intensification, which in turn would lead to land abandoning and displacement making easier dispossession and tropical specialization in hands of the rural elites.

This measure, however, has two drawbacks. I am capturing the total effect of violence on tropical specialization instead of the direct violence perpetrated by paramilitaries and the state, as would be captured if I used the massacres as the literature on violence suggests. However, if violence does not act as a tool in favour of tropical specialization, we expect a negative or no relationship at all. This lack of relationship, therefore, would validate the armed conflict as an obstacle to the development of tropical exports, in other words, violence as a market distortion rather than the engine of agribusiness. Additionally, the analysis does not include the role of the state in promoting violence and the agro-export sector, which is central in the hypothesis of violence as a tool of agrarian capitalism formation. To offset this lack, I provide qualitative information of this relationship in the discussion, while also stress the need to extend the work in this direction.

Finally, I use relative prices (P) for tropical commodities to cereals (Geronimi, Anani, & Taranco, 2017) as the market incentives. Comparative advantages and factor endowments are the main factors of productive specialization of a country when opens to trade (Feenstra & Taylor, 2017, Ch. 2-5). If prices act as an incentive, it should affect the decisions on increasing exports and devoting more land to the profitable crops. In our case, expanding tropical crops exports and buying more cereals abroad would be the expected outcome due to the relative abundance of land under tropical temperatures (Figure 1.6 and 4.9). Tropical prices include coffee, oil palm, banana, and sugarcane, and cereals wheat and maize. This decision was based on the trade basket composition of agricultural products in imports and exports of Colombia. In volume, cereals have been two-thirds of imports since the 1960s of which wheat and maize were more than 70% during 1940–90 and since the 1990s, respectively. Regarding exports, coffee and banana dominated with more than 90% during 1929–55, but this percentage has

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[2] The detailed notation, outputs, and robustness checks for the models are in Appendix C

been completed with sugar, fruit, and oil crops since the 1990s.

Table 4.1: Descriptive statistics of the time series for the VECM, ADF and I(d) tests

Variables	N	Mean	St. Dev.	Min	Max	ADF P-V	I(d)
Tropical crops[1]	56	55.50	6.25	45.62	67.16	0.63	1
Tropical crops (Exp.)[2]	56	6.42	3.46	1.78	13.07	0.48	1
Num. of fatalities	56	813.91	927.94	39	4,520	0.98	1
Mean of fatalities	56	1.74	0.94	0.36	6.50	0.57	1
Relative prices (log)	56	10.62	1.18	8.00	12.58	0.41	1

Note: [1]Percentage of the area harvested under tropical crops: stimulants, sugarcane, fruits, and oil crops. [2]Exports in trillion of kcal of tropical crops. Augmented Dickey-Fuller P-Value (ADF P-V) and Integration order (I(d)) tests were conducted with the variables in logarithms

Table 4.1 also shows that the time series used for modelling fulfil the requirements for co-integration testing and VECM, which are the non-stationary condition and the same integration order. VECM does not account for independent variables, but the main assumption is that the variables compose a stable system of equilibrium where stronger variables are marking the trends of the system and weaker variables adjusting to these trends (ECT). In our case, the system is composed of three variables: (SP), (V) – both total and mean – and (P), thus composed by three equations (4.6, 4.7, 4.8). The model gives information on the direction of the relationship between the variables and the effects coming from the past, which is also known as Granger Causality (Lütkepohl, 2005).

$$\Delta SP_t = \theta_1 + \sum_{i=1}^{p} + [\alpha_{1i} \Delta SP_{t-i} + \beta_{1i} \Delta V_{t-i} + \psi_{1i} \Delta P_{t-i}] + \mu ECT_{t-1} + \epsilon_{1t} \tag{4.6}$$

$$\Delta V_t = \theta_2 + \sum_{i=1}^{p} + [\alpha_{2i} \Delta SP_{t-i} + \beta_{2i} \Delta V_{t-i} + \psi_{2i} \Delta P_{t-i}] + \mu ECT_{t-1} + \epsilon_{2t} \tag{4.7}$$

$$\Delta P_t = \theta_3 + \sum_{i=1}^{p} + [\alpha_{3i} \Delta SP_{t-i} + \beta_{3i} \Delta V_{t-i} + \psi_{3i} \Delta P_{t-i}] + \mu ECT_{t-1} + \epsilon_{3t} \tag{4.8}$$

Therefore, if the μ of the ECT is significant, for our variable of interest (SP) in equation 4.6, it means that there is a long term relationship going from V and P to SP. α, β, and ψ denote the coefficients of the lagged values of SP_{t-i}, V_{t-i}, and P_{t-i}, and inform on the short-term effects. Negative and significant values for β, for example, would indicate that the variations on lagged periods of violence are associate with a decrease of the tropical specialization or the opposite in case of positive sign.

4.3 RESULTS

This section provides the main results on the food supply in calories per capita and its composition by groups of crops to inform findings on the gains in calorific intake and the truncated path of the nutritional transition characterized by the surge in cereal consumption. The aim of the second part is to analyse the role of trade in domestic consumption during the twentieth century. I first account for the evolution of the trade balance and then move to the impact of trade on the capacity for self-sufficiency. These results are discussed in chronological order, paying attention to the domestic and international agricultural policies that influenced the country's food security in terms of availability, trade, and self-sufficiency. Finally, I present the results for the long- and short-term interactions between violence, international prices, and food security from the VECM between 1961 to 2016.

4.3.1 Food consumption

Figure 4.2a plots the domestic production of food and apparent consumption of kilocalories per person and day (kc/p/d). In the long-term, this figure depicts two main features. First, the per capita domestic production of food products was higher than the apparent consumption until 1994, winch means that most of the century the country produced more than its imports and, thereafter, international trade has played an especial role in the provision of calories. Second, there is a lack of kc/pc/d to achieve the minimum threshold up to the late 1960s. Based on the historical evidence of the food shortages and the evolution of the availability of food, I argue there was a tension between domestic production and food exports which was solved by the primary of subsistence family-farming during the first half of the century and increasing regular imports of food during the Second Globalization.

Between 1916 and the 1930s, there were improvements in the number of available calories. Despite food production increased (880 kcal/pc/d in 1915 to 1450 in 1935), this was not enough due to more land was ploughed to grow coffee (Urrego-Mesa et al., 2019). To solve this, the Emergency Law of 1927 opened the door to imports of cereals (Kalmanovitz & López, 2006; Thorp, 2000), but apparent consumption stagnated and the difference between production and consumption rose (1938–55). More coffee was exported and food shortages took place again in 1940–45 and 1950–55 (Safford et al., 2002, 320), though, no famines were recorded. Even, there were increases in living standards between 1905 and 1985 with only punctual reductions (Meisel & Vega, 2007).

Although the strategy of facing food shortages with imports of cereals reported positive, the difference between the consumption and the minimum threshold remained substantial. How was this gap filled? If we assume that the minimum requirements were fitted, which seems plausible in the absence of famines, the difference between this minimum and the official numbers could be a proxy of the weight of subsistence agriculture. In this vein, subsistence agriculture would have provided a maximum of 54% of the calories to fit the nutritional requirements in 1916, an average 25% during 1938–55, and 5% till 1970. Increasing production, international trade, or simply statistics improvements were probably intertwined throughout this success story; in any case, this is a first and raw estimation of the ranges of the contribution of the subsistence-style family-farming to the diet during the first half of the century and more work has to be conducted in this line.

After the collapse of the export-led growth model during the Great Depression (Cárdenas et al., 2000b), the supply of food continued rapidly growing during the state-led growth, but there are two different sub-periods. First, from 1938 to 1955 the slow growth of food production (0.3% annual rates) and the dynamism of population increase (2.6% annual rates) hindered the improvement of food consumption. However, from 1955 to 1975, and despite population register its highest growth (2.8% annual rates) and structural change took place (Flórez Nieto & Méndez, 2000), food production expanded faster (1.5% annual rates) and the country overcame the minimum food security threshold due to the improvements on the yields of crops such as cereals, roots and tubers (Urrego-Mesa et al., 2019).

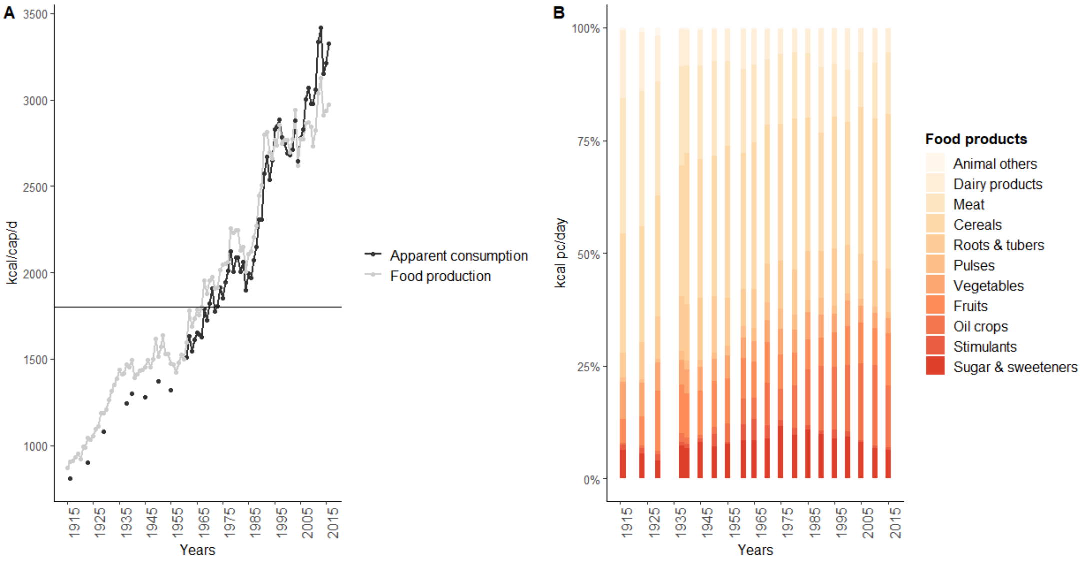

Figure 4.2: **a)** Apparent consumption and production of food in kcal/pc/d and **b)**the composition of consumption (1916–2016). The black line indicates the minimum requirement of calories (1800 kcal/pc/d). *Source: Section 4.2*

However, the leading role of production as the primary source of food provision began to stall, even the yields became stuck (Urrego-Mesa et al., 2019), and a little reverse in the calorific intake took place during the so-called Lost Decade of the 1980s (Bértola & Ocampo, 2012). After that, a quick recovery began till 1997. A mid-term reading from 1997 to 2016 shows the stabilization of per capita consumption near to 3000 kcal/pc/d, though, this process involved a key transformation in the role of food production which fell below the apparent consumption thus stressing the role of international trade as sources of domestic food provision.

This success story of increasing calories is also a staircase growth story of moments of expansion (1916–35, 1960–80, 1985–97, 2007–16) and stability (1935–55/60, 1980–85, 1997–2006). These changing trends are consistent with those shown by the series on heights during the years of export-led growth (Meisel & Vega, 2007). Even more, the falls in average height registered by citetMeisel2007 in 1957–60 were in parallel with the stalemating of food consumption during the mid-1950s. By contrast, the notable gains in calories consumed until 1980 are also consistent with the role of life expectancy as the primary source of Human Development Index growth (Jaramillo-Echeverri, Meisel-Roca, & Ramírez-Giraldo, 2019).

Up to this point, we can infer that domestic production drove these gains in food consumption during a large part of the twentieth-century, but this changed from the 1980s. During the First Globalization (1916–30), food production exceeded the number of calories consumed by more than 10%, but that was reversed during the Second Globalization. Therefore, in addition to the success story of escaping from hunger, there is another telling story of the displacement of domestic production as the leading supplier of food. We shall deal with this process (Section 4.3.2), but let us see the implications of this story for diet composition before.

The main consumption of food in Colombia have been by far that of cereals, which have remained around one-third of the total consumption (Figure 4.2b) and if we add some crops like pulses, roots, and tubers, this share almost reached half of the consumption. More interesting, in the long-term these foods moved from supplying 33% in 1916 to 48% in 1940 and have stayed at around 43–45% of consumption until today. In contrast, animal and oil vegetal sources of calories were half of the total consumption at the beginning of the twentieth century, but declined to a third in 1940, recovered from the late 1980s to 2013 reaching 40%, and currently represents 30% of consumption. Meanwhile, fruit, vegetables, sugar, and stimulants have remained around 20–25%. This sharp reversal of the nutritional transition perhaps is associated with the estimation of meat and the lack of records for vegetal output, especially during 1916–61, as declared (Section 4.2). However, the reversal trend also holds when we look at the more solid data from FAOSTAT (2021) and is particularly evident since the 1980s.

Although the rise of available calories during the Second Globalization is a story of success, the diet composition reveals an unclear nutritional transition or poorer diet starred by more consumption of cereals. The products associated with the nutritional transition or richer diets decreased in relative terms or remained stable. Is there a relationship between the starred role of trade as provider of food and the rise of cereals in diet composition? Now let us analyse the long-term role played by trade in this story.

4.3.2 Calories in trade

In the 1990s, and since 2000, Colombia's agri-food trade balance profile was quite the opposite of the exporter profile for the entire Latin America region (Falconí et al., 2017; Infante-Amate et al., 2020). But before the 1990s the trade balance was also in deficit, around 1.6 Tkcal in 1961–93 and 0.8 Tkcal during the first half of the century (Figure 4.3a). Although the export of higher calorific foods like sugar, fruits, and oil crops expanded after the economic opening (1991), since the 2000s the calories of cereals imported were larger, thus changing the country's profile of the food trade. Understanding the continuities and changes in the food trade involves a look at the history of its domestic policies and international frameworks.

The increase in the amount of coffee (labelled as a stimulants) in exports characterized the overall trend until World War II, accounting for almost the entirety of net exports in 1945 (Figure 4.3b). From the end of the Thousand Days' War in 1902 until 1910, Colombia's regional elites were still seeking potential export businesses, including in cattle, sugar, gold, bananas, and rubber, but the regional interests of the coffee elites took national priority (Safford et al., 2002, 275), becoming the national economic project supported by the state and the main driver of the economic surge (J. A. Ocampo, 1994). This state support of coffee exports served as the main tool to capture foreign exchange and increasing the purchasing capacity to import agricultural implements and machinery.

After 1945 the share of stimulants in total exports began to drop drastically and was replaced by sugarcane first and oil crops thereafter. The International Coffee Agreement (1962–89) helped to stabilise coffee's prices (1950–72) (FNC, 2020), but the negative impact of La Violencia (1948–58) on the growing of coffee became more visible (Bejarano, 2011). The yields of sugarcane grew (Urrego-Mesa et al., 2019) and the number of sugar calories exported surpassed that of fruits in the early 1960s almost attaining the volume of stimulants in 1968, which was possible because of the new opportunities in international sugar markets that opened after the Cuban revolution (1959), especially in the United States.

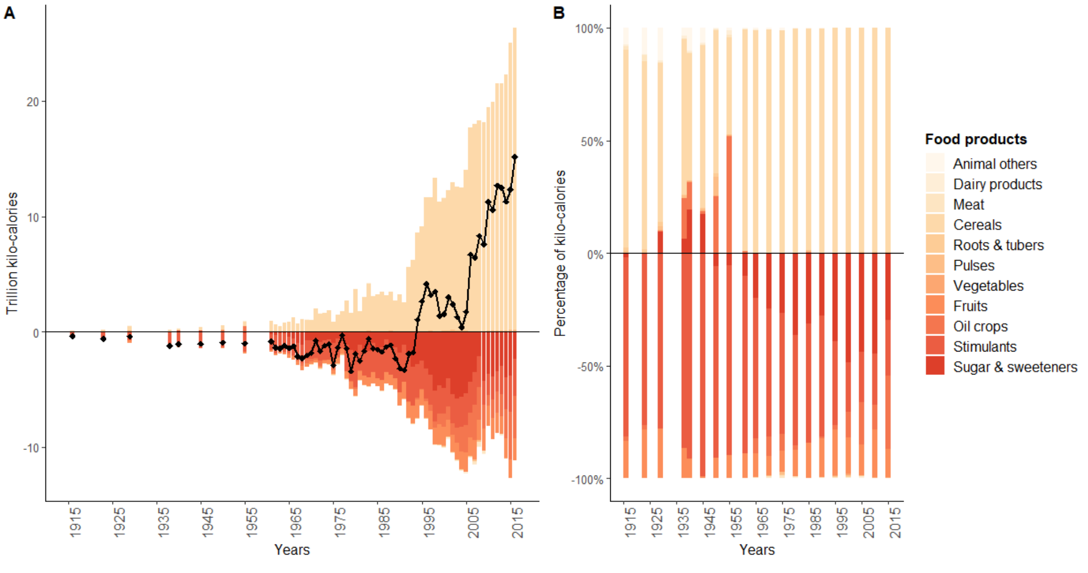

Figure 4.3: **a)** Food trade balance in trillion kilocalories; and **b)** composition (1916–2016). The black line indicates the net imports. *Source: Section 4.2*

The rise in coffee prices during 1975–85 created new incentives to the promotion of technical improvements helping the recovery of the exports of coffee until the early 1990s, though, after 1972 the domestic policy also aimed to transfer public resources to capitalize the agro-exports through infrastructure and credit (Bejarano, 2011, 203). At the aggregate level, however, there was a short period of stagnation of exports during the 1980s. Thus, the surge of the new tropical agro-export model clearly began after the 1990s economic openness with the replacement of coffee by sugar, oil crops, and fruits. Once again, the biased allocation of public credit and labour reforms aimed at increasing Colombia's competitiveness of the agro-export sector (Espectador, 2009; Patel-Campillo, 2010) together with the international price increases for tropical commodities in 2000–10 (IMF, 2020) played a critical role.

Regarding imports, since the First Globalization cereals has shared most of the food imports, but the actual increase began during the Golden Age (1950–72) and since the 1980s. Although the flows of wheat were not big enough to change Colombia's exporter profile, the upward trend is consistent with the emergence of the domestic food industry and its historical disconnection with the agrarian sector (Machado, 1991) on the one hand, and the intensification of agriculture and the beginning of food-aid policy in the United States on the other (McMichael, 2013). The entering of cereals during this period was compatible with the promotion of domestic food production up to the beginning of the 1990s. After this date, however, the imports of cereals moved from 2.5 Tkcal in 1991 to 27 in 2016, thus changing the trade profile of the country to food dependency. At the same food-usage ratio used for production (Appendix C, Table C.3), cereal imports shared 12% and 22% of the food consumption in 1994 and 2016, respectively. The third food regime in Colombia is reflected in its trade profile, in the same way as described by McMichael (2013) for the developing world: agricultural specialization of exports and food dependency on imports.

Did this tropical specialization in exports and cereal imports affect somehow the domestic capacity of agrarian systems to produce food? Is trade responsible for the poorly diet registered in food composition? In the next section, I shall deal with these questions by relating trade and domestic supply and analysing the land-use changes.

4.3.3 Food dependence and tropical specialization

Figure 4.4 plots the SS index for the whole agri-food system and by groups of crops. The total self-sufficiency deteriorated by more than 25% in the long-term. The country was a global supplier of food calories until the 1990s with a notable difference between 1916–50 and 1960–90. During the first period, around 15% of production was exported, except for the periods of food shortage, while during the second period, just over 5% of domestic production formed a part of the exported food calories. The mixed model of the state's maintenance of domestic provisioning and export promotion highlighted in the context of the whole economy (Cárdenas et al., 2000a), helps us understand the improvements in food calorific intake between 1955/60 and 1980. A decade later, however, the country lost both its global role as a net provider of food and its capacity to provide calories domestically.

But if we look at the evolution of SS by group of crops, we observe three different trends. First, food products in which SS deteriorated such as cereals and pulses. Currently, imports provide more than 40% of the domestic supply of cereals for human nutrition and the capacity to produce pulses fell by more than 10%. The second group of products are those that reached or maintained the SS. Within this group were traditional roots and tubers and products associated with the nutritional transition such as vegetables and animal products. Finally, in the third group, there are tropical food products oriented international markets, like stimulants, fruits, sugarcane, and oil crops, which attained a SS index higher than the domestic demand requirements. The relationship between the SS for tropical crops and international trade is clearly shown by the peaks experienced during the First and the Second Globalization. However, the loss of the productive capacity in staple crops only occurred after the 1990s, when the country became importer of cereals.

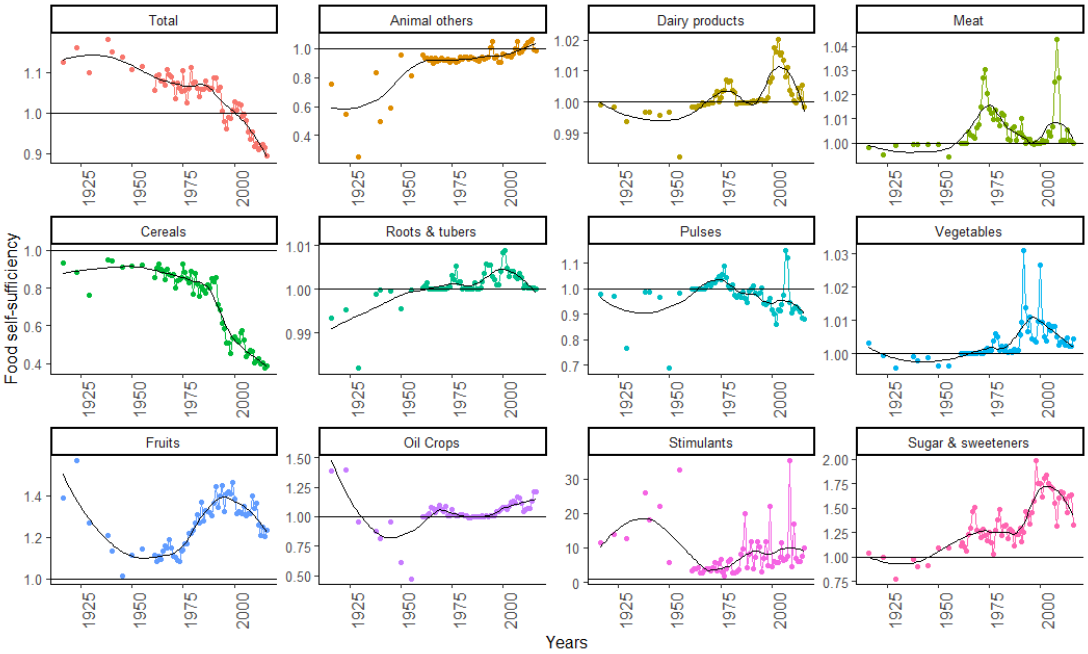

Figure 4.4: Total self-sufficiency and by groups of crops (1916–2016). SS under 1 indicates deterioration of the capacity to produce food. *Source: Section 4.2*

This shifting profile also involved changes in the landscape. Up to the early 1980s, the land-use devoted to SC (Figure 4.5a) and CC (Figure 4.5b) remained evenly distributed around 45% and 50%, but, thereafter, the portion of the area under CC climbed, and this share is currently higher than 60% of the total area harvested. Land specialization in exportable tropical crops was reverse during the 1930s and slowed around the 1970s, while the major accelerations took place during the periods of trade openness, especially the Second Globalization (Figure 4.5c).

Tropical specialization did not necessarily entail a loss of the self-sufficiency capacity during the Firsts Globalization, but it was the major trait of the second period of agricultural trade entering international markets. Clearly the geopolitical frames boosting agricultural trade and the international price incentives shaped these long-term trends, but the constrains of organic agriculture and the domestic agrarian policy also played critical during the twentieth century. Is there another factor to understand this transformation of the agri-food system towards specialization and dependence? The political economy of war literature argues that violence has contributed to the emergence of the renewed tropical agro-export model. The next chapter explores this hypothesis empirically.

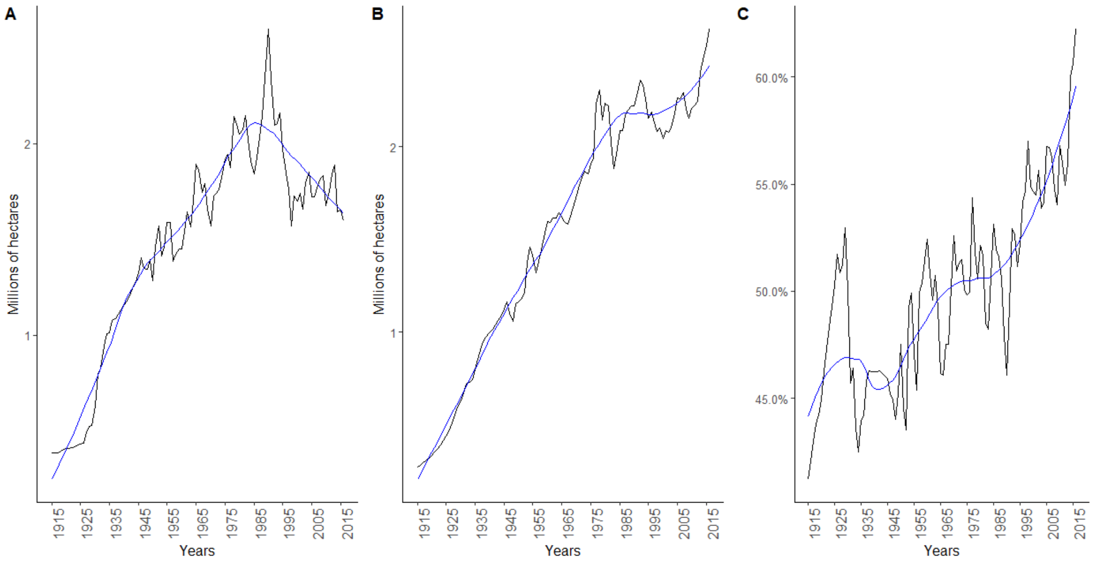

Figure 4.5: Harvest area in millions of hectares allocated to **a)** staple crops, **b)** tropical crops, and **c)** the share of tropical crops on the total area harvested (1916–2016). *Source: Section 4.2*

4.3.4 Did international prices and armed conflict lead to tropical specialization?

The main hypothesis tested here is the role of violence in causing tropical specialization. Therefore, violence as a tool in the tropical specialization of agriculture and entering the international markets, rather than a hindrance for its development beyond the market forces.

The Johansen test for co-integration confirms at least one long-term relationship in the system of variables significant at 1% regardless of the variable of violence used, namely the total number of fatalities (V) or the mean per case $\overline{V}$ (Table 4.2). However, the long-term directions of each of these variables performed differently in the VECM. While model 1 shows a positive relationship that goes from V and P towards SP, in model 2 $\overline{V}$ is negative in the long-term, and $\overline{V}$ is the weak variable which converges towards the equilibrium system (ECT -0.99 [0.32] sig. at 1%). Despite this, and unlike model 1, model 2 does not fit well the robustness checks for the normality distribution of residuals.

Therefore, and based on the normalized co-integrating vector for model 1, 1% increases in V and P are related to 0.5% and 0.2% increases on SP in the long-term. Additionally, the coefficient of the ECT in 4.6 confirms that SP adjusts 35% to the system equilibrium during the first year (-0.35 [0.13], sig. 5%). In other words, changes in V and P lead the SP to move towards the new equilibrium (Figure 4.6).

In the short-term, however, the relationships do not have to go in the same direction (Figure 4.7). As a general picture, there are not positive relationships, but negative ones, that go from the lagged periods of SP_{t-i}, V_{t-i}, and P_{t-i} towards the current outcomes of SP in the equation 4.6. Increases of SP_{t-i} and V_{t-i} in 1% nine and eight years before are related with reductions of 0.6% and 0.1% in SP, respectively. This does not mean that there is no positive relationship at all between tropical specialization

Table 4.2: Maximum Eigenvalue and Trace statistics for constant deterministic terms specification of violence (V) and mean of violence ($\overline{V}$) models

Eigen	test for V	test for $\overline{V}$	10pct	5pct	1pct
r <= 2 |	4.76	4.80	7.52	9.24	12.97
r <= 1 |	19.21	10.20	13.75	15.67	20.20
r = 0 |	38.09	42.87	19.77	22	26.81
Trace					
r <= 2 |	4.76	4.80	7.52	9.24	12.97
r <= 1 |	23.97	15.00	17.85	19.96	24.60
r = 0 |	62.06	57.87	32	34.91	41.07

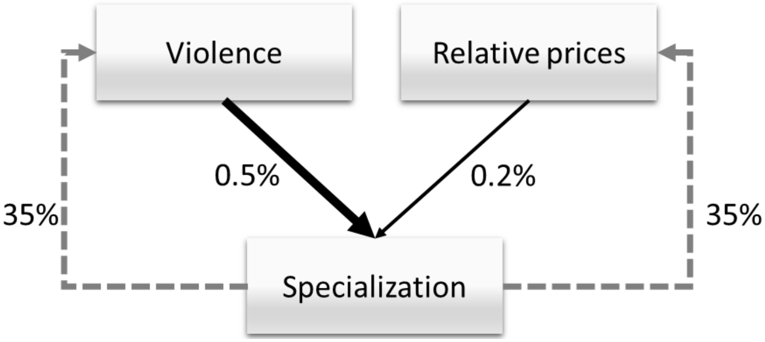

Figure 4.6: Long-term relationships between specialization, violence, and international prices. The black and solid lines are the effect in the co-integration equation to 1% increase. The grey and broken lines is ECT of specialization to the equilibrium in the first year.

and violence.

The results for the equation of violence (eq. 4.7) confirm that the variations of V are positively associated with the variations of the lagged values of SP_{t-i}, V_{t-i}, and P_{t-i}. A 1% increase in SP_{t-i} six to nine years earlier is associated with around 2% increases of violence, which is significant at the 1% level. This process is reinforced by the system of prices whose variations in 1% of its lagged values (P_{t-i}) are associated with a variation of V ranging between 0.56% and 0.75% during the third and fifth lagged year. These effects decline from 0.65% to 0.46% between the seventh and ninth years of lag. Despite the minor effect of P_{t-i} than SP_{t-i} during the fifth and seventh lagged periods, this association is significant at 0.1%.

Finally, violence is a self-reinforcing phenomenon. The past values of V_{t-i} are positively associated with its current outcomes, except for the first lagged period, which indicates that after a year of increase of violence there is a reduction in the next one. However, across the fourth to ninth lagged periods, this relationship is positive with an average effect of 0.52% per 1% variation (sig. at 5% and 1%). In the case of the equation of prices (eq. 4.8), there is only one negative relationship from the third lagged value of SP_{t-i}. Although theoretically solid the effect of this relationship is significant at the 10% level.

In a nutshell there is a positive and long-term relationship going from V and P

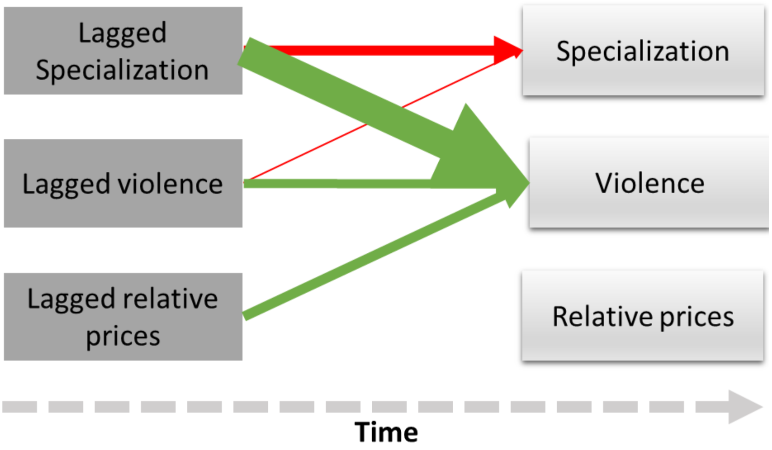

Figure 4.7: Short-term relationships between specialization, violence, and prices in VECM. The width of the arrows corresponds to the average size of the effects significant at the 5% or higher. The grey arrows depict positive relationships and the black ones negative. Time is represented by the broken line.

towards SP. In this system, SP is the weak (or slave) variable adjusting to the equilibrium system. However, in the short-term are the past values of SP_{t-i} and P_{t-i} that shape V. Then, the empirical testing confirms the hypothesis of the use of violence as a tool of tropical specialization as an additional driving factor for market forces in the long-term, but this hypothesis does not hold in the short-term, which also invites us to think of violence as a consequence of agribusiness development and market incentives.

4.4 WHAT CAN BE LEARNT FROM HISTORY?

This section discusses the results of the historical analysis on food security and agricultural trade in the light of the dichotomic debate during the fluctuations of the First and the Second Globalization and introduces the role of the state in the long-term interactions between violence, prices, and tropical specialization.

4.4.1 The dichotomy between agrarian trade and self-sufficiency

The long-term analysis of the Colombian case brings to light two basic ideas. The historical analysis allows us to rethink the relationship between trade policy and food security beyond the dichotomic debate as highlighted by Clapp (2017) and it also contributes to extending the time frame analysis of the world's self-sufficiency policies observed by O'Hagan (1976) back into the past in a developing country of Latin America.

First, different food-security measures told us different stories considering the same policies and periods throughout twentieth-century Colombia. The availability of food and the per capita intake reflects a success story of increasing calories, regardless of the policies of promoting staple or tropical crops as the market-based approach advocates

(Dithmer & Abdulai, 2017; Dorosh, 2001; Runge et al., 2003; Shettima et al., 2019). However, the self- sufficiency index and the land-use change demonstrates the declining productive capacity of staple crops and specialization in tropical crops for international markets, especially during the Second Globalization. These results agree with criticisms of food trade liberalization (Fader et al., 2013; Kumar Sharma, 2016; Patel-Campillo, 2010; UNHRC, 2020). In this same vein, food dependence on imports of cereals has gone hand in hand with a relative decrease in the intake of animal products, which leaves a picture of a truncated nutritional transition or diet impoverishment.

Second, O'Hagan (1976) stated that national self-sufficiency is a political decision by governments in a global context. Therefore, state capture by elites in developing countries also implies self- sufficiency policies being determined by group interests and the power balances within them. As shown for Colombia, the changes in this index are consistent with the start of deterioration in developing countries of Latin America observed by O'Hagan (1976) in the 1970s and thereafter, but the long-term analysis also confirms there was a previous support for self-sufficiency within the frame of the First Globalization and the state-led growth periods. The results show a mixed model of trade integration and domestic production being promoted that maintained self-sufficiency until the 1980s. After this date, international trade openness under the Second Globalization led to the renewed agro-export model and food dependence on imports, as occurred around the developing world (Kumar Sharma, 2016; McMichael, 2013).

4.4.2 Tropical specialization and armed conflict

The spatial pattern of conflict overlaps with the regional distribution of tropical specialization. As Figure 4.8 shows, the accumulated victims of massacres (1980-2012) are spatially located in places where the density of the area under tropical crops is also greater, such as the banana in Urabá and Magdalena, sugarcane in the Cauca Valley, or oil palm in Meta (Figure 4.9). This distribution is according to the idea of the use of violence for the purpose of developing agribusiness projects for tropical products, tested in the VECM, and which was a result of the convergence between the counter-insurgency aims and the economic interests among regional agrarian elites, multinationals, paramilitaries, and the state during the second wave of violence (Ballvé, 2012; Grajales, 2011, 2013; Gutiérrez-Sanín, 2019; Gutiérrez-Sanín & Vargas, 2017; Peña-Huertas et al., 2017; Richani, 2002, 2012; Vargas & Uribe, 2017).

The massacres were used to intimidate the guerrillas' supporters and to recover territorial control. The paramilitaries and the state perpetrated on average 66% (sd. 18) of the massacres between 1980 and 2012, while the guerrillas committed 22% (sd. 16) (CNMH, 2018). Sometimes this was connected with the control of coca production, sometimes with guaranteeing the security and economic interests of the agrarian elites and multinationals, but in any event, it promoted land accumulation.

Land that had been forcibly abandoned was accumulated by exploiting the traditional bias of state institutions and the regulation of property rights to favour landowners (Richani, 2012). This traditional bias was reinforced by the emergence of

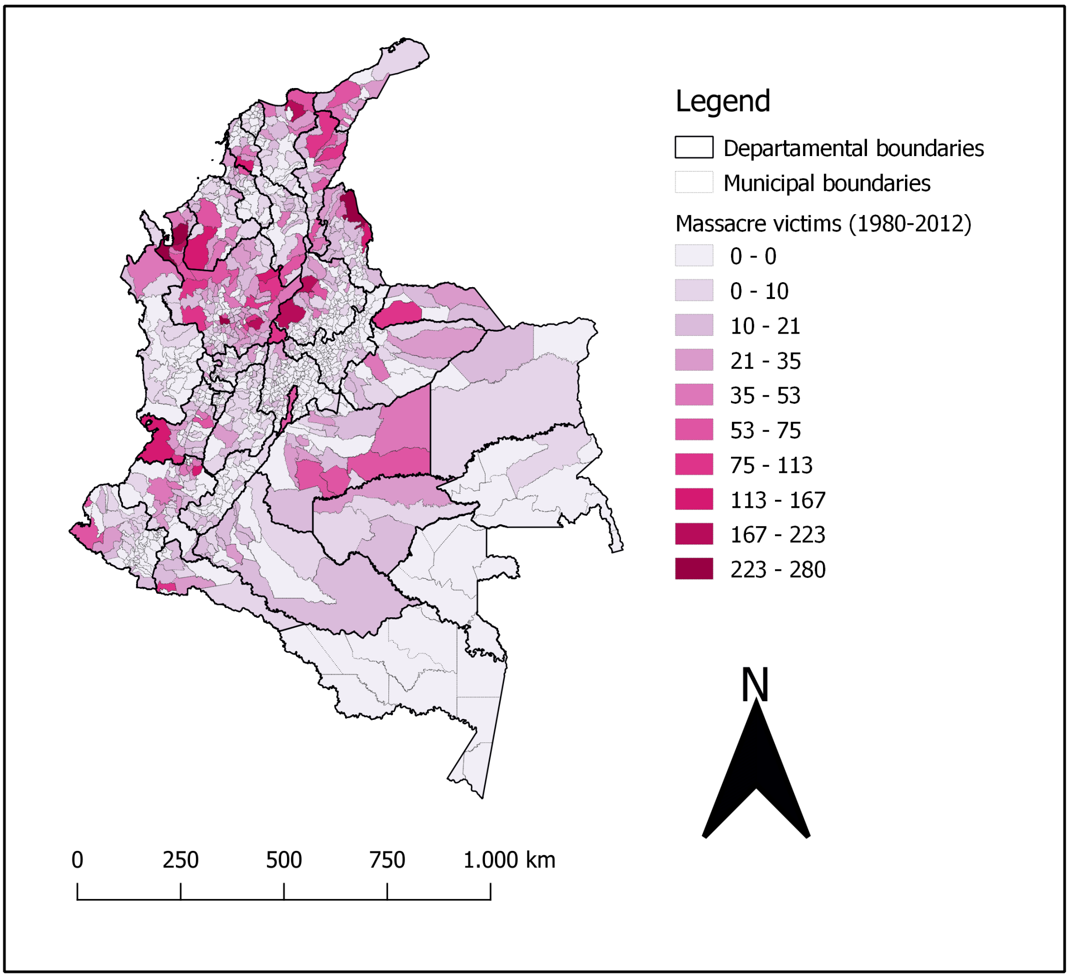

Figure 4.8: Accumulated massacres during 1980 and 2012. Own elaboration. *Source:* CNMH (2018).

new legal tools to promote massive dispossession. In this regard, Peña-Huertas et al. (2017) distinguish three types of legal dispossession during the second wave of violence: the threat of coercion in private transactions, underpayments in private transactions enforced by fear or for protection, and administrative dispossession by obtaining the land titles of persons expelled by violence. Cattle-ranchers, the narco-bourgeoisie, and urban elites bought land as an investment to launder money or to keep their patrimony safe under circumstances of currency devaluation (Richani, 2002), making less profitable to produce food (Rincón-Ruiz, Correa, León, & Williams, 2016).

Once coercion had been introduced and the purchases of abandoned land implemented, government policies promoted the implementation of ago-industrial projects (Figure 4.10). INCODER helped to ease foreign and local investment (Richani, 2012), while the “Agro Ingreso Seguro” would have granted cheap public credit to the narco-bourgeoisie and landowner families (Espectador, 2009), labour reforms aimed to guarantee international competitiveness (Patel-Campillo, 2010), and, eventually, favourable international prices (2000-10) (IMF, 2020) created the incentives to revive tropical specialisation once again. Traditional organizations of the representation of the agrarian elites, such as the Colombian Agrarian Association, the Livestock Federation or the National Federation of Coffee Growers, which had been weakened during the

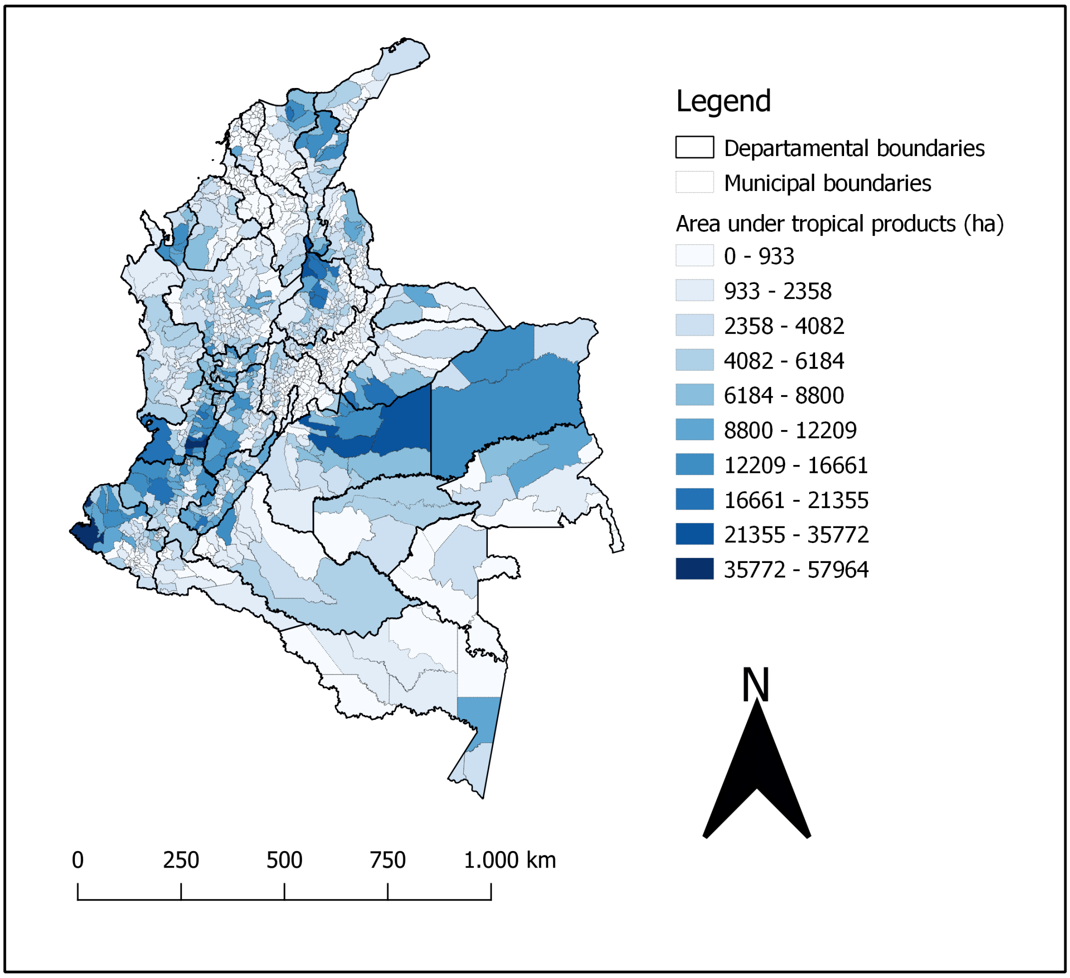

Figure 4.9: The sowed area in tropical products in 2013 includes fruits, seeds and oil crops, aromatic, beverages and spices, and fodder. Own elaboration. *Sources:* DANE (2014)

1980–90s (Richani, 2002, 141-45), recovered their political influence.

Thus, the use of violence has served as a tool to accumulate land in a few hands and protect agribusiness interests in respect of this land entering the global economy. This process occurred in a context of economic incentives from international markets and the support from the state. In the short-term tropical specialization also could acts as a mean to sustain the civil war (Hendrix & Brinkman, 2013; Messer & Cohen, 2007; Messer, Cohen, & Marchione, 2002; Segovia, 2017). Although tentative, this is a hypothesis which needs to be tested by more research.

4.5 FINAL REMARKS

The debate on food security and trade relations highlights the role of trade liberalization as a tool to improve food availability in developing countries against the negative impact of trade and agrarian specialization. The literature also underlines the possible relationship between commodity specialization and conflicts. This research article has contributed to these debates by providing new long-term time series for Colombia along throughout the twentieth century for food availability, agricultural trade, self-

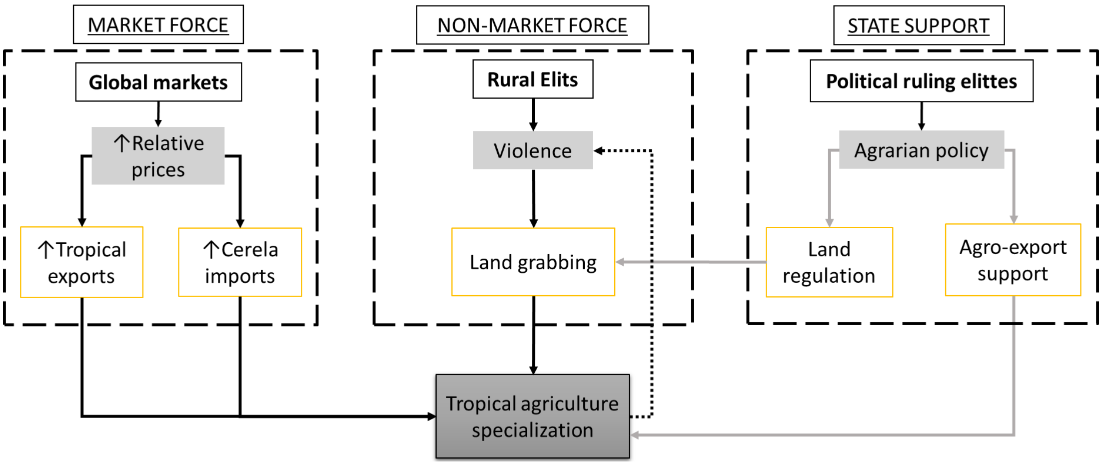

Figure 4.10: The mechanisms of tropical specialization and its actors. The straight black lines and the dotted line are the long- and short-term relationships in VECM, the grey lines are the relationships identified in the literature.

sufficiency, and land specialization. At the same time, the article has shed light on the interactions between tropical specialization, armed conflict, and international prices between 1961 and 2016.

The historical analysis shows a more nuanced way of dealing with the dichotomy between trade and self-sufficiency, while the quantitative analysis confirms a long-term relationship leading from violence and prices to tropical specialization, as well as positive effects in the short-term going from the lagged values of specialization and prices to violence.

The historical analysis reveals a successful story of improving food availability between 1916 and 2016. There was a transition from food shortages and the key role of subsistence agriculture as food supplier, which dominated till the late 1960s, to the current achievement of a per capita intake of around 3000 kcal/pc/d. However, the quality of this diet is not clear at all since the proportion of the basic foodstuffs, especially cereals, also rose in the composition of consumption. The other side of the coin is the evolution of international trade. During the First Globalization, export-led specialization coexisted with domestic staple food production and imports to meet the demand for punctual food shortages, while during the Second Globalization tropical exports were expanded and the self-sufficiency in staple crops fell, risking the food security of the whole country.

The quantitative analysis on the drivers of this change to tropical specialization during the Second Globalization confirms a long-term relationship reflecting the role of violence and relative prices in creating the tropical specialization, but this analysis also stresses that violence appears to be a consequence of tropical specialization and international prices in the short-term. More than contradictory, these results highlight the argument regarding the use of violence by the agrarian elites and the state as a tool to promote tropical specialization and entry into the international markets, while calling for more research on the role of tropical specialization as a cause of violence.

Chapter 5

Energy Efficiency and Sustainability of Extractive Agriculture

Keywords: Agroecological Energy Analysis; energy efficiency; sustainability; tropical agriculture; extractive agriculture; twentieth century in Colombia

5.1 INTRODUCTION

Energy analysis of agroecosystems can provide information on how efficient and sustainable the management of biomass production has been by analysing the transition from traditional-organic to intensive-conventional systems. Agrarian change of tropical agriculture towards input dependence on fertilizers, pesticides, and machinery, and the extractive use of resources such as land, water, and labour has led to nutrient cycling distortion, water pollution, and biodiversity loss since the 1980s (Campbell et al., 2017), while also has contributed to rainforest deforestation (Gibbs et al., 2010). This process is also responsible for 12% of anthropogenic CO_2 emissions of which 98% were caused by land-use change (Foley et al., 2011). A better knowledge of the process of the industrialization of tropical agriculture and its changes in energy efficiency and sustainability are relevant to understanding its current profile. However, long-term energy analysis of the industrialization of tropical agroecosystems remains unexplored. To fill this gap, this work addresses the changes in energy efficiency and sustainability of the whole agroecosystem of a tropical and large developing country such a Colombia throughout the twentieth century.

Energy analysis in agriculture began in the wake of the oil crisis in the 1970s, when the input–output balances demonstrated the inefficiency of industrial agriculture in U.S. (Pimentel et al., 1973) and U.K. (Leach, 1975). Afterwards, this interest has surged again on the eve of the peak oil threat and the climate change concerns (S. Gingrich & Krausmann, 2018; Hercher-Pasteur et al., 2020). Within this renaissance, conventional and agroecological analyses have surged as the most frequently used approaches (Hercher-Pasteur et al., 2020). The former usually provides a sectoral reading focusing on socioeconomic inputs and outputs, that is, the amounts of fossil fuel consumed and of agricultural production going through the markets. Meanwhile, the latter includes marketable and non-marketable flows, namely fossil fuel-based external inputs and reinvested inner biomass, which allows assessment of the reproductive capacity of agroecosystems to be included.

Throughout history, agriculture has transitioned from being solar-based to fossil fuel-based, thus becoming a sink of energy and making agroecosystems less efficient and sustainable. The results obtained so far from European cases show a steep decrease of energy returns to external inputs (i.e. the external energy used per energy produced) and the abandonment of inner recycling throughout the transition from traditional organic farming in the 19th century to conventional agriculture in the 21st in Austria (S. Gingrich & Krausmann, 2018; S. Gingrich et al., 2018), the Czech Republic (Fraňková & Cattaneo, 2018), and Spain (Díez-Sanjuán et al., 2018; Díez-Sanjuán, Olarieta, & Tello, 2019; González de Molina et al., 2020; Guzmán & González de Molina, 2017; Guzmán, González de Molina, Fernández, Infante-Amate, & Aguilera, 2017; Marco, Padró, Cattaneo, Caravaca, & Tello, 2018). In the East Canadian provinces of Prince Edward Island and Montreal (MacFadyen & Watson, 2018; Parcerisas & Dupras, 2018), as well as in the case of coffee in Costa Rica (Infante-Amate & Picado, 2018), this socio-ecological transition (SET) of agriculture resembles that which has taken place in Europe.

However, the downward trend of energy efficiency is far from being either homogenous or linear. In the Great Plains of the United States, dynamics of frontier-led colonization, moving from an initial predominance of cattle-ranching and low population densities towards grain–growing mixed and intensive farming, involved very low energy returns and some gains in energy efficiency with initial intensification (Cunfer, 2005; Cunfer & Krausmann, 2015; Cunfer, Watson, & MacFadyen, 2018). Thus, the effects of the use of external inputs during the early stages of intensification on energy efficiency and sustainability remain unclear. Even conventional energy analysis has provided mixed results on the energy returns (Hall, Dale, & Pimentel, 2011). Sharp losses in energy efficiency were highlighted during agriculture industrialization in U.S. (Cleveland, 1995). Compared to current organic farming, industrial agriculture produces less energy than it invests (Mendoza, 2005; Smith, Williams, & Pearce, 2015), but recent work has also pointed out later improvements in energy returns on investment (EROI) after the spread of the Green Revolution (Pellegrini & Fernández, 2018).

Despite the observed differences, following agroecological readings of agricultural change, increasing allocations of energy to agroecosystems would presumably have replaced the traditional internal loops of biomass reuse in organic farming during industrialization by lineal external fossil fuel-based inputs, making present-day agroecosystems less complex and polluting (Guzmán & González de Molina, 2015; Marull & Font, 2017; Tello et al., 2016). This process mainly took place in two steps: first, early increases in mechanization and the use of industrial fertilizers from the mid-nineteenth century to the 1930s; and, second, the spread of extensive industrial intensification after the Second World War; and even a sort of stabilization thereafter, as pointed by Pellegrini and Fernández (2018). However, AEA clearly also shows two different starting points: the decreasing energy returns in high population density agriculture in Europe on the one hand, and the low energy returns with some gains in efficiency in low population density contexts of agrarian colonization on the other hand, as shown (C.-e. S. Gingrich, Aguilera, & Cunfer, 2021).

Against this background, this paper aims to answer the following research questions:

- How has intensification affected the energy efficiency and sustainability of tropical agroecosystems?
- Does tropical agriculture resemble the path of Europe, the Great Plains or its own?

This work contributes to the debates on energy efficiency and sustainability during agrarian intensification in AEA studies by providing new data on the socio-ecological transition of the whole agrarian system of Colombia, namely agriculture, livestock raising, and forestry throughout the twentieth century. To answer the questions, we measure the bio-economic and agroecological flows and energy returns involved in Colombian agriculture between 1916 and 2015 by following the AEA methodology (Aguilera et al., 2015; Guzmán et al., 2014; Tello et al., 2016) and provide for the periodisation of these changes by using structural-break analysis to make comparisons with the changes to temperate agriculture. We gathered information on energy use and energy production in Colombian agroecosystem from domestic official records, FAOSTAT (2021), and secondary sources. The results are discussed in light of the periodisation and the country's economic history and from the comparison with previous results for temperate agriculture.

The details of the methodology and sources we have used are explained in the following section and the supplementary material. Section three describes the main results. In section four we discuss the results and, finally, we add a conclusion and outlook on the opportunities that family farming and silvopastoral systems can provide as a way of reversing sustainability losses and achieving some gains in efficiency in biomass production at the country level.

5.2 METHODOLOGY AND SOURCES

5.2.1 Methodological approach

To address the changes in energy efficiency and sustainability during the intensification of tropical agriculture, we build on the fund–flow model, multi–EROI analysis, and structural-break analysis of the whole Colombian agroecosystem from 1916 to 2015 at the national level as proposed by Guzmán et al. (2014), Tello et al. (2016), and Guzmán and González de Molina (2017). First, the fund–flow model includes three basic living funds: farmland, livestock, and associated biodiversity, which are interlinked by a set of energy flows managed by the farming community within the system's boundaries (Figure 5.1). The farming community uses external inputs (EI) such as synthetic fertilizers, pesticides, imported feed, machinery, and human labour (HL) to obtain a

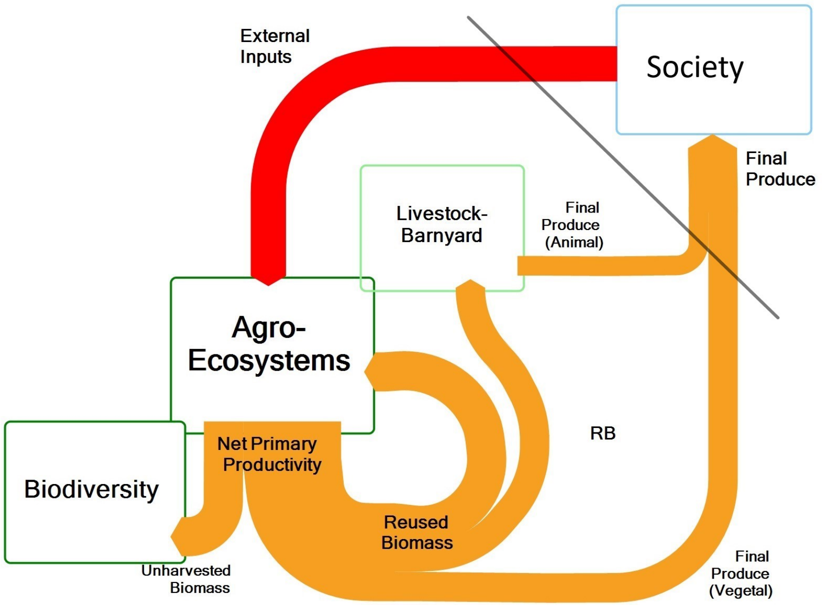

Figure 5.1: Energy flow model for agroecosystems. Based on Tello et al. (2016) and Guzmán and González de Molina (2017). The yellow flows represent outputs intended to reproduce agroecosystems and society, while the red one are the inputs consumed by the system.

flow of final produce (FP) that provides food, fuel, and raw materials. It also makes use of biomass flows that can be either a product (such as pastures, cultivated feed, green manure, local seeds) or by-products (straw, stubble, pruning, bagasse, animal manure) to recirculate within the agroecosystem and reproduce cropland soil fertility, livestock, or the functional farm–associated biodiversity. This internal cycling of biomass reused (BR) plays an integral role among the funds, increasing the complexity of the agroecosystem.

As a form of co-production with nature (Van der Ploeg, 2013), the agricultural output in agroecosystems also relies on less disturbed or non-disturbed nearby ecosystems that provide supporting and regulating ecosystem services such as pollination, soil fertility, water runoff, and the control of pests and diseases (Carpenter et al., 2009; MEA, 2005). Therefore, maintaining the provision of these ecosystem services also depends on the non–humanized energy flows left over as unharvested biomass (UhB) for other non–domesticated species. This below- and above-ground UhB, plus the BR and the vegetal final production (FP–V) appropriated by society through agriculture, compounds the entire NPP of the photosynthesis in the system boundaries accounted for a year (Haberl et al., 2007; Schandl et al., 2002; Vitousek et al., 1986) and can be expressed as:

$$NPP_t = FVP_t + BR_t + UhB_t \tag{5.1}$$

The changes in the size and composition of this flow over a year of time ($_t$) are a keystone of the fund–flow analysis of the sustainability of agroecosystems. By assessing the energy profiles of the fund–flow patterns in agroecosystems, the reproductive analysis can indicate to what extent they are low–entropy dissipative structures with high complexity, circularity, resilience, and diversity, or, on the contrary, simpler and linear due to the increasing the dependence on fossil-fuelled external inputs of a synthetic and mechanical character (Guzmán & González de Molina, 2017; Marull, Cattaneo, et al., 2019; Marull, Herrando, et al., 2019; Tello, Sacristán, Cattaneo, et al., in press)

Second, most energy analyses of agricultural systems assume consumption of a single energy return to the EI, thus disregarding the sustainability role of the internal recirculation, i.e. BR and UhB, leaving the agroecosystem functioning in a black box (Tello et al., 2016). The FP in the EROI analysis of crops by Pellegrini and Fernández (2018),), for example, does not distinguish between the recycling biomass (seed or produced feed) and the net output that goes to society. To overcome this limitation, we use a multi-EROI analysis. In this analysis different combinations of the energy flows allow us to identify changes in the energy returns on investment in the production of goods and services obtained from the agroecosystems' living funds, as well as on their reproductive up-keep to measure the society's energy efficiency and the sustainability of tropical agriculture.

In this vein, the EROIs are split into the bio-economical and agroecological (Díez-Sanjuán et al., 2018; Guzmán & González de Molina, 2015; Guzmán et al., 2017; Tello et al., 2015). In bio-economic terms, we compute Final EROI (FEROI), Internal Final EROI (IFEROI), External Final EROI (EFEROI), and the Final EROI on labour (FEROL). In agroecological terms, we compute the return on the NPP (NPPactEROI), the agroecological Final EROI (AFEROI), and the biodiversity final EROI (BFEROI).

The FEROI measures the energy returns to meet the needs of society in terms of food, fuel, and raw materials relative to the total inputs consumed (TIC) both external (EI) and internal (BR):

$$FEROI_t = \frac{FP_t}{EI_t + BR_t} \tag{5.2}$$

Therefore, FEROI can be split into EFEROI and IFEROI. EFEROI gives information on the capacity of the agrarian system to provide more energy than that received from society and, the other way round, also measures the dependency on EI of the agroecosystem functioning:

$$EFEROI_t = \frac{FP_t}{EI_t} \tag{5.3}$$

IFEROI, in turn, accounts for the energy return on the effort made by farmers to reuse biomass flows to reproduce the live funds of the agroecosystem. Note that an increase of this return may or may not involve a lack of care in the reproductive needs of live funds that would lead to agroecosystem degradation (something that must be assessed through a reproductive analysis of each of these funds):

$$IFEROI_t = \frac{FP_t}{BR_t} \tag{5.4}$$

FEROL provides information on the productivity of the direct investment of labour performed by the farming community:

$$FEROL_t = \frac{FP_t}{HL_t} \tag{5.5}$$

Although IFEROI, as well as the $\frac{EI}{BR}$ ratio, throw some light on the agroecosystem's living funds reinvestment and reproduction, other agroecological EROIs can offer a more detailed picture of the sustainability of the agroecosystem (Guzmán & González de Molina, 2017). NPPactEROI measures the return on the total energy invested and recirculated within the agroecosystem in terms of photosynthetic biomass produced, whatever the origin (TIC and UhB):

$$NPP_{act}EROI_t = \frac{NPP_t}{EI_t + BR_t + UhB_t} \tag{5.6}$$

NPPactEROI assumes that the energy production of biomass provided to society not only relies on human intervention through EI and BR, but also depends on non–colonized energy flows such as the UhB circulating in the agroecosystem. In turn, AFEROI applies the same assumption to the total energy investment and recirculation required to obtain the FP extracted from the agroecosystem.

$$AFEROI_t = \frac{FP_t}{EI_t + BR_t + UhB_t} \tag{5.7}$$

The ratio between AFEROI and FEROI offers a measure of the human colonization of the agroecosystem labelled as BFEROI. It can reach a value of 0 in agroecosystems with a high intervention and 1 in cases of natural ecosystems. Therefore, it is also a measure of perturbation (see Guzmán and González de Molina (2017) for details).

$$BFEROI_t = 1 - \frac{AFEROI_t}{FEROI_t} \tag{5.8}$$

Finally, we introduce a historical periodisation of the process of the socio-ecological transition in Colombia based on the identification of structural changes that are present in the times series. We implement an structural break analysis and group the breakpoints into main periods according to the economic history of the region (Cárdenas et al., 2000a, 2000b; Thorp, 2000) and the country (Bejarano, 2011; Kalmanovitz & López, 2006; Machado, 1991; J. A. Ocampo, 1994) (see Appendix D, Section D.3).

5.2.2 Sources and data processing

5.2.3 Biomass flows

To calculate the NPP, we distinguished among the production of crops, pasture, and forest[1]. Regarding crops, we rely on the records of production statistics from Statistical Yearbooks, U.S. reports, national agricultural magazines, monographs from the period, and results from the contemporary literature. In 1960, we cover 87% of the 1961's production with 30 crops and one aggregate category for fruits other than banana. Thereafter, from 1961 until 2015 we account for all primary production from crops in FAOSTAT (2021). We use technical coefficients from Guzmán et al. (2014), Montero (2018), and previous work (Urrego-Mesa et al., 2019) to estimated residues, roots, and associated weeds, and to convert the physical mass units of the gross production of crops, livestock, and the forest into energy (see Appendix D, Tables A.3 and A.4).

For the livestock sub-sector, we estimate the production based on the productivity of tropical pastures, taking into account the fact that the extraction of pasture bears on the nutritional requirements of the livestock population (Krausmann, Erb, et al., 2008). Livestock production accounts for meat (of cattle, goats, pigs and sheep), milk, fat, and tallow in previous work (Urrego-Mesa, in press) and serves to estimate the animal production share in total FP (see Appendix C.2.1).

Finally, for the forest, we compute the NPP by distinguishing four types of forest, namely Andean forest, dry forest, rainforest and others. We use the rates of change in deforestation given by Etter et al. (2008) and use the factors of above and bellow ground forest productivity drawn up by Scurlock and Olson (2013) according to each type of forest (see Appendix A, Section A.5). Regarding extraction, we have also made some changes in data from Urrego-Mesa et al. (2019). Before 1961 we left out the information from the international trade in wood as an indicator of removals and assumed that this wood extraction was proportional to the share of the rural population, thus smoothing out the sudden increase of 20% in 1961 in the original series. The assumption here is that rural societies consume proportionally more wood for building than urbanized societies. After 1961, we introduced the wood extraction fromFAOSTAT (2021) and completed with firewood consumption available in UPME (2017) since 1975. Before this date, we used the rural per capita consumption of firewood in 1975 and moved it back according to the changes in the share of the rural population over the total.

BR is equal to the pasture extracted by livestock and the residues from cropland, but we also adjust by the final uses of the production. First, the commodity balances in FAOSTAT (2021) allow us to figure out the amount devoted to seed and feed in domestic production (reused feed), and external feed from imports. We computed the percentage of feed and seed in 1961–63 to the domestic supply and assumed the same percentage for reused and external feed per crop in previous years for which no information is available (Appendix D, Table C.3).

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[1] For more detailed information on NPP estimates, see Appendix A, Section A.2

5.2.4 External inputs

The embodied energy in the EI accounts for both the inherent energy of the products in use and the upstream energy required for their production, whether are or not energetic. We first gathered the EI in physical terms (e.g. kg of nitrogen) and then applied the historical factors for embodied energy given in Aguilera et al. (2015). As EI we included fertilizers, pesticides, machinery, agrarian implements, irrigation, and human labour.

In the cases of fertilizers and machinery before 1961, since no information on domestic consumption is available, we calculate it as net imports. In these both cases almost total consumption came from imported products even in the second half of the 20th Century. Regarding fertilizers, we based this assumption on the high share of imports in consumption, 88% in 1961 (FAOSTAT, 2021). The historical data (1916–60) for fertilizers were provided in terms of products, not nutrients. Therefore, we first standardize these data to the “Fertilizers Archive” (1961-2002) and “Fertilizer by Nutrients” (2002–17) databases (FAOSTAT, 2021), as well as Aguilera et al. (2015)’s classifications, to apply the embodied energy factors. Finally, we aggregated by main nutrients (Appendix D, Table D.2). The pesticides before 1990 were estimated back according to the use of synthetic fertilizers.

In the case of machinery, between 1916-1960, we retrieved information from Tafunell (2013) for the period 1935–50 and from National Year Books for the remaining years. We homogenized these historical data to the “Machinery Archive” (1961–2005) database (FAOSTAT, 2021) (Appendix D, Table D.3). The fuel associated with this machinery was estimated using the historical factors in Aguilera et al. (2015). The energy in irrigation came from the information on irrigated area from the FAO (2020) water database and the historically embodied energy to put into energy (Aguilera et al., 2015). Although data quality on irrigation is not so accurate, its share on EI is very thin. Although data quality on irrigation is not so accurate, its share on EI is very thin, therefore it does not alter the results.

Finally, to obtain figures for the working population in agriculture, we started with the percentage of the occupied population in agriculture given by DANE (2020) for 1958–84 and 1991–2017, and the total of the occupied population in Flórez Nieto and Méndez (2000) between 1951 and 1993. We match the series with the information on agrarian employment from FAOSTAT (2021) for 2001 and 2009 up to 2017. Before 1951, we use the economically active population (Flórez Nieto & Méndez, 2000) as a proxy for the occupied population and apply the share of rural population to the total as the percentage of the occupied population in agriculture. Finally, we calculate the energy of human labour in agriculture by assuming dietary energy consumption of 2.2 Mj per person for an 8-hour working day and 200 days per year (S. Gingrich & Krausmann, 2018).

There are some limitations to this study. First, we do not have information on illegal logging or coca crops directly, but the land-use changes affecting the forest includes this indirectly as deforestation. Second, related to the nation-wide calculation of the agrarian social metabolism of Colombia, we ignore regional and altitudinal differences within the country. Although this approach allowed us to tackle the lack of detailed information on the input consumption in each sub-sector, especially human labour allocation, the aggregation level makes it difficult to disentangle the specific changes within the agroecosystem being considered.

5.3 RESULTS

5.3.1 Fund–flow analysis

The long-term fund–flow analysis depicts the broad features and changes in Colombian agriculture during the twentieth century. The main feature is the greater relevance of the UhB over the rest of the energy flowing in the agroecosystem. This flow, has been more than 90% of the NPP from the very beginning of the period till today. This share in much higher than the one estimated in historical perspective for Western agricultures. However, like the NPP, the UhB fell by 10%, from 32.4K PJ in 1916 to 29.8K PJ in 2016. This picture depicts the ecological potential of Colombian agroecosystems to store carbon and hold biodiversity, but the reduction also tells a story of the decline of the reincorporation of biomass, which is essential to the reproduction of the associated biodiversity and to the provision of ecosystem services.

Conversely to this reduction, the proportion of energy extracted by agriculture (BR and vegetal FP) rose from 2% to 7.5% of the NPP between 1916 and 2016 (567 PJ to 2,252 PJ). This increase was mainly explained by pasture and cropland expansion and intensification. Thus, replacing forest in the FP. Together with this change, EI use multiplied by almost 60 (5 PJ in 1916 to 298 PJ in 2016), making agriculture more intensive. In Figures 5.2 and 5.3 we depicts the main flows (a and c) and a zoom of extraction (b and d) for details. In the next sub–sections we analyse more in–deep the implications of increasing energy extraction from nature in the composition of each of these flows.

Biomass flows

The fall in NPP and UhB was mainly driven by the reduction in forest area up to the 1970s. Despite this reduction of forest speeding up, the falling trend of NPP was smoothed out due to the increase in other unharvested biomasses such as the UhB from agricultural lands and shrublands, and even from the increase of BR and FP (Figure 5.4a). Currently, the biomass from the forest is still the main proportion of UhB, 74% in 2016, the other 26% corresponding to the UhB from shrubland (17%) and agricultural lands (9%), especially pasture. In this changing composition, the energy from lower quality land covers, such as secondary vegetation or shrubland and human-driven land uses, have replaced highly productive forest, leading to falls in the yields of biomass production at the country level. Although the human extraction of energy through agriculture, livestock breeding, and forestry (BR and vegetal FP) represents a thin piece of the NPP (7.5%), the current size of Colombian extraction is twice and three times higher than extraction in temperate agricultures like Spain (Guzmán et al., 2017) or Austria (S. Gingrich & Krausmann, 2018). This difference is particularly high

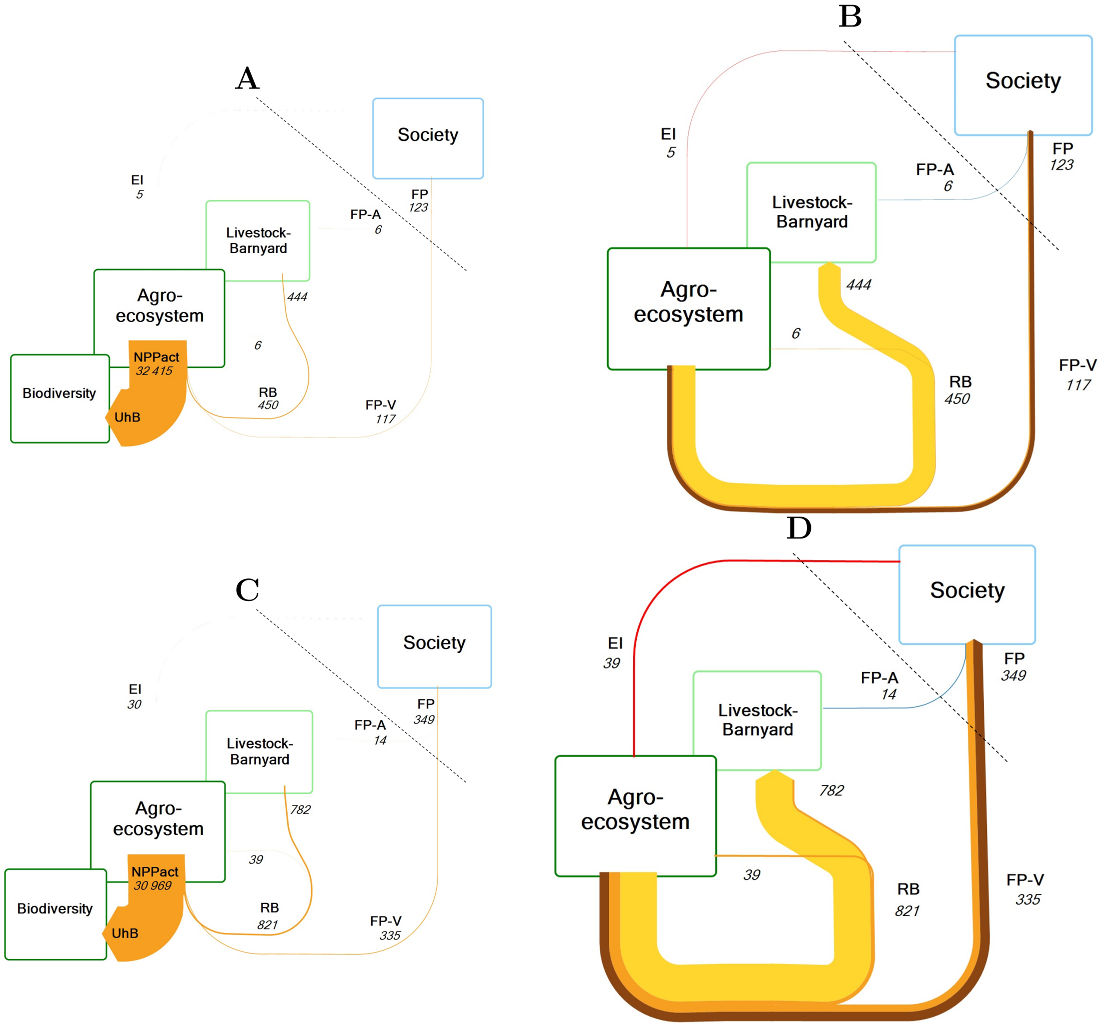

Figure 5.2: Main flows in agroecosystem (a and c) and extraction (b and d) in 1916 and 1960. The yellow, orange and brown flows are the extraction from pastureland, cropland, and forestland, respectively. The external inputs are in red. *Source: Own elaboration, from the sources given in the text, see Section 5.2.2*

in the case of BR as an be seen in Figures 5.2b/d and 5.3b/d.

BR has been the primary piece of extraction (80%), but despite growing 3.5 times (from 450 PJ in 1916 to 1,614 in 2015), its share decreased by 10% during the first half of the period, remaining at around 70% in recent years. Despite the share being almost static in the long term, there have been relevant changes in its internal composition since the mid-1970s (Figure 5.4b). The share of pasture in biomass extraction at the beginning of the century was 80% of the BR, but this portion dropped to 40% in 2015. This 50% fall was offset by the increasing use of other animal feeds, such as crops, crop residues, and, as shown below, feed imported, which went from almost nothing (6 PJ) up to a third (367 PJ) of animal feed between 1916 and 2015. Thus, the main features in BR during the twentieth century were the overwhelming appropriation of pasture to feed the livestock and its progressive displacement as the main source of animal feed.

The other piece of the extraction is the vegetal FP (from cropland and forest land) which accounted for 20% at the beginning of the period (122 PJ in 1916) and which grew by up to one third in 2016 (724 PJ). Historically, forest dominated the vegetal

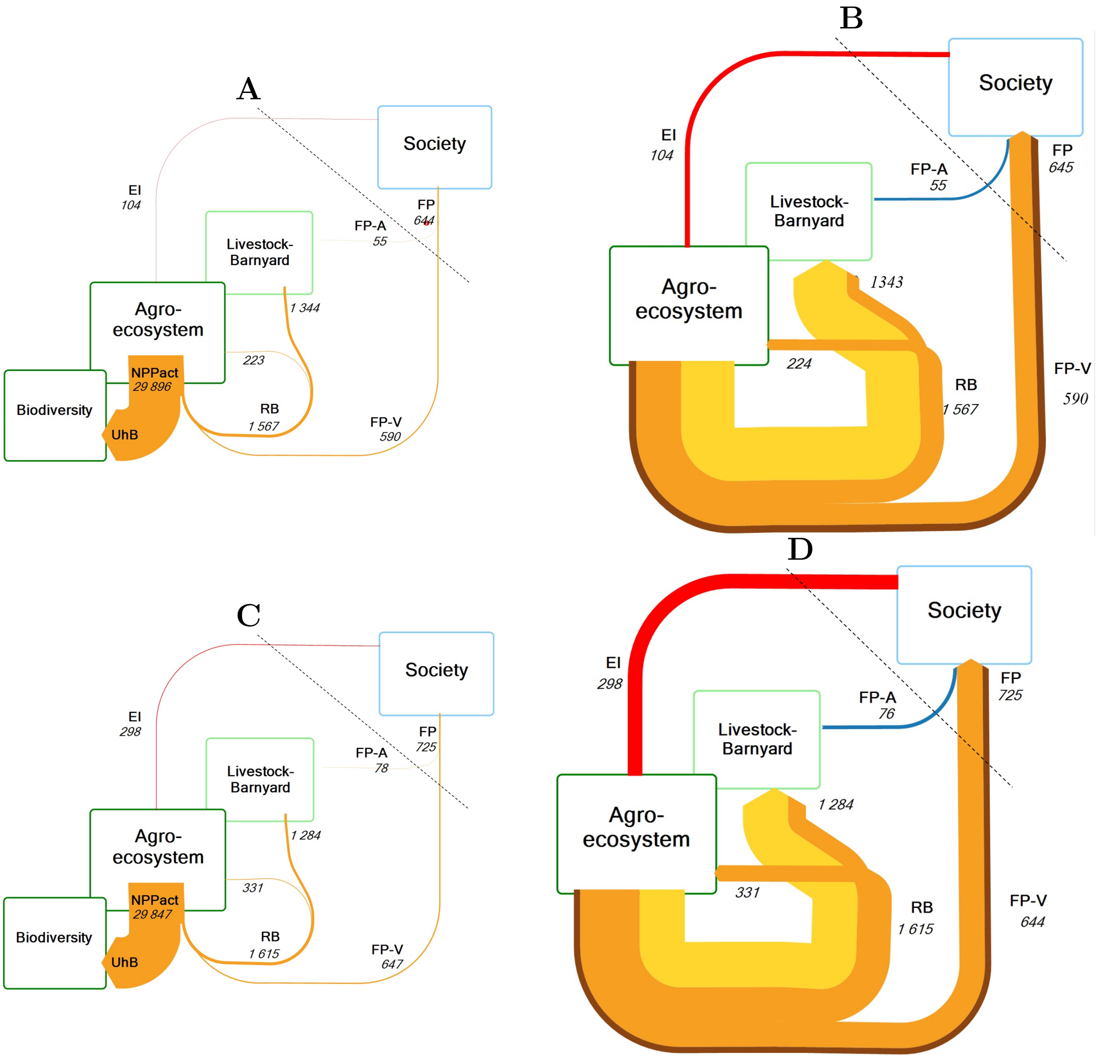

Figure 5.3: Main flows in agroecosystem (a and c) and extraction (b and d) in 2000 and 2015. The yellow, orange and brown flows are the extraction from pastureland, cropland, and forestland, respectively. The external inputs are in red. *Source: Own elaboration, from the sources given in the text and SM, see section 5.2.2*

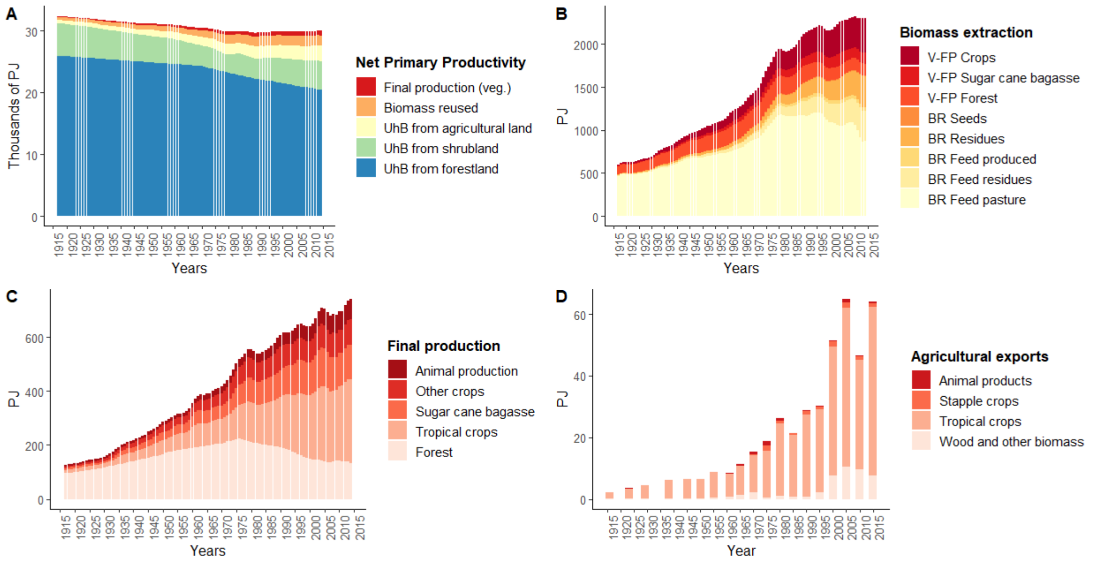

Figure 5.4: Net primary productivity **a)**, biomass extraction **b)**, final produce **c)**, and agricultural exports in PJ **d)** between 1916 and 2015. *Source: see section 5.2.2*

FP, being 76% in 1916, but its significance dropped to 18% of the vegetal FP in 2016. Between 1916 and 1975 forest grew from 94 PJ to 230 PJ, after this date, there was a descending trend of up to 127 PJ in 2016 (Figures 5.4b and c). The high demands for land–based raw materials and fuel during the pre–industrial period (1916–60s) and the process of structural change that boosted urban expansion and fuel substitution are the socioeconomic drivers behind these movements (Malanima, 2021; Soluri, Leal, & Pádua, 2018).

The story of agricultural production, however, is just the opposite. Crop production moved from 19% of the vegetal FP in 1916 (23 PJ) to more than 70% in 2016 (519 PJ), of which bagasse from sugarcane used as a biofuel currently accounts for 20% of the vegetal FP (132 PJ). This increase was especially relevant among tropical crops such as sugarcane, oil crops, and fruits, which currently share two–thirds of all energy coming from the crops (Figure 5.4c). At the same time, tropical products have maintained an average 86% of agricultural exports (Figure 5.4d).

Within agricultural production, the rise of animal production is the second largest change. As we noted before, energy reused to feed livestock decreased in relative terms, especially pasture, but animal output in the forms of meat and milk increased 13 times, from 5.7 PJ to 77.5 PJ between 1916 and 2015, respectively. This growth, 10 times larger than the growth in animal feed, reflects the efficiency gains achieved by the livestock sub-sector during the process of intensification, as we shall see in section 5.3.2. At this point, we only can say that, despite the gains, livestock output remains as small as 10% of final production.

External inputs

The society manages the agrarian sector and shapes its footprints on ecosystems through the farming community. The farming community structures the landscape by conducting the energy flows so they feed both ecosystems and society from a fraction of the NPP. To do that, they also introduce external energy in the agroecosystem. These external inputs (EI) used to be limited to human labour and agricultural tools in organic systems, but they became fossil–fuel based as agricultural industrialization spread. In the case of Colombia, EI moved from 5.4 PJ in 1916 to 298 PJ in 2015, a 55 times growth that involved a systemic change from organic to agro-industrial production (Figure 5.5a). We identify three structural breaks in the EI (i.e. 1948, 1985, and 2000) and categorize agrarian industrialization into four waves (Appendix D, Table D.7).

During the first wave (1916–48), the agrarian system exhibits the usual features of organic systems. Average consumption of EI (10.3 PJ) was low compared to the following period, and EI consisted of agricultural labour (73.4%) and other inputs (13%), mainly agricultural implements (Figure 5.5b). During this period the increasing imports of fertilizers, guano and saltpetre, and some machinery also indicate the starting point of intensification, though the breakdown of organic farming would take place from the mid–century on.

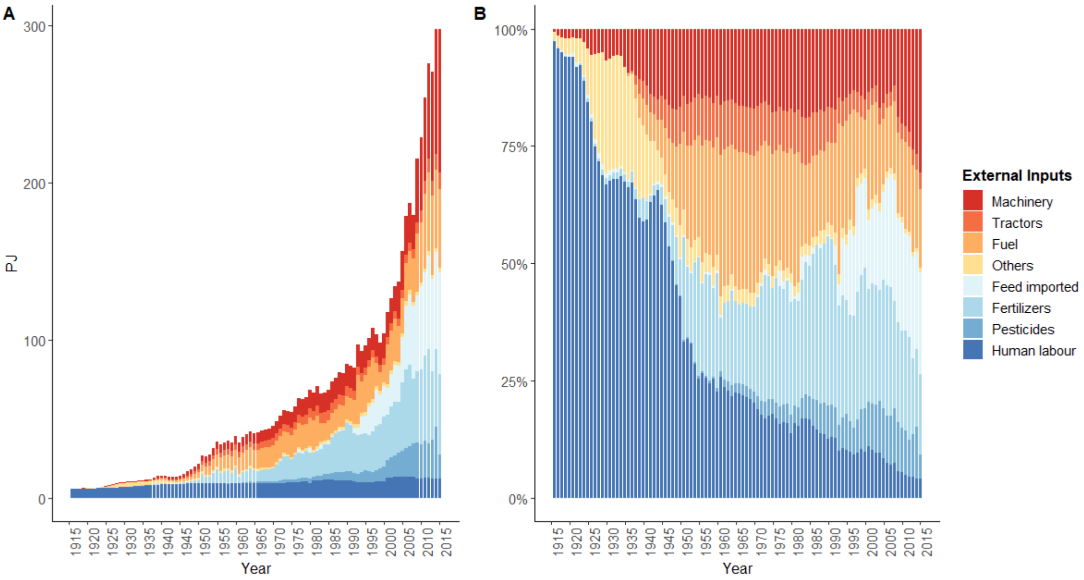

Figure 5.5: External inputs **a)** and its composition **b)** in PJ (1916–2016). *Source: see section 5.2.2*

The second wave of agricultural industrialization (1949–85) began after World War II with the increase in fossil–fuel based inputs as the primary source of external energy. The average consumption of EI multiplied more than 4 times up to 46 PJ. The initial process of mechanization was extended; machinery, tractors, and fuel shared 50%, while the traditional inputs of organic systems, such as agricultural tools and human labour, dropped to 26% of the EI. This process was also linked to the increase in the consumption of synthetic fertilizers (N, P, K) and pesticides, which accounted for another 23% of the EI consumed. However, the performance of these “modern” inputs was not the same. The average growth in fuel, machinery, and tractors together was 4.7%, while fertilizers and pesticides grew at annual rates of 13% and 24% respectively (Appendix D, Table D.7). This dynamism of land-saving inputs can be related to the spread of the Green Revolution compared to the labour–saving inputs that mark the path of the next wave.

The annual rates of the growth in EI slowed during the third wave (1986–2000) from 3.9% to 3%, and the average annual consumption of energy (90.9 PJ) during this time did not succeed in doubling that of the previous stage. However, the use of fertilizers and pesticides jumped almost three-fold from 11.3 PJ to 32.5 PJ, representing a minor advance in mechanization ahead of the spread of the Green Revolution package. Synthetic fertilizers and pesticides grew by 3.7% and 7.8% annually, but the most impressive growth was that of imports of feed, which rose at average annual rates of 127%. These three items shared 45% of EI, while fuel, machinery, and tractors fell from 50% to 40%. Human labour remained at 11% of EI and for the first time reported negative annual rates of growth (Appendix D, Table D.7). This leading position of the consumption of land-saving inputs drove the process of land intensification during the 1985–2000 period and the transition of Colombian agriculture to the industrial model, but its role was not as relevant during the following years as it was in this phase.

The common trait of the last wave of agrarian industrialization in Colombia (2001–15) was the general increase in the consumption of all types of external energy. The EI rose almost three-fold between 2001 (118 PJ) and 2015 (298 PJ), which involved an acceleration never seen before at 7.4% average annual rates. Machinery, tractors, and their associated fuel speeded up their pace of growth at 14.2%, 6% and 13.9% respectively, but paradoxically it also kept pace with the renewed growth of human labour (1.5% average annual rates). We have to note that human labour continued to decline in relative terms during this period and shared 7% of the EI during this wave, although in absolute terms there was a long-term growth trend. On the other hand, land-saving inputs, though slower than before, continued their growth. The main change in composition was feed imports, which reached 20% of EI and, together with fertilizers and pesticides, shared 53% of EI. This rise in all these types of EI ran in parallel to the increase in tropical production and the rise of tropical exports, as shown before.

The increasing consumption of the EI directly relates to land intensification, land yields, and energy productivity. The intensification of land is the most remarkable fact after 1985; the amount of energy per hectare remained much lower during the previous stages, no more than 2.2 GJ/h up to 1975, but from 1976 to 1997 the annal average use of energy in agricultural land climbed to 2.9 GJ/h and moved up to 6.6 GJ/h between 1998 and 2015 (Appendix D, Table D.6). This large transformation in such a short period involved average gains of more than twice in agricultural yields from 1955–75 to 1998-2015 (15.9 GJ/ha to 40.7 GJ/ha), but in the long term each wave of industrialization also involved a decline in energy productivity (Appendix D, Table D.6).

5.3.2 Energy efficiency and sustainability

Having described the main changes in energy outputs and inputs, we shall now analyse how did they interact, i.e. how energy efficiency has evolved through time. To do so we first analyse bio-economic EROIs and then the agroecological ones.

Bio-economic EROIs

Figure 5.6 depicts the ups and downs of the energy returns of the agroecosystems on the total inputs invested (FEROI) (Figure 5.6a), the effort made by farmers to reuse biomass (IFEROI) (Figure 5.6b), the dependency on external inputs (EFEROI) (Figure 5.6c), and the energetic productivity of labour (Labour FEROI) (5.6d). From 1916 to 1960 there were some gains in FEROI (0.27 to 0.44), but thereafter and until the early 1980s energy efficiency dropped to 0.36, where it has remained to date. Despite the gains, energy efficiency remains very low. For each unit of energy invested the return has been roughly a third (0.38) since the sixties. This low energy performance was driven by the outstanding rrelevance of the internal reuses of energy as Figure 5.6b suggests, especially the starred role of pasture seen in Section 5.3.1. Except for 1985 onwards, the series of FEROI is almost identical to that of IFEROI.

The increase in IFEROI during the first half of the century gives the impression that the BR was abandoned as agrarian industrialization developed in the same way as the European process. However, the rise in Colombia's IFEROI during these years did not follow the European path. There was dynamic growth in BR, together with a faster increase of FP up to 1975 (Appendix D, Table D.7). After this date, the rise of pasture continued to drive the growth trend in BR, but the reduction of forest since the mid-sixties led to a slower pace in the growth of FP. These two movements explain the drop in IFEROI between 1960 and 1980. The BR abandonment pattern of agrarian industrialization finally appeared from the 1980s when the replacement of pastures by other sources of feed led to BR stagnation. This stagnation and the FP recovery have driven the last increases of IFEROI since the eighties until recent years

Unlike IFEROI, EFEROI (Figure 5.6c) follows the commonly observed trend in other cases but maintains higher returns. Although its share of the TIC was thin (1% in 1916 and 16% in 2015), the growth in EI was the most dynamic change to take place during the entire period. During the first wave of mechanization (1916–48), and even during the eve of synthetic fertilizers (1949–85) (see Section 5.3.1), the average energy returns of EFEROI were as high as 18 and 9 times respectively more than the unit invested. Since the 1980s, and especially the year 2000, the paths of energy efficiency losses and fossil-fuel dependency deepened. Between 1985 and 2015 EFEROI fell from 8 to 2.4, and during the last phase of intensification of tropical agriculture (2001–15) the pace of this change was the highest, -4.8% average annual rates (Appendix D, Table D.7). Despite this last trend, EFEROI remained positive and EI returned twice as much energy than the unit invested from the entire agrarian system in 2015.

Finally, the energy productivity of labour (FEROL) in Figure 5.6d has experienced the largest gains: more than twice between 1916 and 1980, but since this date, the trend has flattened out. Though data quality for the agrarian working population is not so accurate at the inter-annual variation, at mid-term (1980–2015) the growth in human labour in absolute numbers follow the stagnation of energetic productivity. As already seen, since c. 1980 the intensification of agriculture did not leave aside the

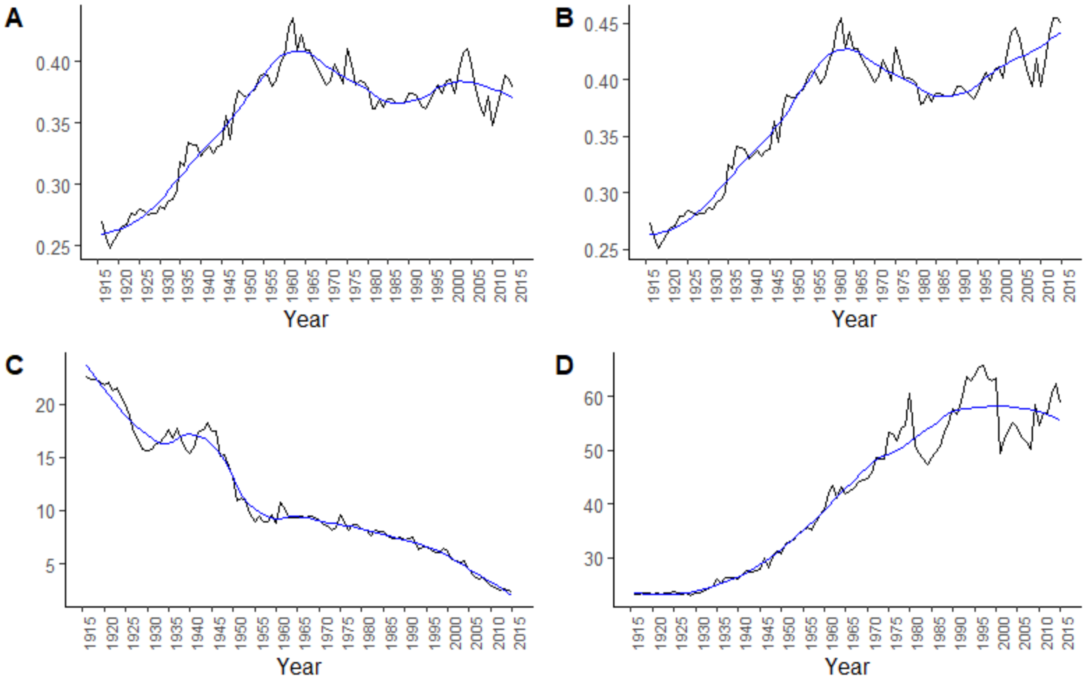

Figure 5.6: Energy returns at different stages **a)** FEROI, **b)** IFEROI **c)** EFEROI and **d)** Labour FEROI. *Source:* see section 5.2.2

re-ruralisation of the labour force, leading to diminishing returns as in the rest of the EI.

Agroecological EROIs

Attending to the size of the NPP and UhB, the movements of agroecological EROIs were on a very small scale, which does not mean changes that are not significant. Broadly we identified significant structural breaks for those EROIs around the 1930s, between the mid-1960s, early 1980s, and close to the year 2000 (see Table 5.1 and Section D.3 in the Appendix D).

In figure 5.7a the NPPactEROI plots a slight but continued improvement (1.003 in 1916 to 1.014 in 1975), which means that there were very few gains in the entire biomass production, that is the NPP, relative to the total of energy introduced in the agroecosystem, whatever its origin (BR or EI), or the levels of human intervention (UhB). In this sense, the human perturbation of the agroecosystem through the huge reuse of biomass and the introduction of EI during the two first waves of agricultural industrialization (1916–85) seems to perform positively to the energy yields of the agroecosystem. However, and as we have shown throughout this paper, the agrarian change to full industrial intensification led to the NPPactEROI peaking at 1.015 during 1976–2000, and finally, to a drop to the levels of the mid-1960s (1.011) at the end of the period. Although very tiny, this latter reduction in the NPPactEROI seems to indicate the starting point of the deterioration of the reproductive capacity of the living funds of the agroecosystem.

AFEROI (Figure 5.7b) introduces the idea that the FP is a result of the interactions between agriculture and ecosystems, which involves understanding agricultural outputs

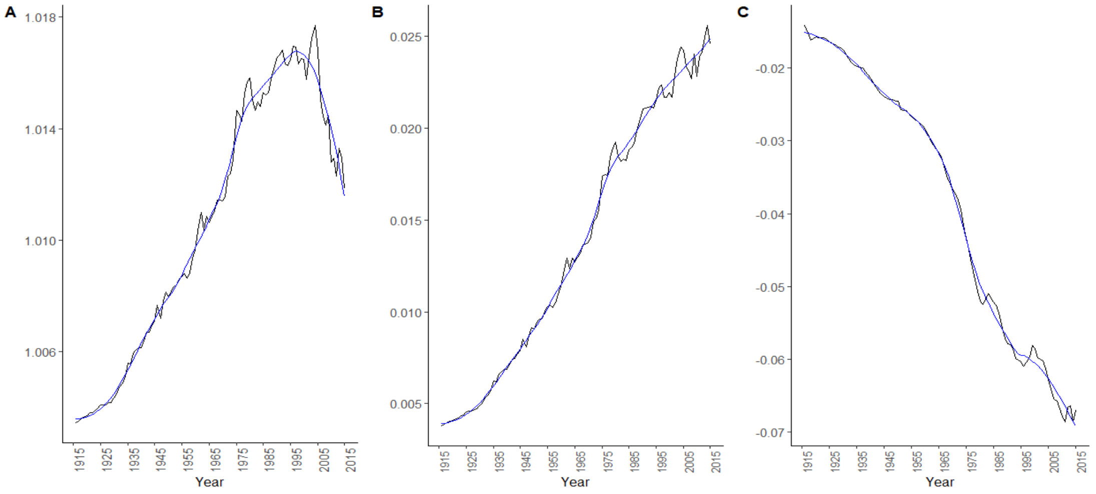

Figure 5.7: Energy returns at different stages **a)** NPPactEROI, **b)** AFEROI **c)** BFEROI. *Source: see section 5.2.2*

as a co- production with nature. In this vein, AFEROI performed well; in this Colombian agroecosystem dominated by tropical forests, it grew by more than 8 times between 1916 and 2015 (0.003 to 0.024). Unlike the NPPactEROI, there was no significant fall in energy efficiency in terms of AFEROI, but a gradual slowdown in the rates of growth, moving from annual averages of 2.7% to 1.1% between 1955–75 and 1976–97, and 0.5% during the last period (1998–2015). The trends of these gains and their slowing down were not driven by the increase of FP but by the weight of the UhB and the pace of its reduction during the century (see Section 5.3.1), which in turn also entailed a less portion of energy in ecosystems to feed wild species as the BFEROI indicates.

Finally, BFEROI in Figure 5.7c relates FEROI to AFEORI to provide a measure of human perturbations to ecosystems through agriculture. In the case of Colombia, the BFEROI indicator is very close to 1, faithfully reflecting the weight of natural ecosystems in the country. This means that, despite the reduction from annual averages of 0.98 in 1916-32 to 0.93 in 1998–2015, natural ecosystems in Colombia produce and consume the largest portion of the energy of the agroecosystem in the form of UhB, thus helping to sustain and reproduce wild heterotrophic chains.

It is worth noting that during the central waves of agrarian industrialization (1955–97) the pace of the fall in BFEROI speeded up, going from average annual rates of -0.03% in the previous stages to -0.08%. This acceleration highlights the effects of the expansion and intensification of agriculture on natural ecosystems during the agrarian changes of the twentieth century. Although the rates of decrease during the following period slowed down (-0.04% in 1998–2015), this falling trend indicates the current threats to tropical forests and their associated biodiversity under the export–led growth model of tropical agriculture.

These worrying trends, observed in the last period in the NPPactEROI, AFEROI, and BFEROI indicators, appear to be very small in a land matrix that is dominated by tropical forests at the country level, but they deserve further study at regional and local scales in those areas that are more affected by the advance of the agricultural frontier of export-led crops.

5.3.3 Periodisation

The results on periodisation came from the structural breaks analysis conducted in relation to the time series of the main energy flows, the EROIs, and some socioeconomic indicators (see Appendix D, Section D.3 for the methodology and partial results). In Table 5.1 we present the resulting breaking points by decades and main periods. Once we had obtained the breakpoints for each time series, we grouped the information by decades and obtained the account, average, and standard deviation to establish the main periods. Moreover, we base the periodisation choices on the economic history trends of the region (Cárdenas et al., 2000a, 2000b; Thorp, 2000) and the country (Bejarano, 2011; Kalmanovitz & López, 2006; Machado, 1991; J. A. Ocampo, 1994). In this way we propose five periods that fit well the classic periodisation of the twentieth century, which are useful in opening discussion of the socio-ecological transition of Colombian agriculture.

First are the expansion of the coffee economy during the First Globalization (1916–32), followed by two periods of internal state-led growth, the birth of state intervention as a tool for coping with external shocks (1933–54); and state-led growth under oriented domestic policies (1955–75). The two final periods extended into the Second Globalization (since the 1980s): the time and implementation of structural reforms leading to economic openness and deregulation (1976–97), and the period of agrarian intensification and expanding agricultural trade since the 2000s. In the next section, we discuss each of these periods considering the results for the energy flows, energy efficiency, and sustainability of the agroecosystem.

Table 5.1: Breakpoints by decades and periodisation

Time series	**1930s**	**1940s**	**1950s**	**1960s**	**1970s**	**1980s**	**1990s**
Crops		1943			1973		
FP	1931				1974		
RuB				1965		1981	1996
UhB		1942	1958		1976		1994
TNPP			1950		1976		1994
EI		1948				1985	2000[1]
FEROI	1934			1960		1980	
EFEROI	1930	1945		1960			2000
IFEROI	1934			1960		1980	
Labour FEROI		1944				1980	2000
NPPEROI	1931				1974		2000
AFEROI	1932				1974		
BEFEROI	1930			1966		1981	1997
Energy Prod. (P)[2]	1930	1945		1960			2000
Energy Prod. (M)		1941	1955				1990
Yields			1959			1987	
Intensification			1950			1983	2000
Count	8	7	5	6	6	8	11
Average	1932	1944	1954	1962	1975	1982	1997
sd	1.69	2.30	4.27	2.85	1.22	2.64	3.47
Period	**1916-32**	**1933-54**		**1955-75**		**1976-97**	
Years by period	16	21		20		21	
Historical periods[3]	*Exp.-Led growth*	*Birth of the Modern state*		*State-Led growth*		*Deregulation*	

Note: [1]We add the year 2000 to the 1990s decade due to there are not breaks thereafter. [2] Energy productivity is measured in physical (P) and monetary (M) terms. [3]The last period is from **1998 to 2015**, which we called one of *Globalized Intensification.*

5.4 THE SOCIO–ECOLOGICAL TRANSITION OF COLOMBIAN AGRICULTURE

Discussions on energy efficiency and sustainability during the early stages of agricultural industrialization and its long-term effects are in the basis of Agroecological Energy Analysis, though, its main conclusions are rooted in the case study of temperate agriculture in developed countries. Introducing into this debate the tropical agriculture of a developing country such as Colombia, contributes to this discussion while places the timing of the long-term socio-ecological transition of Western agriculture beyond temperate agriculture.

First, we argue that there were gains in bio-economic and agroecological EROIs during the early stage of agricultural industrialization related to the role of low population densities and extensive livestock breeding. However, when tropical agriculture was intensified, these gains were lost, and the agroecosystem became unsustainable. Second, in the case of Colombia, this turning point in the intensification of tropical agriculture took place after the 1980s and has deepened since 2000, unlike the transition in temperate agriculture of the Global North that occurred after WWII.

In the following subsections, we set the timing of the SET of Colombian agriculture according to the periodisation presented in subsection 5.3.3 and the socioeconomic history of the country. Then, we compare this process with the energy performance in temperate agriculture.

5.4.1 The socio-ecological transition throughout Colombian history

Land-use change from high–yield forests to lower–yield agricultural land to produce pasture and crops drives the reduction of photosynthetic net primary productivity (NPP) (Smil, 2013, 62-63), while it also generates biodiversity losses and greenhouse gas emissions. The main result for agroecological sustainability in Colombia during the twentieth century was the fall in this NPP, though, this has been at a slower pace since the 1980s. We related these two processes to the land–use changes during the 1915–75 agrarian expansion and the dominance of extensive livestock rearing on the one hand, and the intensification of tropical agriculture thereafter on the other hand. Throughout the twentieth century, the extractive nature of Colombian agriculture would have transited from extensive agriculture and livestock breeding to the intensive tropical agro-export model. However, during the early stages of intensification, there were increases in energy efficiency and in the reproductive capacity of the agroecosystem.

The first export-led growth model (1916–32) based on coffee contributed to the awakening of the modern economy in the country and the transition to advanced organic agriculture. The expansion of coffee fuelled the increasing demand for land, agricultural labour, tools, and some machinery. This process helped to erode the characteristic personal ties of dependency of labour in the hacienda system, while it promoted the extension of paid work and labour mobility (Bejarano, 1976), thus boosting the expansion of agricultural land with the spread of small coffee-growing settlers and their families in the mountain of the centre of the country (Parsons, 1949). Though more land was put under the plough and the area harvested grew faster (5.5% annual rates), the low population densities (Table D.5) and the historical roots of land inequality enforced the role of pastureland under extensive livestock as the main agricultural land use (Gutiérrez-Sanín & Vargas, 2017; Richani, 2012).

Between 1915 and 1978 pasture and cropland climbed from 8% to 25% of the land area (9.2 Mha up to 27.8 Mha) (Urrego-Mesa et al., 2019) at expense of the Andean forestland and the rainforests (Etter et al., 2008). During this process, the land-use change to pasture as the main source of animal feed, accompanied to a lesser extent by crop expansion, would have led to deforestation and the fall of the NPP, thus degrading the yield capacity of the forest and contributing to the increase in CO_2 emissions in the long-term (Houghton et al., 1991). However, the transition from organic to advanced organic agriculture during the first export–led growth period triggered the early gains of FEROI and the NPPactEROI (see Section 5.3.2).

In the case of FEROI, a major use of land, human labour, and agricultural tools led to faster increases in FP than in BR. In the second case, the greater speed of the extraction led to a faster drop in UhB than the fall of the NPP, which meant more human ecosystem disturbance. Does the NPPactEROI reflect the evolution of the sustainability of agroecosystems? If so, extensive livestock breeding, which ensured biomass recycling and labour-intensive agriculture with agrarian frontier expansion, would be the key elements of efficiency and sustainability during the first export-led growth and even until the mid–1960s. But it seems that NPPactEROI does not provide information about the extractive nature of extensive livestock breeding in tropical contexts, since this extensive use led to deforestations of more productive land covers.

These socio-metabolic changes in advanced organic agriculture also contributed to breaking up the social bases of Conservative rule, thus paving the way to the advent of the modern state and the starting point of agricultural industrialization. The Liberal Party started modernizing the Colombian state (1930–46) by following the previous policy of promoting coffee exports and extended protectionist policies as a tool against the shocks experienced from the Great Depression and World War II (Thorp, 2000, 82), while also promoting the domestic cultivation of staple foodstuffs. Eventually, this response became the main policy until the early 1970s. Therefore, the transition from advanced organic agriculture to fossil fuel-based intensification under the leading role of the state should be analysed throughout this time window.

Trade protectionist policies started in the 1930s by means of rising tariffs, real devaluations (1931–32), and import controls (Thorp, 2000), but they tightened thereafter with the tariff-reforms of 1950, 1959, and 1964 (Cárdenas et al., 2000a), which favoured the domestic producers (J. A. Ocampo, 1994). Additionally, low tariffs on imports of machinery and supplies for agriculture (Bejarano, 2011; Kalmanovitz & López, 2006) promoted the acquisition of the new technology, which became the primary source of land intensification during 1949–85 (see Section 5.3.1). At this time, international advice also allowed the initial spread of the new technologies of the Green

Revolution.

As a complement to protectionism, the state promoted new institutional settings and mechanization to "modernize" agriculture. Sectorial promotion campaigns started in the 1940s in tobacco, cotton, barley, and cattle-raising, with the help of new experimental centres. There was also support to private associations of producers like the National Federation of Coffee Growers (1927) and others related to the sugarcane (Asocaña), rice (Fedearroz), cereals (Fenalce), cotton (Federalgodon), and livestock (Fedegan) sectors (Cárdenas et al., 2000a). The development of agricultural banks (Caja Agraria, Banco Cafetero, Banco Gandero) also became relevant in financing the sector and its capitalization (Tafunell, 2013). The deployment of new infrastructure to build the domestic market positively impacted the agrarian output allocation. The railway expanded from the centre to the ports to serve coffee exports, but from 1950 onwards the railway was overtaken by road transport (Cárdenas et al., 2000a) as the main driver of the domestic market integration of agricultural products. Finally, during the 1960s land redistribution emerged again as an institutional way of confronting social unrest and increasing agricultural output (Gutiérrez-Sanín, 2019).

Unlike the advanced organic agriculture, during this process of industrialization (1934–75) the changes in the traditional flows became more evident. Land intensification led to some increases in agricultural yields (1933–75) (Urrego-Mesa et al., 2019). The introduction of machinery, tractors, and fuel allowed agricultural labour to decline without eroding the bases of population growth and structural change (1955–75) (J. A. Ocampo, 1994). Since the FP grew faster than the internal and external inputs, energy efficiency continued to grow, but this virtuous cycle ended in the mid-1960s due to the acceleration of EI consumption, and especially the speeding up of the reuse of new sorts of biomass (see Figures 5.4b and 5.6b).

At this point, the policy of increasing agricultural output and providing support to industrialization led the agrarian system into the trap of dependence on fossil fuel energy (Tello et al., in press), but pasture was recycled to feed extensive livestock, which became the actual burden of energy efficiency until mid–1975. In terms of sustainability, the continued growth of FP and BR, and the low weight of EI relative to the energy of the NPP kept the gains in the NPPactEROI up to 1974. Humanized landscapes expanded, taking more of the UhB of the wild populations, but it seems that the critical point in the deterioration of living funds would have started with the intensification of export-led tropical agriculture and not with mechanization or the increasing consumption of pasture to feed livestock in this period.

The effectiveness of the state's inward-looking policies was questioned from the 1970-80s as a result of the Latin American debt crisis, which had built up during the second half of the 1970s and blew up in 1983. Monetarist policies and the neoliberal ideology emerged as the main tools to cope with the ravages of the oil and foreign debt crises, thus boosting the change towards the new agro-export model. The sudden withdrawal of petrodollars accumulated during the previous stage led to the Latin American foreign debt crises and international advice on structural reforms from the International Monetary Fund.

Although the debt crisis in Colombia was not so hard as it was in the rest of the region (Thorp, 2000), the focus on boosting agricultural exports and the application of restrictive monetary and fiscal policies to service the debt became the general trends across the developing world (McMichael, 2013). Together with the ideology, the higher international prices for tropical commodities relative to cereals (IMF, 2020) promoted tropical specialization. The impetus of the commodity prices after 2000 deepened this new situation in agriculture. This integration of the agrarian system into the chains of the global market encouraged biomass specialization (Infante-Amate et al., 2020), land intensification, and external inputs growing dependence of tropical agriculture across Latin America (Hall et al., 2000).

In parallel, in Colombia, the Chicoral agreement of 1972 ended with the efforts associated with the progressive policies of the state (Gutiérrez-Sanín, 2019) and meant that land and credit were guaranteed to the larger landowners, thus shifting the approach to the problem of increasing agricultural output by seeing it as a problem of modernization instead of distribution (Machado, 1991). Therefore, international and national contexts contributed to establishing the goal of “modernizing” agriculture by specializing in tropical exports and spreading the green revolution package (1976–97).

The deep agricultural intensification during the last stages of industrialization in Colombia (1975–2015) have contributed to accelerating the pace of fossil-fuel dependence (Figure 5.6c) and eroded the sustainability of the agroecosystem (Figure 5.7a). The FP fell due to the energy transition, associated with urbanization and less consumption of firewood as in the rest of Latin America (Soluri et al., 2018, 269), and additionally, the gains in crop yields did not performed as well as in the past (Appendix D, Table D.5). This reduction of the FP, however, did not affect all crops in the same way. Tropical crops expanded in parallel with the growing fossil-fuel dependence and specialization in tropical exports, while the land devoted to staple crops like grains, roots and tubers fell (Urrego-Mesa, in press). Thus, decreasing FP and increasing EI were the driving forces of the loss of energy efficiency, though the abandonment of BR led by livestock intensification also contributed to balancing FEROI, the fall in EFEROI speed up since the 1975/80s.

Livestock intensification came from the replacement of pasture by new feedstuffs (Figure 5.4b), mainly imported ones (Figure 5.5b), leaving some gains in the yields of animal production. However, the energy efficiency of the sub–sector remains lower than the global average, it being by far the largest consumer of energy in the agrarian system. In 1916, for every TJ of feed consumed, whatever its origin, only 12 GJ in form of milk, meat, and fat were produced, this proportion scaled up to 60 GJ in 2015; that is, 1:77 and 1:16, respectively, against the current global average of 1:10 (Davis & D’Odorico, 2015). Despite the integrated systems of livestock breeding and silviculture under family farm management (Perfecto et al., 2019) having reported positively on tropical ecosystem management and rural incomes (Chará et al., 2019), the general approach to livestock in the country has been the change from extensive to intensive, that is, from being the major driver of the NPP and UhB reductions towards a new trade-dependent intensification more in line with global trends (Davis & D’Odorico, 2015).

This same process of the tropical intensification of agriculture and livestock also led to the degradation of the sustainability of the agrarian system. The NPPactEROI reports for the first time a reduction since mid–1975 and a fall after the 2000s. However, the falling pace of the NPP slowdown seems contradictory. First, the main reason for the drop in the NPPactEROI was that the intensive use of EI (i.e. synthetic fertilizers, pesticide, machinery, and fuel) became a driving force for the deterioration of the living funds, while the remaining flows stayed almost stationary (BR and UhB) according to the slowdown in the NPP. The increase in tropical production also contributed to this second process by enhancing the relevance of the humanized energy flows from cropland in UhB production and the replacement of pasture in the BR.

The changing trend in the NPP can be attributed to the second vegetation recovery observed regionally between 2000 and 2010 in spatial analyses (Armenteras, Rodriguez, & Retana, 2013; Sánchez-Cuervo, Aide, Clark, & Etter, 2012) and shrubland recovery nationally from the 1980s (Urrego-Mesa et al., 2019). However, we also argue that crop production, which was primarily rooted in the expansion of tropical exportable crops (Figure 5.4c) contributed to more UhB coming from agricultural lands since the 1980s (Figure 5.4a). This replacement of less quality land covers under tropical crops might also be behind the starting point of the erosion of living fund reproduction observed in the NPPactEROI.

5.4.2 The Colombian case in the international SET

We now compare the results of the energy balances of the Colombian agroecosystem with the dataset compiled by the international project on Sustainable Farm Systems: Long-term Socio-ecological Transition in Western Agricultures (2012–18) in temperate countries (Figure 5.8). We focus on the low energy returns under the extensive advance of the agricultural frontier by livestock and the gains in energy efficiency during the early stages of intensification on the one hand, and the ecological potential of the tropical agroecosystems and the common trend of the deterioration of living funds in tropical and temperate agriculture during the late stages of full-industrial intensification on the other hand.

The extractive feature of Colombian agriculture is embedded in the low returns of FEROI, which are among the lowest in the sample (Figure 5.8a). Only the FEROI values of the late-colonizing counties of the arid Great Plains in 1880 are lower at the beginning of the series (Chase, Decatur, and Nemaha). The only European cases that approach the initial low level of Colombian FEROI are Manacor (Spain) in 1860 and Grünburg (Austria) in 1830/60. In the first case, extensive latifundia farming predominated (Tello, Jover, Murray, Fullana, & Soto, 2018), while in the second, specialization in cattle and pig-rearing and low population densities (73h/km2 in 1869) stand out. Currently, the cases with high components of livestock, such as the Vallès (Spain), Grünburg (Austria), and Quebec (Canada), also remain at comparative low levels. Thus, regardless of whether production is extensive or intensive, these low energy returns highlight the low efficiency of livestock bioconversion of animal feed into meat, dairy, and other products in energy terms. However, they also point out the relevance of the low densities, extensive livestock-rearing and prevailing agrarian class

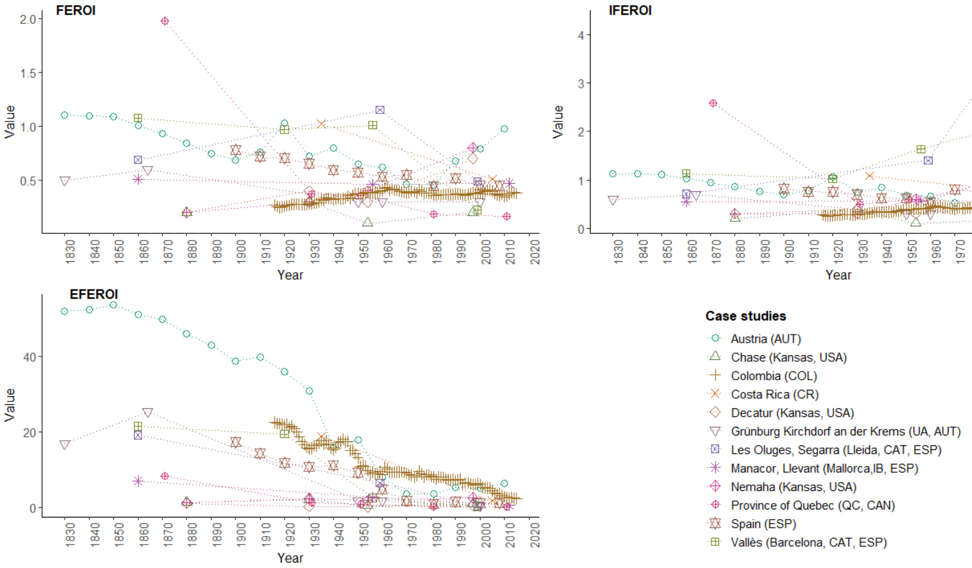

Figure 5.8: Colombian energy returns in the context of Western Agriculture (1830–2016). Final produce energy returns (FEROI) **a)** and it internal (IFEROI) **b)** and external returns (EFEROI). *Source: see section 2.2 in the main document and Tello et al. (in press)*

structure in the energy patterns of the agroecosystem and its performance at the start of intensification.

Colombian FEROI values move in accordance with an opposite trend to the majority of cases except for the US Great Plains. This points to a common feature: late agricultural colonization under cattle ranching in situations of low population densities and a change towards a greater share of cropland in land uses. Crop intensification led to early energy-efficiency gains in the case of wheat in the Great Plains and tropical foods like coffee in Colombia during the First Globalization. After intensification was consolidated, this process ended in the Great Plains with the dust bowl and the expansion of mechanization, as it was in Colombia. In this case, increasing intensification of tropical agriculture is eroding the reproduction of the agroecosystem's living funds since 2000.

Low population density, cattle-ranching, and the latifundia structure of agriculture make FEROI trends and levels largely resemble those of IFEROI (Figure 5.8b), meaning a lower EFEROI relevance in FEROI levels at that time, but also a larger capacity of EFEROI to further increase the joint FEROI returns. This does not mean that the industrialization of agriculture was not in place but denotes a low $\frac{EI}{BR}$ ratio due to the high reuse of pasture biomass for feeding livestock. This process was also stressed by Díez-Sanjuán et al. (2018) at the municipal level in Spain and contributes to the debate on the relevance of the mixture between traditional intensification and modern input-use as a positive way to increase the efficiency of agroecosystems without eroding their sustainability (Guzmán & González de Molina, 2017; Tello et al., 2016) when rates of biomass reuse are high.

Colombian EFEROI followed a similar long-term trend to the other case studies of temperate agriculture (Figure 5.8c), meaning a decreasing external energy return of agricultural industrialization. However, the process differs somewhat in its timing.

Compared to the national series for Austria and Spain, advanced organic agriculture and first mechanization arrived later in Colombia (1916–48), though the shocks from the Great Depression and the Second World War are still a common feature. After that, temperate agriculture in developed countries intensified, but in Colombia this process slowed until the starting of the Second Globalization. Since then, EFEROI has not recovered, and from 1992 and 2000 onwards external dependence increased in parallel with the expansion of this new sort of export-led tropical agriculture.

Colombia's ecological potential makes it one of the leading countries on planet earth (SiB, 2020) and this potential is also reflected in its capacity to feed many types of natural organisms. The long-term deforestation and mid-term recovery affecting the trend in NPP led to the reduction of the UhB, thus threatening the food chains on which this biodiversity depends, as seen above. However, the UhB levels remained the largest energy flow in the Colombian agroecosystem, and even today it shares more than 90% of the NPP. If compared with Spain, this share hardly exceeded 70% in organic systems and only reaches 30% in today's conventional agriculture (Díez-Sanjuán et al., 2018; Galán et al., 2016; Guzmán et al., 2017). Despite these differences, the role of forest in either the FP or the UhB is still a common feature affecting the performance of energy efficiency and the living funds' reproductive capacity both in temperate (Díez-Sanjuán et al., 2018; Guzmán et al., 2017; Marco et al., 2018) and tropical agroecosystems in the long term. In the case of Colombia, the relevance of the UhB and its shrinking pattern may highlight both the country's ecological potential and its fragility, as the agroecological EROIs stress.

The deterioration in the living funds is pointed out by the NPPactEROI, having peaked in the 1980s and fallen since the 2000s. This chronology is very different from other cases in which works have documented fund deterioration since the 1930s and the 1960s in Costa Rica (Infante-Amate & Picado, 2018) and Spain (Díez-Sanjuán et al., 2018; Guzmán et al., 2017), respectively. Regarding

AFEROI, as shown for European agriculture (Guzmán & González de Molina, 2017), we observe energy return gains. Nevertheless, in Colombia, these occurred from 1916–80, while in the case of Spain they occurred between 1960 and 2010. The differences in the levels of AFEROI are due to the relevance of UhB in Colombia, 36 times larger in the early twentieth century. However, UhB reduction also drove a convergence of up to five times.

Finally, BFEROI confirms the relevance of non–colonized ecosystems in Colombia compared with Spain (Guzmán et al., 2017), with figures of 98% and 86% at the beginning of the period respectively. During the twentieth century human colonization progressed deeper and faster in Spain than in Colombia, with acceleration in both since the 1960s. Recent work in Colombia confirms a 50% increase in the human footprint between 1970 and 2015, a reduction to less than half of the natural areas, and a progressive fragmentation of the rainforest and its connectivity with the Andean forest (Ayram et al., 2020). Thus, the human footprint and ecological connectivity also appear to be common outcomes of industrial agriculture in both temperate and tropical regions.

5.5 OUTLOOK ON SUSTAINABLE BIOMASS PRODUCTION

Our results help us review some recommendations for improvements to biomass production regarding the sustainability and energy efficiency of Colombia's agroecosystem. An increase in NPP can be achieved through land-use changes toward more family farming (Perfecto et al., 2019) and silvopastoral tropical systems (Perfecto et al., 2019).

The increasing land-matrix complexity of family farming and its capacity to offer ecological connectivity contributes to guarantee biodiversity conservation and reproduction by replacing monocultures with the integrated management of complex and diverse agroecosystems, which is also positive for peasant food security (Perfecto et al., 2019). Farm communities and indigenous practices knowledge could play keystone in engaging these forms of management, especially in tropical forests (Yoamara et al., 2020). Secondary vegetation and shrubland recovery in silvopastoral systems would increase UhB and NPP, being ways to reduce the impact of human colonization on ecosystems beyond the current expansion of pasture and tropical crops.

In tropical forests, silvopastoral systems can increase "dry matter, digestible energy, and crude protein per hectare than purely grass-based systems and thus can increase milk and meat production while reducing the need for external inputs such as chemical fertilizers and concentrated feeds" (Chará et al., 2019, 8), which means enhancing rural incomes and reducing dependence on international markets.

Such a reduction of external dependence on fewer fossil-fuel inputs could impact positively on FEROI, especially by reducing feed imported and increasing energy efficiency in the livestock sub-sector by means of its multi-purpose use and co-production. Family farming and silvopastoral systems may contribute to dealing with the ecological crisis by guaranteeing more available energy to feed both biodiversity and human food security. Reducing the market's dependence on international grain imports, fertilizers, pesticides, and fossil fuels can make agriculture more resilient in the face of climate change.

Chapter 6

Conclusions: From Tropical Extractivism to Tropical Inclusivism

This thesis has aimed to contribute to understanding the changes in the material bases of tropical agriculture through its transition from organic to conventional, to explore the role of the institutional setting, both nationally and internationally, that drove this process, and to assess the environmental consequences associated with this agrarian change. To achieve these goals, the thesis has proposed a conceptual framework in which the interaction between inner and foreign socioeconomic bases leads agriculture towards extractivism. I argue that the extractive profile of the biophysical flows of matter and energy of tropical agriculture is just a mirror of its institutional extractivism. This institutional setting is shaped by the social-class relations between the actors involved in agriculture, and the economic incentives and constraints coming from the international arena.

To explore the interactions between these material and immaterial bases of tropical agriculture, I conducted socio-metabolic and historical research rooted in the case study of Colombian agriculture during the twentieth century. This research was guided by three questions: how did agrarian change occur in Colombia from a biophysical point of view? What were the forces driving these changes? What were the environmental consequences of the agrarian change?

Following these questions, I scanned the Colombian agroecosystem to identify the size of its main flows (Chapter 2), explored the long-term patterns of the ecologically exchange in Latin America's international trade with the rest of the world (Chapter 3) and the market and non-market mechanisms driving agrarian change towards food dependence and tropical export specialization of Colombia's agrarian trade (Chapter 4). Finally, I set out the process of extensification and intensification, and its implications for the energy efficiency and sustainability of the agroecosystem nationally (Chapter 5). The following of this chapter summarizes what we know on these questions after this thesis, the limits of the research, and the future pathways that derive from it. I also devote some lines to pointing out how this knowledge can contribute to the agroecological transition of tropical agriculture towards more resilient models

How did the agrarian change take place in Colombia from a biophysical point of view?

NPP and UhB stand out as the main flows of the Colombian agroecosystem in both matter and energy, which does not imply low levels of biomass extraction but the opposite. Despite UhB in Colombia currently being more than 90% of NPP, while in Spain the figure is 30%, extraction in Colombia is twice and three times higher than in Spain (Guzmán et al., 2017) and Austria (S. Gingrich & Krausmann, 2018), respectively. This extraction is mainly marked by the appropriation of pasture and cash crops. The development of the cash crops drew the broad lines of the agrarian change by means of extensification (1915–45), intensification (1945–75), and a change in crop composition (1975-2005) (Figure 2.10) throughout the development of the coffee economy, the "modernization" of domestic and commercial agriculture, and the tropical export-led specialization, respectively.

The energy analysis allows us to define a more accurate periodisation of this socio-ecological transition according to the changing profile of the consumed inputs and the five periods that are usually referred to in the economic history for the whole region. First was export-led growth during the First Globalization (1916–32). This period featured increasing demand for land, labour, and agricultural tools to serve the expansion of the coffee economy and extensive cattle-rearing. As a response to the external shocks of the Great Depression and the Second World War during the second period (1933–54), and as a domestic policy during the third period (1956–75), domestic agriculture received more support for its "modernization". According to the development goals of industrialization, the growth of agricultural output became a need. Credit and import facilities boosted the entry of tractors, machinery, and some fertilizers, which helped to reverse the low energy efficiency of an agrarian system dominated by extensive livestock-rearing and low densities of population.

During the fourth period (1976–97), the scaling up of land intensification due to the technological innovations of the Green Revolution occurred in parallel to the change in the composition of land-use towards more tropical crops. The start of the tropical specialization was the main factor explaining the growth in agricultural output during this time. The transition of agriculture from tropical-extensive under coffee and cattle-ranching towards tropical-intensive under sugarcane, oil palm, banana, and "modern" livestock-rearing involved increasing dependence on fertilizers, pesticides, and imported feed. However, since the last period (1998–2016), tropical export-led specialization also relied on the expansion of the agricultural frontier and the intensive use of traditional inputs such as human labour. This blended use of external inputs fairly reflects the spirit of the material bases of agrarian extractivism and the turn to re-primarization which started since the 1980s structural reforms and accelerated at the beginning of the 21st century.

This long-term agrarian change of tropical agriculture from organic to conventional clearly differed from the socio-ecological transition in temperate agriculture recorded in the developed countries. Then, it contributes to the narrative of the transition of

Western agriculture. As a central aspect of Western agriculture, the socio-ecological transition of tropical agriculture is clearly a result of the Second Globalization (since c. 1980) instead of a product of the second post-war period, as it was across developed countries. Additionally, this first description of a case from the Global South also highlights the primary role of rural elites and international markets as the main actors driving the extractive profile of tropical agriculture since the First Globalization.

What were the main forces driving the agrarian change?

The economic incentives from international markets and the geopolitical frame that ruled agricultural production and trade during the twentieth-century food regimes have been key elements in understanding the material bases of agriculture and its changes in Colombia. Starting with the Latin American situation, we find that the biophysical trade was characterized by unequal exchange throughout the twentieth century and a sort of shifting specialization, namely biomass during the First Globalization, fossil fuels during the state-led growth model, and metal ores and biomass since the beginning of the Second Globalization. This integration in international markets as the eternal provider of raw materials, has served the material needs of Europe, United States, and, eventually, China.

During the latter period (since c. 1980), a Great Acceleration has dominated the trends in biophysical trade between Latin America and the rest of the world at the expense of its natural decapitalization. This sharp upward trend in the trade in natural resources started during the 1980s and intensified from 2000, having been driven globally first by the growth in population, and then by the emergence of the global middle class (Oberle et al., 2019; T. Wiedmann, Lenzen, Keyßer, & Steinberger, 2020), especially in China (Milanovic, 2016). However, the institutional changes that opened the Pandora's box of re-primarization were the structural reforms across the developing world, suggesting export promotion from the primary sector and state function deregulation as the ways of coping with the failed policies of industrialization and of servicing the foreign debt (Kumar Sharma, 2016; McMichael, 2013). To sum up, the traditional role of raw material exporters and the changes introduced after the debt crisis shaped somehow the incentives and the rules followed by the Latin American Countries from the First to the Second Globalization.

In the case of the agricultural trade in Colombia, however, there was a shift of profile from the country being a net exporter of tropical crops to a net importer of cereals (after c. 1990). This did not mean the end of specialization and intensification but the opposite. Although less intuitive in terms of unequal exchange theory, this pattern reflects the general trends of specialization according to the natural resource endowment observed for the biophysical trade of the region. It also resembles the biomass dependence in the balance of trade identified for Mexico and Peru during the same period. The development of regressive agricultural crops that use land and capital intensively, such as fresh vegetables, flowers, sugarcane, banana, and oil palm, took the lead, while the capacity to produce basic foods self-sufficiently deteriorated.

These new trends in trade, commonly defined as the third food regime, explain the import profiles of these countries, but additionally Chapter 4 explored the role of violence and relative prices of tropical commodities in making tropical specialization of Colombian agricultural trade. In the long term, there is a positive relationship going from violence and prices towards tropical specialization, which validates the argument from the political economy of war on the use of violence as a tool to develop agribusiness projects that favour agrarian elites. In the short term, however, violence is also a consequence of price incentives and agricultural specialization. Therefore, market and non-market mechanisms are associated with the change towards tropical specialization in the long term, and perhaps the expansion of commodity crops have served to sustain the civil war in the short term. In addition to the market incentives and the use of violence, the institutional support of the state has also been of primary concern to the economic interests of the rural elites and the development of the agro-export sector.

Examining the history of the agrarian policy of the country allows us to conclude that the outstanding position of pasture and cash crops, mainly devoted to international markets in tropical products, was also shaped by the institutional bias of the agrarian policy, which has systematically favoured land accumulations for extensive cattle-ranching and the privileged access to new technology and markets for commercial agriculture both domestic and internationally. Although the correlation of forces was favourable to the peasants at some moments, the agrarian elites and their economic interests have prevailed in drawing up public policies for the agrarian sector for most of the period studied. After the breakup of the traditional system of the hacienda and the industrial development policies, the bargaining power of the peasant movement increased, its demands being joined to the needs of the industrial classes, but the counter-reformist attacks of the rural elites have always been stronger. The state support to export model under the Conservative Republic, the 1946 counter-reform, the Chicoral agreement of 1972, the support for agro-exports during the A. Uribe government, and the blocking of the implementation of the rural reform of the peace agreements are examples of the regressive opposition of the agrarian elites to the demands of the peasant movements.

Thus, agrarian change towards the tropical specialization of agro-exports has been associated with the economic incentives and geopolitical constraints of the international context on the one hand, and the formal and informal institutional support at the domestic level favouring the economic interests of the rural elites – namely the bias of the agrarian policies and the use of violence – on the other hand.

What were the environmental consequences of the agrarian change?

The energy returns of Colombian agriculture performed poorly compared to that of temperate agriculture, which is in agreement with the dominant role of the extensive cattle-ranching, the low population density, and the relative abundance of land under pasture and forest. In contexts such as the present, however, long-term research on the energetic profile of tropical agriculture unveils some noteworthy features. Before the establishment of the intensive model, there were several transformations of the material and socioeconomic bases of agriculture that perhaps help to draw possible future paths.

The expansion of the agricultural frontier and the initial intensification regarding the use of labour, agricultural tools, and some mechanization had a positive effect on the energy efficiency of agriculture and the reproductive capacity of the agroecosystem. In social terms, the increasing bargaining power of the peasant movement led to the consolidation of the family-farm coffee-growing model, which allowed such families to capture some gains from the export sector. This is not to say that deforestation and the consequent reduction in the NPP have not been threats to the long-term maintenance of ecological sustainability, only that those historical experiences in between extreme conservationism and ecological depredation can inform ways to increase energy efficiency without eroding the sustainability of agroecosystems (Fullana-Llinàs, Tello-Aragay, Murray-Mas, Jover-Avellà, & Marull-López, in press).

After the structural change and the elites' counter-attack of the 1980s, agriculture succumbed to the energy trap. The institutional support to the livestock sector and commercial agriculture led to a rapid increase in the use of internal (1970–80) and external inputs (since c. 1980). This new intensification put an end to the gains in the energy efficiency of agriculture and the reproductive capacity of the agroecosystem achieved during the previous stages. The scaling up of tropical export-led agricultural intensification involved negative energy returns and fossil-fuel dependence, but this path to deterioration accelerated after 2000, when frontier expansion and the intensive use of traditional inputs such as human labour were added to the process of intensification. This sort of combination between intensification and extensification is at the core of the current material bases of agrarian extractivism in Colombia and characterizes the present turn back to the tropical specialization model.

But such specialization in sugarcane, banana, and oil palm causes more than just deforestation, landscape homogenization, and fossil fuel dependence. This specialization has also contributed to the breaking out of the natural cycles. The increasing relevance of these crops to agricultural output and their high energy and biomass content, that moves far away from the agroecosystem throughout international trade, hinders the recycling of matter and energy to the maintenance of soil fertility and biodiversity (Montero et al., 2021). However, these large amounts of residues could play an integrating role in agroecological management systems and shorter distribution chains. Thus, the agrarian change towards intensive and extensive tropical crop specialization and the commercial integration of these crops into international markets are behind the agrarian system's losses in energy efficiency and the erosion of the reproductive capacity of the agroecosystem since the beginning of the Second Globalization.

Answering these research questions by analysing Colombian agriculture brings into the social metabolism framework of agroecosystems the close relationship between the material and socioeconomic bases of agriculture in the long term. This work has highlighted the extractive nature of the material bases of the current tropical agriculture, as well as the role of international and domestic institutional settings leading to this extractivism. However, this is only the first approximation. The extractive agriculture of the Colombian case, we have scanned in this thesis through its material and energy flows, can contribute with empirical results on the conceptualizations held by the literature on the agrarian extractivism model across the developing countries and especially Latin America.

To dive into this relationship becomes relevant in light of the required transition of conventional agriculture from its globalized fossil fuel-dependent profile towards more sustainable models. Meanwhile agrarian metabolism helps to measure the past, current, and hypothetical impacts of the agricultural managements, the institutional factors guide the social relations and policy-making to tackle this change

Therefore, the case of Colombia since the 1980s could be illustrative of the transition of agriculture across the developing world and of tropical agriculture, and its linkages with the changes of temperate agriculture in the Global North. A process of intensification led by the economic incentives of international markets and the ruling geopolitics of the third food regime that comes together with the domestic prevalence of the agrarian elite's interests and the active role of the state in favouring them by means of its agrarian policy. In the medium term, these external and internal frames could play a primary role in leading the material profile of agriculture towards greater sustainability, in the same way that they have acted historically to create the current unsustainable profile of tropical agriculture.

The historical case of Colombia allows us to envision the potential of some types of crops, such as coffee, and to see how they could fit the current needs of rural development in contexts of tropical export agriculture while helping to mitigate the effects of climate change and the ecological crisis. Although coffee is a land-intensive crop, the exportable piece of coffee (the grain) is characterized by its low content of biomass and energy. This characteristic involves the possibility of recycling matter and energy into the soil by the use of labour while reducing the physical extraction of the export sector and fossil-fuel dependence. Besides the positive returns of this agroecology management of labour-intensive crops such as coffee, difficult to scale up or family farming-based, with high ratios of prices to energy or matter content in international markets, could also fit well the need to obtain foreign exchange in developing regions while boost rural employment and agroecological transition.

In the case of extensive cattle-ranching, the replacement of pastureland for shrubland and secondary vegetation under silvopastoral management systems could turn back the historical profile of extensive cattle-rearing into a more sustainable one without competing with forest and food production. Intercropping and silvopastoral integrated systems are not only beneficial to ecological restoration, they also contribute to reducing the dependence of agriculture and food provision on international markets, which is positive for rural incomes and food security while contributing to increasing the NPP and capturing more CO_2.

These changes, however, need the state's institutional support to family farming for its access to land, technologies, local markets and networks, credit, etc., which means opening a direct confrontation with the economic interests of the rural elites. Is this binomial situation the only one? In-deep analysis of gender, race, income, and cultural features at the local level could bring some light to stress different socio-metabolic profiles and different strategies in managing the agroecosystems. However, the exploration of the transition and the lessons from history beyond the Colombian case and the national level are among the major limitations of this thesis.

This work compares the performance of Colombian agriculture to set its socioecological transition into the frame of the Western agriculture of developed countries, which helps to establish some interdependencies of the process of transition, but there is a lack of comparison with other developing countries or contexts of tropical agriculture and there is not a disaggregated analysis by regions of specialization, types of crops, neither socioeconomic features at the local level.

Although limited in its scope, the thesis opens up a window to explore the extractive nature of tropical agriculture, its impacts on the energy efficiency and reproductive capacity of agroecosystems across the Global South, while establishes the conceptual and methodological framework with which to analyse the long-term relationships between the material and immaterial bases of the agrarian extractivism of tropical agriculture in developing countries both nationally and locally.

Future lines of research, therefore, must pass by the extension of this analysis at these two levels, global and regional. These approaches will allow us to clearly disentangle the interactions between the ecological dimensions of agriculture and its socioeconomic settings. Thus, to develop the agrarian metabolism in this line involves enquiring about the role of inequalities in land, income, gender, race, political participation, and state capacity on the performance of the energetic efficiency, the reproductive capacity of the agroecosystems, and the surge and resolution of environmental conflicts at the regional or local level. But the research also has to deepen on the role played by the biophysical trade in creating different paths of the socio-ecological transition of agriculture and energy efficiency between the South and the North at the global level.

In this way, the thesis contributes to advance in the comprehension of the material and institutional constraints that are hindering the agroecological transition of tropical agriculture through the case of Colombia, while also invite to rescue past experiences of ecological and social sustainability across the developing world to help design the needed agroecological landscapes for the future transition.

Appendix A

Pastures and Cash Crops: Biomass Flows in the Socio-metabolic Transition of Twentieth-Century Colombian Agriculture

Keywords: Biomass Accounting; Material Flow Accounting; Social Metabolism; Colombian Agriculture; Twentieth-Century

A.1 INTRODUCTION

This supplementary document aims to introduce the whole data used in the elaboration of the article "Pastures and Cash Crops: Biomass Flows in the Socio-metabolic Transition of Twentieth-Century Colombian Agriculture". In the first section we describe the sources and procedures applied to figure the missing values for crop production and harvested area. Additionally, we provide details for the most important crops: maize, sugarcane, and coffee. In the second section, we present the scientific literature used to estimate the harvest index, root-shoot ratio, weeds in traditional, low-input and conventional agricultural systems, and NPP for pastures and tropical forest. The fourth section is devoted to forest and pasture covers; there we show the data on pasture, cattle and cattle density employed to estimate pastureland and discuss the available data for permanent pastures, meadows, and shrubland. Regarding forest, the annual rates of change in clearing are presented. The fifth section describes the methodological procedure to estimate the average weight and the nutritional requirements of the livestock, including a sensitivity analysis of the animal feed requirements and the biomass extracted. The series of NPP, extraction and uses resulting from our research are provided in a "cash_crops_sup.xlsx" file.

The dataset is part of a broader project on the physical analysis of Colombian agriculture in the long-run, aimed to appraise the evolution the sustainability, the energetic efficiency and socio-ecological impact of the agricultural transition during the twentieth century in the country. The primary goal of the project is to place the experience of a peripheral country into the socio-metabolic transition of western agriculture. This research is funded by the projects “Sustainable Farm Systems: Long-Term Socio-Ecological Metabolism in Western Agriculture” (Canadian Social Sciences and Humanities Research Council Partnership Grant 895-2011-1020), and“Sustainable Farm Systems and Transitions in Agricultural Metabolism” (Spanish Ministry of Science grant HAR2012-38920-C02-02) which has also funded the cost of this publication in Open Access.

A.2 CROP PRODUCTION AND CROP AREA MISSING VALUES

Before 1961 there is information at the national level, but not all years are available. Kalmanovitz et al. (1999) provide annual production series for twelve crops, namely: maize, wheat, barley, rice, potatoes, beans, tobacco, sugar cane, cocoa, banana, and coffee. We compared these series with data on production and area from other national sources for 1915, 1925, 1928-30, 1932-46, 1948-50, yields from other countries in the region (see section 2.2.2 in the main text), and introduce some modifications accordingly. Moreover, we completed the lacking information for cassava, coconuts, agave, cotton, fifteen vegetables, and one aggregate category for fruits different to banana and plantain. Regarding the area in 1915, we adjust the data from the DGE (1915) according to the production data fromKalmanovitz et al. (1999). Missing years, both in production and area, were estimated employing linear interpolation or assuming steady yields. In the case of vegetables, the estimation extended the per capita production of 1961 for each crop backwards. As for fruits, we have used total fruit supply from FAO in 1935–39 and 1946 (FAO, 1948), except for banana and plantain, to obtain per capita supply. This ratio and the population series (Flórez Nieto & Méndez, 2000) were used by periods to figure the fruit production. We describe the cases of maize, sugar cane, and coffee below, as they are the most relevant crops concerning their physical and economic weight.

A.2.1 Maize

In the case of maize, the data of Kalmanovitz et al. (1999) exceeds the production of the Yearbook in 1915 (DGE, 1915) and Wylie (1942)’s estimation for 1925-28 by a factor of two, but the differences after the 1930s (figure A.1a). When we cross production data from Kalmanovitz et al. (1999) with the available information of area (figure A.1b), the difference entails yields higher than 1500 kg/h and even 2000 kg/h (figure A.2a). By contrast, the yields obtained with the data from Wylie (1942) are consistent with the yields in 1932-1940 (800-1000 kg/h) and with those of countries like Ecuador (1280 kg/h between 1938-42) (DNE, 1944), Cuba (916 kg/h in 1945) (MAC, 1951), or Venezuela (1000 kg/h in 1949) (UNECLA, 1953).

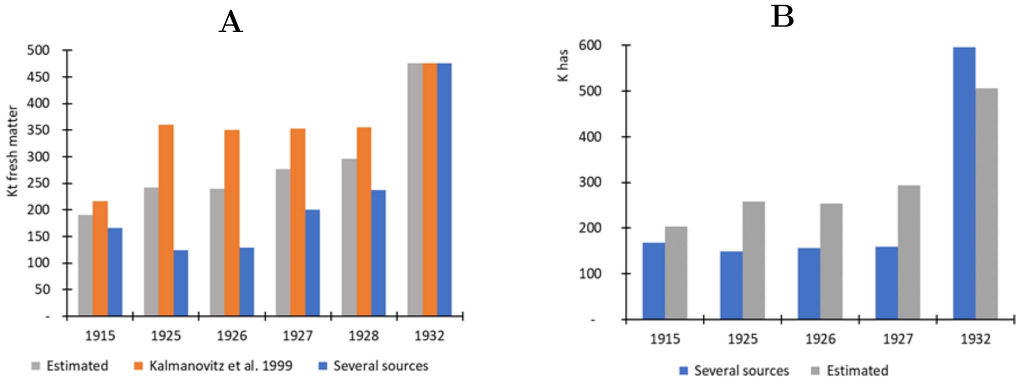

Figure A.1: a) Maize production in thousands of tonnes (Kt) of fresh matter from our estimation, Kalmanovitz et al. (1999), and other sources (i.e.: Bejarano (2011); DGE (1915); Wylie (1942)) and b) the area under maize in thousands of hectares (Khas) from several sources (i.e.: Bejarano (2011); DGE (1915); Wylie (1942)) and our estimation for 1915, 1925-28, and 1932.

These differences could derive either from the occultation of the harvested area or the overestimation of production in the series given by Kalmanovitz et al. (1999), but we are unable to identify which one of them is behind the issue. Therefore, we estimate production as the average between the information inKalmanovitz et al. (1999) and from the other sources (i.e.: Bejarano (2011); DGE (1915); Wylie (1942)). Regarding the area, the missing values were obtained by assuming that average yields in 1915, 1925-27, and 1932 (941 kg/h) remained constant during the period 1915-1932.

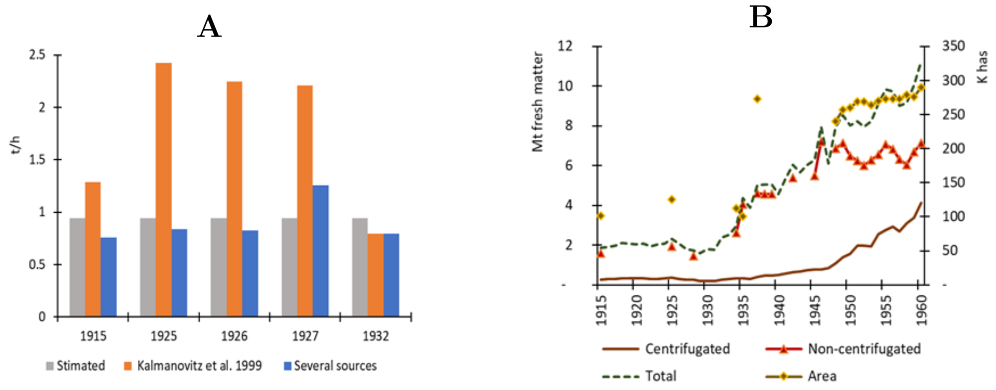

Figure A.2: a) Yields of maize in tonnes per hectare in fresh matter from Kalmanovitz et al. (1999)and several sources (i.e.: Bejarano (2011); DGE (1915); Wylie (1942)) in 1915, 1925-27, and 1932. b) Centrifuged, non-centrifuged, and total sugarcane in millions of tonnes of fresh matter (left axis) and the area under sugarcane (right axis) in thousands of hectares (Khas) during 1915–60.

A.2.2 Sugarcane

The data on sugar cane before 1961 is usually the amount of centrifuged sugar produced (figure A.2b). Non-centrifugated sugar and molasses, very relevant during the first half of the twentieth century, are not taken into account in the studies. We standardize the values before 1961 with the information in FAOSTAT (2021). The yield of centrifuged, non-centrifuged sugar, and molasses in the 1940s ranged between 10 and 11% of cut sugarcane (Varela Martínez, 1949, 85), so we apply 0.1 to the data of Kalmanovitz et al. (1999) and to the whole sugarcane production in several sources for 1915, 1925, 1928, 1934-35, 1937-39, 1942, 1945-46, 1948-50 (Atkinson, 1969; Bejarano, 2011; DGE, 1915, 1933, 1934, 1937; Diot, 1976; Varela Martínez, 1949; Wylie, 1942). For the years in between, we use the value of the ratio of centrifuged over non-centrifuged sugarcane. This ratio moved from 0.18 in 1915 to 0.58 in 1960, but during 1915-1950 the amount of centrifugated sugar remained almost constant (A.2a) at average of 0.14 (sd. 0.05). Regarding the area, the missing values were estimated by linear interpolation. The values for 1934-35 were rejected as yields were closer to the mid-1960 than 1925 or 1937 which is not consistent. Finally, the estimated average yield between 1941-1945 is 23 tonnes per hectare; very close to the yield of 27 tonnes per hectare in Cuba in 1945.

A.2.3 Coffee

Data for coffee production between 1915 and 1947 is from (GRECO, 1999). These series shows the effect of the Great Depression and the WWII better than the data of Kalmanovitz et al. (1999), but we use their data for 1948-1950 since it is consistent with the figures given by Atkinson (1969), which also provided the information between 1950 and 1960. After 1960, as usual, we used FAOSTAT (2021). Regarding the area, in the 1915 Yearbook there is no information for Caldas and the total area under coffee for whole the country is 46,295 has. However, Caldas was the primary producer of coffee at this time with a share of 30% of the domestic production. Due to this relevance, we estimated the lacking area by applying the average yields of the other departments (830 kg/h), which is the most conservative estimation considering the specialization of Caldas. The estimation leads to an area of 25,370 has for the department and rise the total national area under coffee in 1915 up to 71,665 has (see table A.1). For the rest of the years there is information on area for 1925/27 (Bejarano, 2011; Diot, 1976), 1932/34 (DGE, 1933, 1934), 1946 (Varela Martínez, 1949), 1948–60 (Atkinson, 1969), and since 1961 from FAOSTAT (2021). The years in between were figured by linear interpolation.

Regarding the yields, we observe a decreasing trend during the first half of the century from 930 kg/has in 1915 to 450 kg/has on average during the years of the IIWW (figure A.3a). According to Cárdenas et al. (2000a) a weakening of the coffee economy began after the Great Depression and they argue that despite the prices grew after 1945 (figure A.3b), the area and the production did not; plantations deteriorated, and the productivity per hectare fell to 1% (Cárdenas et al., 2000a). However, our data on exportations and area does not fit well with this story.

Based on the series of GRECO (1999), between 1915-1955 the production and the area under coffee, in physical terms, rose on average at 6% annually. Production increased four-fold and the area ten-fold. Coffee production grew from 67 Mt to 377. The area increased from 71 Khas in 1915 to 360 Khas in 1932/34 and to more than 800 Khas in 1955. The expansion in production and area slowed down between 19955 and the early 1970s, which have been explained by the agrarian historiography due to the ageing of coffee trees during the years of La Violencia (1948–58) (Bejarano, 2011)

Table A.1: Coffee area and production in Colombia by departments in 1915

	Department	Area (ha)	Production (kg)	Yields
1	Antioquia	2,416	1,777,988	736
2	Atlántico			
3	Bolivar	151	85,075	563
4	Boyacá	30	18,742	625
5	Caldas	253,701	21,057,152	830[1]
6	Cundinamarca	15,517	20,060,475	1,293
7	Cauca	1,781	76,066	427
8	Huila	2,175	821,874	378
9	Magdalena			
10	Nariño	443	63,512	1,434
11	Santander N.	10,515	13,476,400	1,282
12	Santander	4,163	1,433,700	344
13	Tolima	35	3,677,670	1,051
14	Valle	5,604	5,604,000	1,000
15	Total	71,665	69,408,856	

Note: [1] The average yield of the other departments was used to calculate the area. Source: DGE (1915)

and the downtrend of the prices. After mid-1970s the international prices rose again creating incentives to relaunching boots the coffee economy (figure A.3a and b).

Our interpretation of the decline in coffee yields between 1915–45 is related to the expansion of the agrarian frontier, instead of the loss of dynamism in coffee production. The land ploughed for coffee expanded at 5% annually until 1946, but the population growth in the coffee zone was slower, which means less yields from land relative to labour. We gathered data for the population in Antioquia and Caldas for 1918, 1928, 1938, and 1951 to test this idea (DANE, 1955b; DGE, 1924, 1930, 1944). The average rate of growth of the population during these years was 2.5% while it was 1.6% for rural population, for this latter data is only available for 1928, 1938, and 1951. If we focus on the evolution of Caldas, since it was the most dynamic zone of coffee, population growth (3.1%) remained lower than the expansion of the area. The greater dynamism of the frontier expansion over the available labour could explain the decrease of the yields during the first half of the century. After 1955, and despite the older trees, the production grew slowly while the area stabilized. This movement is partly related to advances in intensification during the 1960s, but the actual increase of yields occurred with the 1970s rise of international prices. The spread of new technologies (i.e., new species, management, and fertilizers) would has allowed to reduce the land devoted to cultivating coffee.

A.3 CONVERSION FACTORS OF CROPS

In computing the factors we have followed the methodology proposed by Guzmán et al. (2014) and extended with the literature presented in table A.2. We assigned factors according to the similitude of crops or used average figures when the specific factor was

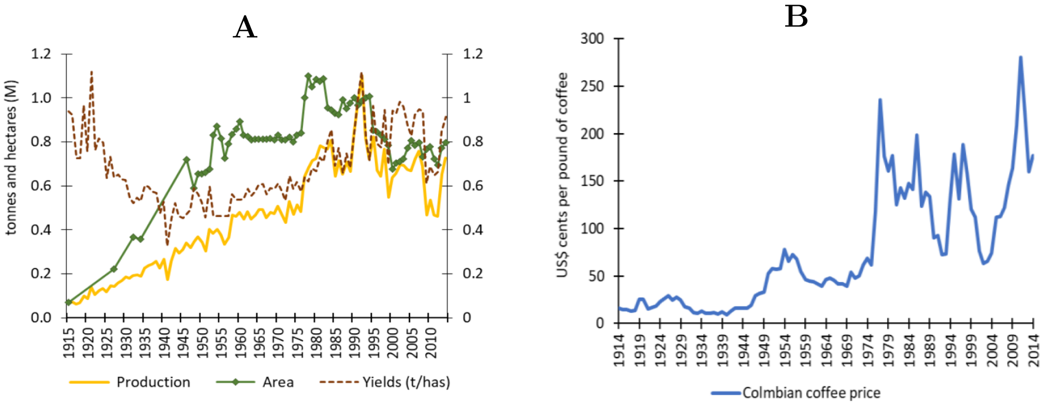

Figure A.3: a) Coffee production in millions of tonnes, the area in millions of hectares (left axis) and the coffee yields in tonnes per hectare (right axis). b) International prices for Excelso coffee (453.6 gr.) in US$ cents per pound. Sources: for the coffee area and production see the main text. Excelso coffee prices are from the Federación de Cafeteros de Colombia (FNC, 2018)

not available. The table A.3 still a working progress, for specificities on crops, factors or improvements in the dataset please contact by email [1].

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Table A.2: Literature review for factors of harvest index, root-shoot ratio, weeds in traditional, low-input and conventional agricultural systems, and NPP for pastures and tropical forest

Harvest index	Weeds			NPP	
and root-shoot–ratio	Traditional system	Loi-input system	Conventional system	Pastures	Forest
Guzmán et al. (2014)	Begna et al. (2001)	Begna et al. (2001)	Begna et al. (2001)	Borda and Ramírez Nader (2003)	Álvarez Sánchez (1991)
Funes, Villa, and Aguilera (2017)	Bradshaw and Lanini (1995)	Bradshaw and Lanini (1995)	Bradshaw and Lanini (1995)	Moreno Durango and Padilla Valle (1972)	Gómez and Gallopin (1991)
Kyle et al. (2011)	Guzmán et al. (2014)	Guzmán et al. (2014)	Chauhan and Johnson (2011)	Padilla Quintero (2017)	Raich et al. (1991)
Madden and Darby (2012)	Khanthavong, Oudthachit, Souvannalat, and Matsumoto (2016)	Khanthavong et al. (2016)	Cheema, Khaliq, and Tariq (2002)		Scurlock and Olson (2013)
Montero (2018)	M. Liebman, Bastiaans, and Baumann (2004)	M. Liebman et al. (2004)	Cierjacks, Pommeranz, Schulz, and Almeida-Cortez (2016)		
Robinson, Cox, and Koo (2016)	Marambe and Sangakkara (1995)	Liebman and Davis (2000)	Guzmán et al. (2014)		
Sethuraj (1981)	Mohler and Liebman (1987)	Papamichail, Eleftherohorinos, Froud-Williams, and Gravanis (2002)	Khanthavong et al. (2016)		
	Papamichail et al. (2002)	Ryan et al. (2010)	Liebman and Davis (2000)		
	Ryan et al. (2010)	Tixier et al. (2011)	M. Liebman et al. (2004)		
	Tixier et al. (2011)	Wilson, Wright, Brain, Clements, and Stephens (1995)	Mohler and Liebman (1987)		
	Wilson et al. (1995)		Ryan et al. (2010)		
			Tixier et al. (2011)		
			Zafar, Tanveer, Cheema, and Ashraf (2010)		

Table A.3: Conversion factors for crops

	Code	FAO name	P	R	RF	R:S	WC	WLI	WT
1	15	Wheat	0.88	0.87	1.36	0.20	61	437	1,267
2	27	Rice, paddy	0.86	0.91	1.20	0.46	530	585	640
3	44	Barley	0.88	0.86	1.20	0.21	130	669	440
4	56	Maize	0.86	0.88	0.94	0.24	308	717	855
5	71	Rye	0.88	0.92	1.30	0.85	252	666	822
6	75	Oats	0.87	0.91	1.43	0.40	252	666	822
7	79	Millet	0.88	0.90	1.22	0.15	252	666	822
8	83	Sorghum	0.86	0.87	1.69	0.09	252	666	822
9	89	Buckwheat	0.88	0.87	1.36	0.20	252	666	822
10	92	Quinoa	0.89	0.88	1.25	0.15	252	666	822
11	94	Fonio	0.87	0.95	1.50	0.15	252	666	822
12	97	Triticale	0.87	0.88	1.25	0.15	252	666	822
13	101	Canary seed	0.88	0.87	1.36	1.50	252	666	822
14	103	Grain, mixed	0.88	0.90	1.33	0.53	252	666	822
15	108	Cereals, nes	0.87	0.95	1.50	0.15	252	666	822
16	116	Potatoes	0.23	0.20	0.70	0.07	26	79	500
17	122	Sweet potatoes	0.23	0.30	0.89	0.15	263	1,690	2,775
18	125	Cassava	0.42	0.30	0.67	0.15	500	3,300	5,050
19	135	Yautia (cocoyam)	0.23	0.30	1.22	0.13	263	1,690	2,775
20	136	Taro (cocoyam)	0.25	0.30	1.22	0.13	263	1,690	2,775
21	137	Yams	0.25	0.30	1.00	0.15	263	1,690	2,775
22	149	Roots and tubers, nes	0.23	0.20	0.06	0.15	263	1,690	2,775
23	156	Sugar cane	0.29	0.48	0.43	0.18	561	606	651
24	157	Sugar beet	0.25	0.16	1.00	14.29	477	1,751	2,867
25	161	Sugar crops, nes	0.27	0.32	0.67	0.18	561	606	651
26	176	Beans, dry	0.92	0.89	1.17	0.08	339	721	784
27	181	Broad beans, horse beans, dry	0.92	0.89	1.17	0.08	339	721	784
28	187	Peas, dry	0.90	0.91	2.33	0.06	446	570	694
29	191	Chick peas	0.94	0.89	1.70	0.08	339	721	784
30	195	Cow peas, dry	0.92	0.89	1.00	0.08	339	721	784
31	197	Pigeon peas	0.91	0.30	1.86	0.15	339	721	784
32	201	Lentils	0.90	0.93	2.08	0.15	339	721	784
33	203	Bambara beans	0.91	0.91	2.03	0.07	339	721	784
34	205	Vetches	0.90	0.91	1.24	0.60	339	721	784
35	210	Lupins	0.89	0.89	2.33	0.08	339	721	784
36	211	Pulses, nes	0.91	0.30	1.86	0.15	339	721	784
37	216	Brazil nuts, with shell	0.90	0.75	1.22	0.15	187	1,611	2,895
38	217	Cashew nuts, with shell	0.90	0.75	1.50	0.15	477	1,751	2,867
39	220	Chestnut	0.50	0.80	1.50	0.15	477	1,751	2,867
40	221	Almonds, with shell	0.69	0.69	2.28	0.15	477	1,751	2,867

41	222	Walnuts, with shell	0.75	0.83	1.50	0.15	477	1,751	2,867
42	223	Pistachios	0.80	0.80	1.50	0.15	477	1,751	2,867
43	224	Kola nuts	0.50	0.80	1.50	0.15	477	1,751	2,867
44	225	Hazelnuts, with shell	0.93	0.75	1.70	0.15	477	1,751	2,867
45	226	Areca nuts	0.65	0.30	4.26	0.15	477	1,751	2,867
46	234	Nuts, nes	0.90	0.75	1.22	0.15	477	1,751	2,867
47	236	Soybeans	0.86	0.89	1.86	0.39	339	721	784
48	242	Groundnuts, with shell	0.91	0.91	2.03	0.07	477	1,751	2,867
49	249	Coconuts	0.20	0.38	0.52	0.29	184	1,559	2,652
50	254	Oil palm fruit	0.65	0.30	4.26	0.15	477	1,751	2,867
51	256	Palm kernels	0.83	0.81	2.22	0.13	477	1,751	2,867
52	257	Oil, palm	1.00	1.00	4.26	0.15	477	1,751	2,867
53	260	Olives	0.54	0.70	0.95	0.21	800	2,248	3,000
54	263	Karite nuts (sheanuts)	0.90	0.75	1.70	0.15	477	1,751	2,867
55	265	Castor oil seed	0.65	0.30	2.00	0.15	477	1,751	2,867
56	267	Sunflower seed	0.94	0.93	2.30	0.06	477	1,751	2,867
57	270	Rapeseed	0.91	1.00	2.45	0.15	477	1,751	2,867
58	275	Tung nuts	0.83	0.81	2.22	0.13	477	1,751	2,867
59	277	Jojoba seed	0.83	0.81	2.22	0.13	477	1,751	2,867
60	280	Safflower seed	0.91	1.00	3.54	0.06	477	1,751	2,867
61	289	Sesame seed	0.83	0.95	2.70	0.15	477	1,751	2,867
62	292	Mustard seed	0.91	1.00	2.45	0.15	477	1,751	2,867
63	296	Poppy seed	0.83	0.81	2.22	0.13	477	1,751	2,867
64	299	Melonseed	0.88	0.85	2.21	0.24	215	1,238	1,993
65	305	Tallowtree seed	0.83	0.81	2.22	0.13	477	1,751	2,867
66	310	Kapok fruit	0.83	0.82	1.08	0.15	414	2,020	3,612
67	311	Kapokseed in shell	0.83	0.81	2.22	0.13	414	2,020	3,612
68	328	Seed cotton	0.92	0.92	1.50	0.15	219	2,137	4,055
69	329	Cottonseed	0.93	0.85	1.60	0.15	219	2,137	4,055
70	333	Linseed	0.93	0.85	2.85	0.15	414	2,020	3,612
71	336	Hempseed	0.83	0.81	2.22	0.13	414	2,020	3,612
72	339	Oilseeds nes	1.00	1.00	2.33	0.15	477	1,751	2,867
73	358	Cabbages and other brassicas	0.10	0.18	0.74	0.15	491	615	2,087
74	366	Artichokes	0.12	0.20	1.40	0.15	215	1,238	1,993
75	367	Asparagus	0.05	0.30	3.59	0.15	215	1,238	1,993
76	372	Lettuce and chicory	0.06	0.17	0.39	0.15	215	1,238	1,993
77	373	Spinach	0.10	0.18	0.10	0.15	215	1,238	1,993
78	378	Cassava leaves	0.18	0.18	0.92	0.15	500	3,300	5,050
79	388	Tomatoes	0.06	0.13	0.96	0.14	212	527	1,510
80	393	Cauliflowers and broccoli	0.09	0.19	0.53	0.15	491	615	2,087

81	394	Pumpkins, squash and gourds	0.11	0.30	0.14	0.15	215	1,238	475
82	397	Cucumbers and gherkins	0.09	0.20	0.25	0.15	215	1,238	1,993
83	399	Eggplants (aubergines)	0.09	0.20	0.69	0.15	215	1,238	1,993
84	401	Chillies and peppers, green	0.25	0.30	2.33	0.15	215	1,238	1,993
85	402	Onions, shallots, green	0.08	0.30	0.79	0.15	97	2,177	4,257
86	403	Onions, dry	0.06	0.20	0.61	0.15	97	2,177	4,257
87	406	Garlic	0.30	0.30	0.01	0.15	215	1,238	1,993
88	407	Leeks, other alliaceous vegetables	0.10	0.21	0.01	0.15	97	2,177	4,257
89	414	Beans, green	0.10	0.30	1.60	0.08	339	721	784
90	417	Peas, green	0.10	0.30	2.33	0.06	339	721	784
91	420	Vegetables, leguminous nes	0.18	0.24	1.97	0.15	339	721	784
92	423	String beans	0.10	0.30	1.60	0.08	215	1,238	1,993
93	426	Carrots and turnips	0.08	0.20	0.88	0.15	215	1,238	1,993
94	430	Okra	0.12	0.16	0.63	0.15	215	1,238	1,993
95	446	Maize, green	0.22	0.88	0.94	0.24	308	717	855
96	449	Mushrooms and truffles	0.09	1.00	0.01	0.15	215	1,238	1,993
97	459	Chicory roots	0.14	0.30	1.17	0.15	63	1,238	1,993
98	461	Carobs	0.92	0.89	0.49	0.15	458	1,559	2,652
99	463	Vegetables, fresh nes	0.09	0.15	0.59	0.15	215	1,238	1,993
100	486	Bananas	0.25	0.25	1.50	0.41	190	1,664	3,138
101	489	Plantains and others	0.25	0.25	1.50	0.41	458	1,559	2,652
102	490	Oranges	0.12	0.20	0.17	0.29	700	2,425	4,150
103	495	Tangerines, mandarins, clementines, satsumas	0.12	0.20	0.10	0.15	458	1,559	2,652
104	497	Lemons and limes	0.12	0.20	0.20	0.29	458	1,559	2,652
105	507	Grapefruit (inc. pomelos)	0.12	0.20	0.08	0.15	458	1,559	2,652
106	512	Fruit, citrus nes	0.12	0.20	0.08	0.24	458	1,559	2,652
107	515	Apples	0.16	0.69	0.37	0.15	458	1,559	2,652
108	521	Pears	0.18	0.69	0.34	0.15	458	1,559	2,652
109	523	Quinces	0.16	0.69	0.37	0.15	458	1,559	2,652
110	526	Apricots	0.19	0.71	0.41	0.15	458	1,559	2,652
111	530	Cherries, sour	0.26	0.82	0.50	0.15	458	1,559	2,652
112	531	Cherries	0.26	0.71	0.50	0.15	458	1,559	2,652
113	534	Peaches and nectarines	0.21	0.69	0.25	0.15	458	1,559	2,652
114	536	Plums and sloes	0.24	0.82	0.25	0.15	458	1,559	2,652
115	541	Fruit, stone nes	0.23	0.75	0.38	0.15	458	1,559	2,652
116	542	Fruit, pome nes	0.15	0.69	0.37	0.15	458	1,559	2,652

117	544	Strawberries	0.10	0.30	1.00	0.15	215	1,238	1,993
118	547	Raspberries	0.13	0.20	0.01	0.15	458	1,559	2,652
119	549	Gooseberries	0.12	0.20	0.01	0.15	458	1,559	2,652
120	550	Currants	0.12	0.20	0.01	0.15	458	1,559	2,652
121	552	Blueberries	0.12	0.68	1.22	0.15	458	1,559	2,652
122	554	Cranberries	0.12	0.10	0.01	0.15	458	1,559	2,652
123	558	Berries nes	0.13	0.68	1.22	0.15	458	1,559	2,652
124	560	Grapes	0.29	0.65	0.53	0.15	983	1,559	2,652
125	567	Watermelons	0.06	0.20	0.10	0.15	215	1,238	1,993
126	568	Melons, other (inc.cantaloupes)	0.08	0.20	0.33	0.15	215	1,238	1,993
127	569	Figs	0.20	0.81	0.61	0.15	458	1,559	2,652
128	571	Mangoes, mangosteens, guavas	0.15	0.68	1.22	0.15	458	1,559	2,652
129	572	Avocados	0.27	0.68	0.41	0.25	458	1,559	2,652
130	574	Pineapples	0.20	0.20	2.85	0.05	458	1,559	2,652
131	577	Dates	0.82	0.30	0.25	0.15	458	1,559	2,652
132	587	Persimmons	0.12	0.68	1.22	0.15	458	1,559	2,652
133	591	Cashewapple	0.90	0.75	1.50	0.15	458	1,559	2,652
134	592	Kiwi fruit	0.19	0.20	0.46	0.67	458	1,559	2,652
135	600	Papayas	0.23	0.68	0.01	0.29	458	1,559	2,652
136	603	Fruit, tropical fresh nes	0.15	0.68	1.22	0.15	458	1,559	2,652
137	619	Fruit, fresh nes	0.15	0.30	0.44	0.15	458	1,559	2,652
138	656	Coffee, green	0.72	0.68	1.76	0.20	235	588	668
139	661	Cocoa, beans	0.72	0.68	1.70	0.29	210	1,073	1,660
140	667	Tea	0.23	0.20	0.01	0.15	235	588	668
141	671	Máte	0.23	0.20	0.01	0.15	235	588	668
142	677	Hops	0.23	0.81	2.22	0.13	477	1,751	2,867
143	687	Pepper (piper spp.)	0.23	0.68	0.73	0.15	215	1,238	1,993
144	689	Chillies and peppers, dry	1.00	1.00	2.33	0.15	215	1,238	1,993
145	692	Vanilla	0.95	1.00	0.01	0.15	477	1,751	2,867
146	693	Cinnamon (canella)	0.89	1.00	0.01	0.15	477	1,751	2,867
147	698	Cloves	1.00	1.00	0.01	0.15	477	1,751	2,867
148	702	Nutmeg, mace and cardamoms	0.90	1.00	0.01	0.15	477	1,751	2,867
149	711	Anise, badian, fennel, coriander	0.15	1.00	4.00	0.15	477	1,751	2,867
150	720	Ginger	0.14	0.30	1.17	0.15	63	1,238	1,993
151	723	Spices, nes	0.23	1.00	4.00	0.15	477	1,751	2,867
152	748	Peppermint	0.10	0.18	0.10	0.15	215	1,238	1,993
153	754	Pyrethrum, dried	1.00	0.91	0.25	0.18	414	2,020	3,612
154	767	Cotton lint	0.90	1.00	1.60	0.15	219	2,137	4,055

155	773	Flax fibre and tow	0.93	0.85	0.54	0.15	414	1,650	2,385
156	777	Hemp tow waste	0.91	0.91	0.25	0.18	414	2,020	3,612
157	778	Kapok fibre	0.83	0.83	0.54	0.16	414	2,020	3,612
158	780	Jute	0.29	0.83	0.54	0.16	414	2,020	3,612
159	782	Bastfibres, other	0.83	0.83	0.54	0.18	414	2,020	3,612
160	788	Ramie	0.00	0.00	0.00	0.00	414	2,020	3,612
161	789	Sisal	0.83	0.83	0.54	0.16	414	2,020	3,612
162	800	Agave fibres nes	0.83	0.83	0.92	0.16	414	2,020	3,612
163	809	Manila fibre (abaca)	0.83	0.83	0.54	0.16	414	2,020	3,612
164	813	Coir	0.20	0.38	0.52	0.29	184	1,559	2,652
165	821	Fibre crops nes	0.72	0.83	1.00	0.16	414	2,020	3,612
166	826	Tobacco, unmanufactured	0.15	0.80	0.50	0.80	235	588	668
167	836	Rubber, natural	0.40	1.00	2.33	0.50	477	1,751	2,867
168	839	Gums, natural	0.40	1.00	2.33	0.50	477	1,751	2,867
169	1717	Cereals,Total	0.87	0.88	1.25	0.15	252	666	822
170	1720	Roots and Tubers,Total	0.26	0.27	0.06	0.13	263	1,690	2,775
171	1726	Pulses,Total	0.91	0.90	1.86	0.15	339	721	784
172	1729	Treenuts,Total	0.80	0.76	1.52	0.15	477	1,751	2,867
173	1732	Oilcrops, Oil Equivalent	0.83	0.81	2.22	0.13	477	1,751	2,867
174	1735	Vegetables Primary	0.12	0.29	0.63	0.15	63	1,238	1,993
175	1738	Fruit Primary	0.24	0.46	0.50	0.19	458	1,559	2,652
176	1753	Fibre Crops Primary	0.83	0.83	0.54	0.16	414	2,020	3,612
177	1804	Citrus Fruit,Total	0.12	0.20	0.08	0.15	700	2,425	4,150
178	1814	Coarse Grain, Total	0.87	0.88	1.25	0.15	252	666	822
179	1817	Cereals (Rice Milled Eqv)	0.88	0.90	1.22	0.15	252	666	822
180	1841	Oilcrops, Cake Equivalent	0.91	0.81	2.22	0.13	477	1,751	2,867
181	9999	Others	0.51	0.62	1.19	0.26	368	1,423	2,327
182	17350	Vegetables, total[1]	0.10	0.34	0.81	0.15	215	1,238	1,993
183	17380	Fruits, total[1]	0.17	0.51	0.43	0.17	458	1,559	2,652

Notes: [1] Own categories to match historical fruits and vegetables with FAO. P: dry matter content of the main product, R: dry matter content of the residue, RF: the factor of residue to product in kg of fresh matter, R:S: root shoot ratio, WC, WLI, and WT: weeds in conventional, low input, and traditional systems

Table A.4: Coefficients for tropical grassland and forestland

	Item	ANPP	BNPP	TNPP	Sources	Comments
1	Tropical grassland	6.75[1]	5.40	12.16	Scurlock and Olson (2013);Raich et al. (1991);Gómez and Gallopin (1991); Funes et al. (2017)	The average of grassland for rainfall areas > 1000 mm and temperature > 24º. I exclude the high values of Costa Rica and Thailand, which implies a conservative estimation. This data is complemented with the information of the model of Gomez and Gallopin for tropical and subtropical grassland. The BNPP is obtained by mean of the shoot:root coefficient for tropical pastures from Funes et al. (2017) (0,8)
2	Kikuyo traditional	0.91	0.73	1.64	Borda and Ramírez Nader (2003); Funes et al. (2017)	Minimum tillage. The BNPP is obtained by mean of the shoot:root coefficient for tropical pastures from Funes et al. (2017) (0,8)
3	Kikuyo low-input	1.61	1.29	2.90	Borda and Ramírez Nader (2003); Funes et al. (2017)	Minimum tillage, renewed, and green fertilization (only clover). The BNPP is obtained by mean of the shoot:root coefficient for tropical pastures from Funes et al. (2017) (0,8)
4	Kikuyo conventional	3.62	2.90	6.52	Borda and Ramírez Nader (2003); Padilla Quintero (2017); Funes et al. (2017)	This is the average of data from Borda and Ramírez Nader (2003) for managements with fertilization and renovation and the average of the 60 field observations from Padilla Quintero (2017). The BNPP is obtained by mean of the shoot:root coefficient for tropical pastures from Funes et al. (2017) (0,8)

5	Pastures introduced in lowlands	2.96	2.37	5.34	Moreno Durango and Padilla Valle (1972); Funes et al. (2017)	This is the average of types of pastures introduced during the 1970s in Colombian lowlands, namely: Guinea, Pangola, Para and Puntero. The BNPP is obtained by mean of the shoot:root coefficient for tropical pastures from Funes et al. (2017) (0,8)
6	Savanna (shrubland)	18.60	15.74	15.74	Raich et al. (1991)	BNPP for savanna , which is used for shrubland, is the average of tropical grassland, dry forest, rainforest, and montane forest.
7	Colombian tropical forest	13.60	10.62	24.22	Scurlock and Olson (2013)	Observations for Magdalena, Colombia in 1970
8	Tropical dry forest	12.58	2.83	15.40	Scurlock and Olson (2013)	ANPP average of tropical forest filtered by annual precipitation between 1000-2000 mm and temperature >24. It includes: cnn, drn, kde, ses (see codes in Scurlock and Olson (2013)). The average of ratio ANPP:BNPP of: kde and ses was used to get the BNPP value
9	Rainforest	13.46	9.18	22.63	Scurlock and Olson (2013); Álvarez Sánchez (1991); Gómez and Gallopin (1991)	ANPP is the average of tropical forest with annual precipitation higher than 2000 and temperatures >24º. It includes: brr, lql, mgd, psh, scr, slv and the values in Álvarez Sánchez (1991)and Gómez and Gallopin (1991). BNPP is the average of the ratio ANPP:BNPP of: lql, psh, scr, slv.; Mexico, N. Guinea, Guatemala, Venezuela, Guayana, Colombia, Panamá, Brasil, Malasia, and Costa de Marfil

10	Montane forest	11.72	8.21	19.93	Scurlock and Olson (2013)	ANPP was estimate with the data for N Guinea, Guatemala, and Zaire. We pick up places with latitut > 1000 mamsl (it ranges from 900 to 2450) and precipitation from 1273 to 3985. BNPP was estimate at 0.7 ANPP:BBPP ratio

Note: [1] Tonnes per hectare in dry matter. ANPP: aerial net primary productivity; BNPP: belowground net primary productivity; TNPP: total net primary productivity.

A.4 CROP CATEGORIES FROM FAO AND OUR AGGREGATIONS

Table A.5: Aggregation of categories from FAO

	AG2	Aggregation 2	AG1	Aggregation 1	FAO	Product FAO
1	11	Cereals	15	Wheat	15	Wheat
2	11	Cereals	27	Rice, paddy	27	Rice, paddy
3	11	Cereals	44	Barley	44	Barley
4	11	Cereals	56	Maize	56	Maize
5	11	Cereals	108	Cereals, nes	71	Rye
6	11	Cereals	108	Cereals, nes	75	Oats
7	11	Cereals	108	Cereals, nes	79	Millet
8	11	Cereals	108	Cereals, nes	83	Sorghum
9	11	Cereals	108	Cereals, nes	89	Buckwheat
10	11	Cereals	108	Cereals, nes	92	Quinoa
11	11	Cereals	108	Cereals, nes	94	Fonio
12	11	Cereals	108	Cereals, nes	97	Triticale
13	11	Cereals	108	Cereals, nes	101	Canary seed
14	11	Cereals	108	Cereals, nes	103	Grain, mixed
15	11	Cereals	108	Cereals, nes	108	Cereals, nes
16	13	Roots and Tubers	116	Potatoes	116	Potatoes
17	13	Roots and Tubers	149	Roots and tubers, nes	122	Sweet potatoes
18	13	Roots and Tubers	125	Cassava	125	Cassava
19	13	Roots and Tubers	149	Roots and tubers, nes	135	Yautia (cocoyam)
20	13	Roots and Tubers	149	Roots and tubers, nes	136	Taro (cocoyam)
21	13	Roots and Tubers	149	Roots and tubers, nes	137	Yams
22	13	Roots and Tubers	149	Roots and tubers, nes	149	Roots and tubers, nes
23	25	Sugar & Sweeteners	156	Sugar cane	156	Sugar cane
24	25	Sugar & Sweeteners	15600	Sugar, Other	157	Sugar beet
25	25	Sugar & Sweeteners	15600	Sugar, Other	161	Sugar crops, nes
26	12	Pulses	176	Beans, dry	176	Beans, dry
27	12	Pulses	211	Pulses, nes	181	Broad beans, horse beans, dry
28	12	Pulses	211	Pulses, nes	187	Peas, dry
29	12	Pulses	211	Pulses, nes	191	Chick peas

30	12	Pulses	211	Pulses, nes	195	Cow peas, dry
31	12	Pulses	211	Pulses, nes	197	Pigeon peas
32	12	Pulses	211	Pulses, nes	201	Lentils
33	12	Pulses	211	Pulses, nes	203	Bambara beans
34	12	Pulses	211	Pulses, nes	205	Vetches
35	12	Pulses	211	Pulses, nes	210	Lupins
36	12	Pulses	211	Pulses, nes	211	Pulses, nes
37	21	Fruits	2625	Fruits, other	216	Brazil nuts, with shell
38	21	Fruits	2625	Fruits, other	217	Cashew nuts, with shell
39	21	Fruits	2625	Fruits, other	220	Chestnut
40	21	Fruits	2625	Fruits, other	221	Almonds, with shell
41	21	Fruits	2625	Fruits, other	222	Walnuts, with shell
42	21	Fruits	2625	Fruits, other	223	Pistachios
43	21	Fruits	2625	Fruits, other	224	Kola nuts
44	21	Fruits	2625	Fruits, other	225	Hazelnuts, with shell
45	26	Other plant products	9999	Others	226	Areca nuts
46	21	Fruits	2625	Fruits, other	234	Nuts, nes
47	12	Pulses	211	Pulses, nes	236	Soybeans
48	22	Oil crops	2570	Oilcrops, Other	242	Groundnuts, with shell
49	22	Oil crops	249	Coconuts	249	Coconuts
50	22	Oil crops	2570	Oilcrops, Other	254	Oil palm fruit
51	22	Oil crops	2570	Oilcrops, Other	256	Palm kernels
52	22	Oil crops	257	Oil, palm	257	Oil, palm
53	22	Oil crops	2570	Oilcrops, Other	260	Olives
54	22	Oil crops	2570	Oilcrops, Other	263	Karite nuts (sheanuts)
55	22	Oil crops	2570	Oilcrops, Other	265	Castor oil seed
56	22	Oil crops	2570	Oilcrops, Other	267	Sunflower seed
57	22	Oil crops	2570	Oilcrops, Other	270	Rapeseed
58	22	Oil crops	2570	Oilcrops, Other	275	Tung nuts
59	22	Oil crops	2570	Oilcrops, Other	277	Jojoba seed
60	22	Oil crops	2570	Oilcrops, Other	280	Safflower seed
61	22	Oil crops	2570	Oilcrops, Other	289	Sesame seed
62	22	Oil crops	2570	Oilcrops, Other	292	Mustard seed
63	22	Oil crops	2570	Oilcrops, Other	296	Poppy seed
64	22	Oil crops	2570	Oilcrops, Other	299	Melonseed

65	22	Oil crops	2570	Oilcrops, Other	305	Tallowtree seed
66	21	Fruits	2625	Fruits, other	310	Kapok fruit
67	22	Oil crops	2570	Oilcrops, Other	311	Kapokseed in shell
68	22	Oil crops	328	Seed cotton	328	Seed cotton
69	22	Oil crops	2570	Oilcrops, Other	329	Cottonseed
70	22	Oil crops	2570	Oilcrops, Other	333	Linseed
71	22	Oil crops	2570	Oilcrops, Other	336	Hempseed
72	22	Oil crops	2570	Oilcrops, Other	339	Oilseeds nes
73	14	Vegetables	17350	Vegetables, total	358	Cabbages and other brassicas
74	14	Vegetables	17350	Vegetables, total	366	Artichokes
75	14	Vegetables	17350	Vegetables, total	367	Asparagus
76	14	Vegetables	17350	Vegetables, total	372	Lettuce and chicory
77	14	Vegetables	17350	Vegetables, total	373	Spinach
78	13	Roots and Tubers	125	Cassava	378	Cassava leaves
79	14	Vegetables	17350	Vegetables, total	388	Tomatoes
80	14	Vegetables	17350	Vegetables, total	393	Cauliflowers and broccoli
81	14	Vegetables	17350	Vegetables, total	394	Pumpkins, squash and gourds
82	14	Vegetables	17350	Vegetables, total	397	Cucumbers and gherkins
83	14	Vegetables	17350	Vegetables, total	399	Eggplants (aubergines)
84	14	Vegetables	17350	Vegetables, total	401	Chillies and peppers, green
85	14	Vegetables	17350	Vegetables, total	402	Onions, shallots, green
86	14	Vegetables	17350	Vegetables, total	403	Onions, dry
87	14	Vegetables	17350	Vegetables, total	406	Garlic
88	14	Vegetables	17350	Vegetables, total	407	Leeks, other alliaceous vegetables
89	14	Vegetables	17350	Vegetables, total	414	Beans, green
90	14	Vegetables	17350	Vegetables, total	417	Peas, green
91	14	Vegetables	17350	Vegetables, total	420	Vegetables, leguminous nes
92	14	Vegetables	17350	Vegetables, total	423	String beans
93	14	Vegetables	17350	Vegetables, total	426	Carrots and turnips

94	14	Vegetables	17350	Vegetables, total	430	Okra
95	14	Vegetables	17350	Vegetables, total	446	Maize, green
96	14	Vegetables	17350	Vegetables, total	449	Mushrooms and truffles
97	14	Vegetables	17350	Vegetables, total	459	Chicory roots
98	21	Fruits	2625	Fruits, other	461	Carobs
99	14	Vegetables	17350	Vegetables, total	463	Vegetables, fresh nes
100	21	Fruits	486	Bananas	486	Bananas
101	21	Fruits	489	Plantains and others	489	Plantains and others
102	21	Fruits	2625	Fruits, other	490	Oranges
103	21	Fruits	2625	Fruits, other	495	Tangerines, mandarins, clementines, satsumas
104	21	Fruits	2625	Fruits, other	497	Lemons and limes
105	21	Fruits	2625	Fruits, other	507	Grapefruit (inc. pomelos)
106	21	Fruits	2625	Fruits, other	512	Fruit, citrus nes
107	21	Fruits	2625	Fruits, other	515	Apples
108	21	Fruits	2625	Fruits, other	521	Pears
109	21	Fruits	2625	Fruits, other	523	Quinces
110	21	Fruits	2625	Fruits, other	526	Apricots
111	21	Fruits	2625	Fruits, other	530	Cherries, sour
112	21	Fruits	2625	Fruits, other	531	Cherries
113	21	Fruits	2625	Fruits, other	534	Peaches and nectarines
114	21	Fruits	2625	Fruits, other	536	Plums and sloes
115	21	Fruits	2625	Fruits, other	541	Fruit, stone nes
116	21	Fruits	2625	Fruits, other	542	Fruit, pome nes
117	21	Fruits	2625	Fruits, other	544	Strawberries
118	21	Fruits	2625	Fruits, other	547	Raspberries
119	21	Fruits	2625	Fruits, other	549	Gooseberries
120	21	Fruits	2625	Fruits, other	550	Currants
121	21	Fruits	2625	Fruits, other	552	Blueberries
122	21	Fruits	2625	Fruits, other	554	Cranberries
123	21	Fruits	2625	Fruits, other	558	Berries nes
124	21	Fruits	2625	Fruits, other	560	Grapes
125	14	Vegetables	17350	Vegetables, total	567	Watermelons
126	14	Vegetables	17350	Vegetables, total	568	Melons, other (inc.cantaloupes)
127	21	Fruits	2625	Fruits, other	569	Figs

128	21	Fruits	2625	Fruits, other	571	Mangoes, mangosteens, guavas
129	21	Fruits	2625	Fruits, other	572	Avocados
130	21	Fruits	2625	Fruits, other	574	Pineapples
131	21	Fruits	2625	Fruits, other	577	Dates
132	21	Fruits	2625	Fruits, other	587	Persimmons
133	21	Fruits	2625	Fruits, other	591	Cashewapple
134	21	Fruits	2625	Fruits, other	592	Kiwi fruit
135	21	Fruits	2625	Fruits, other	600	Papayas
136	21	Fruits	2625	Fruits, other	603	Fruit, tropical fresh nes
137	21	Fruits	2625	Fruits, other	619	Fruit, fresh nes
138	24	Stimulants	656	Coffee, green	656	Coffee, green
139	24	Stimulants	661	Cocoa, beans	661	Cocoa, beans
140	24	Stimulants	2922	Stimulants nes	667	Tea
141	24	Stimulants	2922	Stimulants nes	671	Máte
142	26	Other plant products	9999	Others	677	Hops
143	24	Stimulants	2922	Stimulants nes	687	Pepper (piper spp.)
144	14	Vegetables	17350	Vegetables, total	689	Chillies and peppers, dry
145	24	Stimulants	2922	Stimulants nes	692	Vanilla
146	24	Stimulants	2922	Stimulants nes	693	Cinnamon (canella)
147	24	Stimulants	2922	Stimulants nes	698	Cloves
148	24	Stimulants	2922	Stimulants nes	702	Nutmeg, mace and cardamoms
149	24	Stimulants	2922	Stimulants nes	711	Anise, badian, fennel, coriander
150	24	Stimulants	2922	Stimulants nes	720	Ginger
151	24	Stimulants	2922	Stimulants nes	723	Spices, nes
152	24	Stimulants	2922	Stimulants nes	748	Peppermint
153	26	Other plant products	9999	Others	754	Pyrethrum, dried
154	23	Fibre Crops	821	Fibre crops nes	767	Cotton lint
155	23	Fibre Crops	821	Fibre crops nes	773	Flax fibre and tow
156	23	Fibre Crops	821	Fibre crops nes	777	Hemp tow waste
157	23	Fibre Crops	821	Fibre crops nes	778	Kapok fibre
158	23	Fibre Crops	821	Fibre crops nes	780	Jute
159	23	Fibre Crops	821	Fibre crops nes	782	Bastfibres, other
160	23	Fibre Crops	821	Fibre crops nes	788	Ramie

161	23	Fibre Crops	821	Fibre crops nes	789	Sisal
162	23	Fibre Crops	800	Agave fibres nes	800	Agave fibres nes
163	23	Fibre Crops	821	Fibre crops nes	809	Manila fibre (abaca)
164	26	Other plant products	9999	Others	813	Coir
165	23	Fibre Crops	821	Fibre crops nes	821	Fibre crops nes
166	24	Stimulants	826	Tobacco, unmanufactured	826	Tobacco, unmanufactured
167	26	Other plant products	9999	Others	836	Rubber, natural
168	26	Other plant products	9999	Others	839	Gums, natural
169	11	Cereals	108	Cereals, nes	1717	Cereals,Total
170	13	Roots and Tubers	149	Roots and tubers, nes	1720	Roots and Tubers,Total
171	12	Pulses	211	Pulses, nes	1726	Pulses,Total
172	21	Fruits	2625	Fruits, other	1729	Treenuts,Total
173	22	Oil crops	2570	Oilcrops, Other	1732	Oilcrops, Oil Equivalent
174	14	Vegetables	17350	Vegetables, total	1735	Vegetables Primary
175	21	Fruits	2625	Fruits, other	1738	Fruit Primary
176	23	Fibre Crops	821	Fibre crops nes	1753	Fibre Crops Primary
177	21	Fruits	2625	Fruits, other	1804	Citrus Fruit,Total
178	11	Cereals	108	Cereals, nes	1814	Coarse Grain, Total
179	11	Cereals	108	Cereals, nes	1817	Cereals (Rice Milled Eqv)
180	22	Oil crops	2570	Oilcrops, Other	1841	Oilcrops, Cake Equivalent
181	26	Other plant products	9999	Others	9999	Others
182	14	Vegetables	17350	Vegetables, total	17350	Vegetables, total
183	21	Fruits	2625	Fruits, other	17380	Fruits, total

A.5 LAND USE CHANGE: FOREST AND PASTURE

A.5.1 Change of forestland

Table A.6: Annual rates of change of the forest clearing by types of forest

	Forest type	**1915–20**	**1920–70**	**1970–2000**[1]
1	Dry forest	-0.43	-0.75	0.16
2	Andean forest	-0.21	-0.41	-1.43
3	Rainforest	-0.03	-0.03	-0.14
4	Total forest	-0.08	-0.12	-0.49

Note: [1] We apply the same rate to dry, rain, and Andean forest between 2000 and 2015. Source: Etter et al. (2008)

A.5.2 Change of pastureland

Table A.7: Pasture, cattle and cattle density

	Years	Pasture	Cattle	Density
1	1950	13,437,000	10,714,246	0.80
2	1960	14,605,954	13,310,556	0.91
3	1970	17,464,571	16,391,916	0.94
4	1992	23,374,004	21,073,681	0.90
5	2015	24,094,072	22,850,647	0.94

Note: Between 1915–90 cattle came from Kalmanovitz et al. (1999), between 1991–2000, I use the rates of change from FAOSTAT (2021) and since 2001 information is from FEDEGAN. Pasture for 1950 is from Varela Martínez et al. (1952) and for 1960/70 is from the national agrarian census (DANE, 1964, 1974); since 1992 there is annual data from UCL-CCI in FAOSTAT (2021)

We use data from UCCL-CCI in FAOSTAT (2021) for pasture (16 Mhas) and shrubland (7.5 Mhas) during 1992–2015 to estimate the area devoted to pastureland for grassing since it fits well with the data in the 2014 agrarian census, and because the "permanent meadows and pastures" series from citetFAOSTAT2018 is an aggregate category, which makes difficult the cattle density estimation. We are perhaps underestimating the series between 1961 and 1992, and overestimating between 1992 and 2015 (figure A.4). However, there are not conclusive data among the sources.

The FAOSTAT's series is almost constant between 1961 and 2015, 35 Mhas and 41 Mhas respectively (figure A.4a). In the land cover map of 2010–12, the addition of pastures (17.5 Mhas), grassland (14.5 Mhas), shrubland (2.5 Mhas), and secondary vegetation (4 Mhas) raises to 38.5 Mhas. Lastly, in the 2014 census natural and seeded pastures amount to 24.8 Mhas, but if we add the 9.6 Mhas of shrubs it reaches 34.4 Mhas. According to these data, the area under pastures and permanent meadows during 2010–15 ranges between 34.4 and 41 Mhas, and the area for grassing must be between 17 Mhas (pasture) and 24 Mhas (when we add natural grassland for grassing). Our pastureland series match well with these values, but we cannot say the same for shrublands & other, since this is our residue. The highest differences between our aggregate data and the FAOSTAT series reach 5% of the total land area, so, if the FAOSTAT series is right, there is some room to improve. However, FAOSTAT (2021)'s estimation lacks variation.

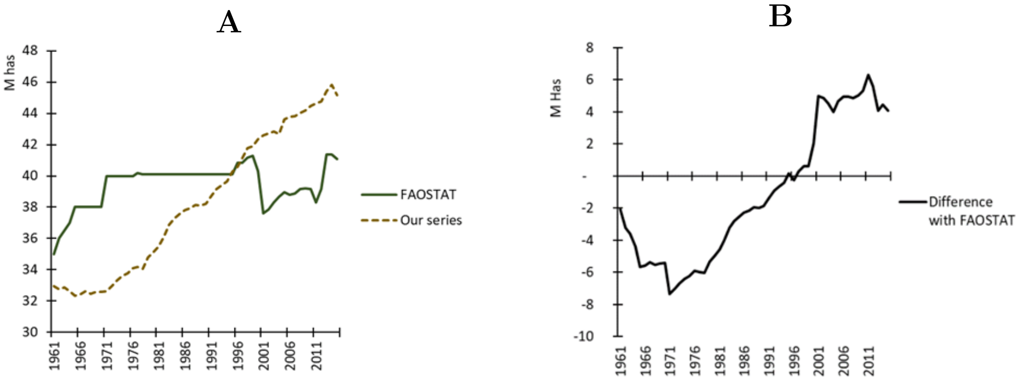


Figure A.4: a) Data for pasture and permanent meadows from FAOSTAT (2021) and our series of pasture and shrubland & others in millions of hectares and b) its differences 1961–2015.

A.6 DOMESTIC EXTRACTION OF PASTURE

A.6.1 Changes in the weight of livestock

The average weight of livestock was estimated tracing the evolution of the most critical animal in pasture extraction: cattle. Additionally, we introduced some historical variation for other species when the data was available. The information on the average weight was compiled from the sources specified in the main text (see section 2.2.2) and table A.8. Besides, in the case of cattle, we have adjusted the average weight by accounting the age structure Kalmanovitz et al. (1999).

Table A.8: Evolution of the average weight by species in selected years (kg)

	Years	**Cattle**	**Cattle by age**	**Pigs**	**Sheep**	**Goat**	**Horses**[1]	**Mules**[1]	**Asses**[1]	**Sources**
1	1916	392.2	330.4				326.0	326.0	172.0	DGE (1916, Exports)
2	1918	448.0	368.9	70.0	37.0	24.0				
3	1923	364.9	312.4							DGE (1923, Exports)
4	1938	412.2	342.5	81.8						DGE (1938b, Exports)
5	1942	430.0	352.1							Wylie (1942)
6	1945	431.3	349.9							DGE (1945, Exports)
7	1950	382.0	316.9	90.0	32.0	26.0				Varela Martínez et al. (1952)
8	1965	367.5	300.5							Hertford et al. (1982)
9	1969	384.0	311.0							DANE (1969, Exports)
10	1980	445.0	342.4							DANE (1980, Exports)
11	2010	419.5	324.5	99.4	37.6	30.0	405.7	319.8	319.8	DANE (2018)
12	2016	415.9	322.4	108.0	31.8	31.8				DANE (2018)

Note: [1] It is the average weight of horses, mules, and donkeys for 1860 and 1999 in Marco et al. (2018).

A.6.2 Nutritional requirements of livestock

We use animal weight in table A.8 and nutritional requirements to obtain the feed intake (see section 2.2.2 in the main text for details on sources). We use between 2.5% and 3% of body weight as a yardstick except in the case of pigs since the available information is a diet of corn and soybean (NRC, 1998). In this case, we estimate a general dry matter equivalent by applying the gross calorific value (GCV) for maize and legumes used as fodder in Guzmán et al. (2014) and the average GCV in CSIRO (2007, 5) for carbohydrates as cellulose (18.4 Mj/kg). Finally, the intake of the pigs obtained as a percentage of the body weight ranges between 2.5% and 2.2% for 1916–2016.

Table A.9: Livestock feed intake for Colombia in selected years (kg dm per head/day)

	Years	**Cattle**	**Cattle by age**	**Pigs**	**Sheep**	**Goat**	**Horses**	**Mules**	**Donkeys**
1	1916	10.79	9.09				8.96	9.78	5.16
2	1918	12.32	10.14	1.78	1.06	0.63			
3	1923	10.04	8.59						
4	1938	11.34	9.42	2.10					
5	1942	11.82	9.68						
6	1945	11.86	9.62						
7	1950	10.51	8.71	2.10	0.92	0.68			
8	1965	10.11	8.26						
9	1969	10.56	8.55						
10	1980	12.24	9.42						
11	2010	11.54	8.92	2.34	1.08	0.78	11.16	9.59	9.59
12	2016	11.44	8.87	2.34	0.91	0.83			

A.6.3 Sensitivity analysis of nutritional requirements of livestock and biomass extraction

The nutritional requirements of the animals were compared with the average feed intake for the Latin American given by Krausmann, Erb, et al. (2008). This test confirms the usefulness of our age adjustment for cattle (figure A.5a). For other livestock, we found differences between using our data and using the values from Krausmann, Erb, et al. (2008). The most relevant case is the difference in the nutritional requirements of pigs (figure A.5b). The gap between the two series increases during the twentieth century, though, the dietary requirement as a percentage of the body weight decreases, as noted in the previous section A.6.2. This is due to the exceptional increase in the average weight of pigs, that moved from 70 kg in 1918 to 108 kg in 2016 (table A.8). Moreover, this does not detract from our estimations, since the nutritional requirements of cattle constitute 80% of total needs and that for pigs, although growing since 2006, is less than 8%.

There are several series of biomass extraction in Colombia from 1970 until 2015, but they are not entirely comparable with ours due to two elements: first, the authors of these series follow a MFA methodology but not an agroecological one; namely, they account for pasture in dry matter while the rest of the biomass remains in fresh matter

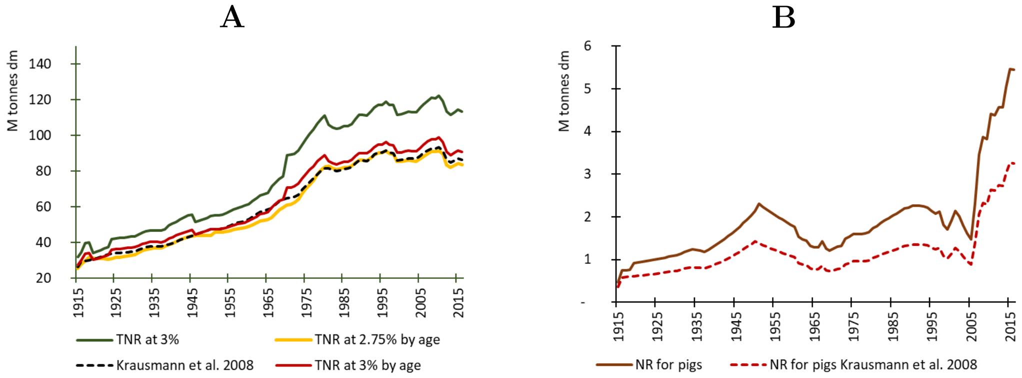


Figure A.5: a) TNR: total nutritional requirements for livestock. Total requirements (at 3%, 2.5% percentages of the body weight of cattle and adjusted by age) and the series with values from Krausmann, Erb, et al. (2008). b) NR: nutritional requirements for pigs. Requirements for pigs and the series with the the values from Krausmann, Erb, et al. (2008).

(see section 2.2.1 in the main text). Second, the differences on the number of cattle. If compared the intensity of biomass extraction in indexes numbers the water content present in crops stands up (figure A.6a). As shown in the results of the main text (section 2.3), the biomass extracted from cropland increased mainly due to more cash crops which have higher content of water than the basic grains. This is the case of fruits, oil crops, and especially sugarcane, in which water amounts to more than 25 M tonnes or a fifth of the total dry matter accounted at the end of the period. Second, additional to the water content, the main element making the differences in levels is cattle. As we depicted in the main text 2.2.1 and this section, the nutritional requirements of herd grounds on the national series of cattle, namely Kalmanovitz et al. (1999) and FEDEGAN (2021) which have 4 and 3 million less of heads than the series from FAOSTAT (2021). These two elements helps to understand our estimation of extraction in the context of the data on the topic (figure A.6b).

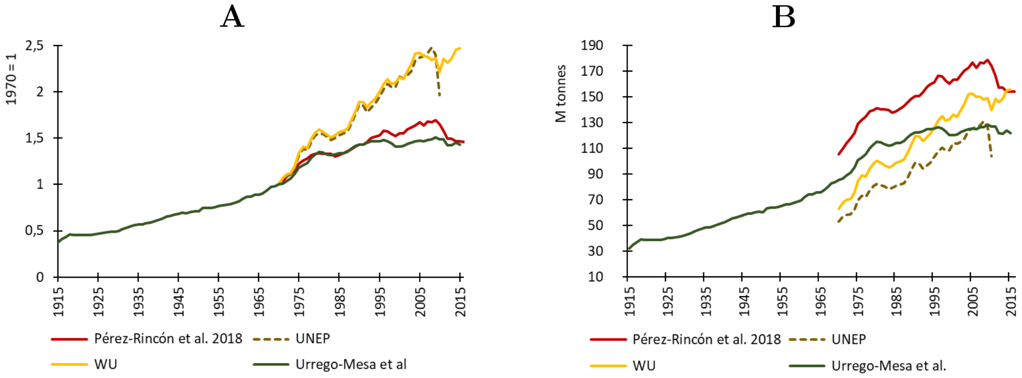


Figure A.6: a) Index numbers of the biomass extraction series 1970=1. b) Biomass extraction series in Colombia in millions of tonnes. Our series in dry matter and the others in a mix of dry and fresh matter.

Appendix B

Las venas abiertas de América Latina en la era del Antropoceno: un estudio biofísico del comercio exterior (1900–2016)

Keywords: Países por regiones; comercio material; fuentes

B.1 Clasificación de países por regiones

Table B.1: Países que componen cada región en América Latina

	Región	**Países**
1	México	México
2	Centro	Guatemala, Honduras, El Salvador, Costa Rica, Nicaragua
3	Andinos	Bolivia, Colombia, Venezuela, Ecuador, Chile
4	Brasil	Brasil
5	Sur	Argentina, Uruguay, Paraguay

Table B.2: Países que componen cada región del mundo

	Región	Países
1	África	Angola, Burundi, Benin, Bonaire, Burkina Faso, Botswana, Central African Rep., Côte d'Ivoire, Cameroon, Dem. Rep. of the Congo, Congo, Comoros, Cabo Verde, Djibouti, Algeria, Egypt, Eritrea, Western Sahara, Ethiopia, Fmr Ethiopia, Gabon, Ghana, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Kenya, Liberia, Libya, Lesotho, Morocco, Madagascar, Mali, Mozambique, Mauritania, Mauritius, Malawi, Mayotte, Namibia, Niger, Nigeria, Réunion, Rwanda, Fmr Sudan, Sudan, Senegal, Saint Helena, Sierra Leone, Somalia, South Sudan, Sao Tome and Principe, Swaziland, Seychelles, Chad, Togo, Tunisia, United Rep. of Tanzania, Uganda, So. African Customs Union, South Africa, Zambia, Zimbabwe, Fmr Rhodesia Nyas, Fmr Tanganyika,
2	Asia-Pacifico	Afghanistan, Neth. Antilles, Neth. Antilles and Aruba, United Arab Emirates, American Samoa, Australia, Bangladesh, Bahrain, Bhutan, China, Cook Isds, Fiji, FS Micronesia, Guam, China, Hong Kong SAR, Heard Island and McDonald Islands, Indonesia, India, India, excl. Sikkim, Br. Indian Ocean Terr., Iran, Iraq, Israel, Jordan, Japan, Cambodia, Kiribati, Rep. of Korea, Kuwait, Lebanon, Sri Lanka, China, Macao SAR, Marshall Isds, Myanmar, Mongolia, N. Mariana Isds, Malaysia, New Caledonia, Norfolk Isds, Niue, Nepal, Nauru, New Zealand, Oman, East and West Pakistan, Pakistan, Fmr Pacific Isds, Pitcairn, Philippines, Palau, Papua New Guinea, Dem. People's Rep. of Korea, State of Palestine, French Polynesia, Qatar, Saudi Arabia, Singapore, Solomon Isds, Syria, Thailand, Tokelau, Timor-Leste, Tonga, Tuvalu, Fmr Dem. Rep. of Vietnam, Fmr Rep. of Vietnam, Viet Nam, Vanuatu, Wallis and Futuna Isds, Samoa, Fmr Arab Rep. of Yemen, Yemen, Fmr Dem. Yemen, Peninsula Malaysia, Sabah, US Misc. Pacific Isds, Other Asia, nes, Western Asia, nes, Oceania, nes, Ryukyu Isd
3	Asia Central	Azerbaijan, Belarus, Brunei Darussalam, Georgia, Kazakhstan, Kyrgyzstan, Lao People's Dem. Rep., Russian Federation, South Georgia and the South Sandwich Islands, Fmr USSR, Tajikistan, Turkmenistan, Turkey, Uzbekistan

4	Europa	Albania, Andorra, Armenia, Austria, Belgium, Belgium-Luxembourg, Bulgaria, Bosnia Herzegovina, Switzerland, Czechoslovakia, Cyprus, Czechia, Fmr Dem. Rep. of Germany, Fmr Fed. Rep. of Germany, Germany, Denmark, Spain, Estonia, Finland, France, Faeroe Isds, United Kingdom, Gibraltar, Greece, Croatia, Hungary, Ireland, Iceland, Italy, Lithuania, Luxembourg, Latvia, Rep. of Moldova, TFYR of Macedonia, Malta, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Serbia and Montenegro, San Marino, Serbia, Slovakia, Slovenia, Sweden, Ukraine, Holy See (Vatican City State), Fmr Yugoslavia,
5	Latino América	Anguilla, Argentina, Antigua and Barbuda, Bahamas, Saint Barthélemy, Belize, Bermuda, Bolivia (Plurinational State of), Brazil, Barbados, Cocos Isds, Chile, Colombia, Costa Rica, Cuba, Curaçao, Christmas Isds, Cayman Isds, Dominica, Dominican Rep., Ecuador, Falkland Isds (Malvinas), Guadeloupe, Grenada, Guatemala, French Guiana, Guyana, Honduras, Haiti, Jamaica, Saint Kitts and Nevis, Saint Kitts, Nevis and Anguilla, Saint Lucia, Maldives, Mexico, Montserrat, Martinique, Nicaragua, Fmr Panama, excl., Canal Zone, Panama, Fmr Panama-Canal-Zone, Peru, Paraguay, El Salvador, Suriname, Saint MaartenTurks and Caicos Isds, Trinidad and Tobago, Uruguay, Saint Vincent and the Grenadines, Venezuela, Br. Virgin Isds, US Virgin Isds, LAIA, nes, Caribbean, nes, CACM, nes
6	Norte América	Canada, Greenland, Saint Pierre and Miquelon, United States, Minor Outlying Islands, USA (before 1981), North America and Central America, nes
7	Otros	Free Zones, Antartica, Antarctica, Fr. South Antartic Terr., Fr. South Antarctic Terr., Bunkers, Special Categories, Br. Antarctic Terr., Neutral Zone

Table B.3: Fuentes comercio físico: resumen de las fuentes utilizadas

	Fuentes (Período)	Información	Notas
1	United Nations Comtrade Database (1962-2016)	Comercio bilateral físico y monetario	En Colombia, Costa Rica, Guatemala y Nicaragua la serie empieza en 1965. En El Salvador y Honduras en 1963. En Uruguay en 1970.
2	Liga de Naciones (1913, 1920-1934)	Comercio físico total	México (1925-1934), Honduras (1921, 1922, 1924, 1925), Nicaragua (1913), Bolivia (1913, 1920-1931), Chile (1925-1934), Ecuador (1913, 1920-1928, 1931, 1932), Paraguay (1913, 1920, 1921, 1924-1931), Perú (1923-1934), Venezuela (1913. 1920-1933)
3	Anuarios Estadísticos de Comercio Exterior	Comercio físico total	Argentina (1910-1912, 1914-1919, 1935-1962), Bolivia (1911, 1912, 1914-1919, 1942, 1945-1950, 1952-1959), Brasil (1906-1912, 1914-1919, 1935-1961), Chile (1917-1922), Colombia (1919, 1935-1962), Costa Rica (1901-1912, 1914-1919, 1935-1949), Ecuador (1909-1909), México (1911-1924[1], 1935-1962), Paraguay (1914-1916, 1953-1959), Perú (1935-1962), El Salvador (1909-1912, 1914-1919, 1940-1949, 1952-1962), y Venezuela (1911, 1912, 1914-1919, 1934-1962).
4	Instituto Internacional de Agricultura (1928-1948)	Comercio físico agropecuario	Los datos de 1909 a 1921 no siempre son consistentes con las cantidades del periodo siguiente, debido diferencias grandes en cantidad de productos registrados.
5	Mitchell (2015)	Series históricas para una selección de países y productos	Colombia: petróleo y café; Ecuador: cacao y café; Perú: algodón; Venezuela: petróleo; Chile: hierro; Brasil: carbón, petróleo, hierro, café, cacao, algodón, goma, azúcar; Argentina: carbón, carne, lana, algodón, trigo, lino y maíz; Uruguay: carne y lana.

6	Base de datos WTO (2019) y MOxLAD (2019)	Índice de importaciones y exportaciones en comercio monetario y físico por país	Proxy para interpolar los valores no disponibles

Notes: [1] Corresponde a exportaciones de petróleo.

Appendix C

Food Security, Trade Specialization, and Violence in Colombia (1916–2016)

Keywords: Food Security Series, Colombian Historical Sources, Data Processing, Meat Estimations, Historical Coefficients; VECM

C.1 INTRODUCTION

This appendix provides the technical coefficients of the yields of carcass, the share of food in domestic supply, and the gross calorific values used between 1916 and 1960. It also contains the specifications, outputs, and checks for the vector error correction models presented in the main text: "Food Security, Trade Specialization, and Violence in Colombia (1916–2016)". The time series of net imports, food availability, food self-sufficiency, and staple to cash crops ratios are available in the "trade_food_sup.xlsx" file.

C.2 TECHNICAL COEFFICIENTS (1916–60)

Bellow are presented the coefficients used to figure the estimations of meat, food, and gross calorific values before 1960.

C.2.1 Carcass yields

Table C.1: Carcass yields (kg of meat per head)

Year	**Cattle** (sex-weighted)	**Pigs**	**Sheep**	**Goat**	**Method of obtaining meat**	**Sources**
1918	193	59	21	14	Cattle and pigs: in source. Sheep and goat: own calculation	DGE (1918)
1928	198	60	18	15	Cattle and pigs: in source. Sheep and goat: own calculation	Cattle and pigs: DGE (1928); Sheep, goat: Urrego-Mesa et al. (2019)
1935	186	68			Cattle: in source. Pigs, sheep and goat: own calculation	Cattle: DGE (1935); Pigs, sheep, goat: Urrego-Mesa et al. (2019)
1936	187	66			Cattle and pigs: in source. Sheep and goat: own calculation	Cattle and pigs: DGE (1936); Sheep, goat: Urrego-Mesa et al. (2019)
1937	179	85			Cattle and pigs: in source. Sheep and goat: own calculation	Cattle and pigs: DGE (1937); Sheep, goat: Urrego-Mesa et al. (2019)
1938	199	60			Cattle and pigs: in source. Sheep and goat: own calculation	Cattle and pigs: DGE (1938a); Sheep, goat: Urrego-Mesa et al. (2019)
1949	195	68			Cattle: in source. Pigs, sheep and goat: own calculation	Cattle: DGE (1949); Pigs, Sheep, goat: Urrego-Mesa et al. (2019)
1950	201	77			All yields in source	Varela Martínez et al. (1952)
1961	175	59	14	15	All yields in source	Balances sheets in FAOSTAT (2021)

Note: Sometimes yields per head were in the sources, other times only the standing weight before slaughter was available. In the latter case, I use the yield coefficients in Table C.2 to get the yield value. Meat production is the slaughter figure multiplied by the yields per head in the range of years available.

Table C.2: Yield coefficients for 1950 from Varela (1952)

Cattle (average of both sexes)	Pigs	Sheep	Goat
0.52	0.85	0.57	0.57

Note: Meat production is the slaughter figure multiplied by the yields per head in the range of years available.
Source: Varela Martínez et al. (1952)

C.2.2 Food in domestic supply

Table C.3: The share of food in domestic supply for 1916-60

Agricultural products	**Share of food**
Cereals	53%
Pulses	67%
Roots and Tubers	51%
Vegetables	91%
Fruits	57%
Oil crops	34%
Stimulants	70%
Sugar & Sweeteners	56%
Meat	83%
Dairy products	40%
Animal others	61%

Note: This is the share of food in domestic supply from FAOs' balance sheets. From 1961 I use the percentage resulted in each year. See the methodology section in the main document for details.

C.2.3 Gross calorific value

Table C.4: Gross calorific value coefficients for 1916-60

Agricultural products	**(MJ/Kg)**
Barley	15.37
Cereals, nes	17.3
Maize	15.77
Rice, paddy	15.63
Wheat	15.81
Beans, dry	15.72
Pulses, nes	16.2
Cassava	10.58
Potatoes	7.25
Roots and tubers, nes	9.84
Vegetables, total	5.46
Fruits, other	6.75
Bananas	3.99
Plantains and others	3.99
Oil, Palm	36.75
Oilcrops, Other	32.04
Coconuts	26.79
Seed cotton	32.97
Cocoa, beans	19.66
Coffee, green	19.63
Tobacco, unmanufactured	17.7
Stimulants nes	70.92
Sugar cane	16.76
Sugar, Other	16.66
Meat	14.8
Dairy products	12.36

Note: It is the average value of the categories involved in trade between 1961 and 1963. From 1961 I use specific coefficients to each product. See the methodological section in the main document for details and sources.

C.3 Vector Error Correction Model

Here I give the information on the specifications, the tests, and the different results of the variations of the main model according to the steps suggested in Lütkepohl (2005). I use the function `tseries` from package implemented by Trapletti and Hornik (2020) into the R Core Team (2020) system. To built a VECM we need non-stationary time series integrated in the same order. Therefore, I test for non-stationarity with the Augmented Dickey-Fuller test from `adf.test()` function and integration order with `ndiffs()`. Once I confirmed non-stationarity and I(1) for the time series, moved to estimate the optimal lag order of the model.

First, I looked at the dependency of each variable with `acf()` and the `pacf()` functions to choose the maximum lags and use this value in `VARselect()` function to for the to estimate the optimal lags. I run optimal order for constant specification terms and choose the AIC value as the optimal lag (10 years for the two models) in the Johansen co-integration test with the function `co.jo()`. I validate the number of co-integration relations at the 1% of confidence (Table 2 in the main document) and build the two VECMs with the function `VECM()` from the `urca` package.

Following the main notation of model 1 given in the main document (equations 6, 7, and 8), I estimate one variation of the model to test the intensity of violence $\overline{V}$, instead of the total number of victims (V): this is model 2. For tropical specialization (SP) I use the interaction between the share of land under tropical crops and the amount of these crops in exports and relative prices (P) are the ratio between the international prices for tropical products to cereals. The time series were modelled in logarithms (Section 2.2 for details on the variables and sources in the main text for details).

Although there were not so significant differences between the two models, I choosed the model 1 due to this model fit better the checks for normal distribution. To run the tests of robustness on the models, I transform the VECM to VAR in levels with `vec2var()` function and then check for serial correlation (`serial.test()`), autoregressive conditional heteroscedasticity (`arch.test()`), and normality distribution of the residuals of the model and by each variable (`normality.test()` and `shapiro.test()`).

The following subsections present the outputs and the checks for each of these models.

C.3.1 Model 1

OUTPUT

$$\begin{pmatrix} \Delta SP_t \\ \Delta V_t \\ \Delta P_t \end{pmatrix} = + \begin{pmatrix} -0.35(0.13)^{*} \\ 0.21(0.37) \\ 0.59(0.52) \end{pmatrix} ECT_{-1} \begin{pmatrix} 9.79(3.58)^{*} \\ -6.43(10.21) \\ -16.26(14.50) \end{pmatrix}$$

$$+ \begin{pmatrix} -0.08(0.18) & -0.13(0.09) & -3.1\text{e-}03(0.06) \\ -0.39(0.52) & -0.75(0.24)^{**} & 0.28(0.18) \\ -0.53(0.74) & 0.25(0.35) & -0.08(0.25) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-1} \\ \Delta V_{t-1} \\ \Delta P_{t-1} \end{pmatrix}$$

$$+ \begin{pmatrix} -0.10(0.18) & 8.1\text{e-}03(0.08) & -0.08(0.06) \\ -0.27(0.52) & -0.05(0.24) & 0.03(0.18) \\ 0.08(0.74) & -0.05(0.34) & -0.18(0.25) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-2} \\ \Delta V_{t-2} \\ \Delta P_{t-2} \end{pmatrix}$$

$$+ \begin{pmatrix} -0.29(0.17) & 0.01(0.07) & -0.06(0.06) \\ -0.29(0.47) & 0.42(0.20)^{\cdot} & 0.56(0.18)^{**} \\ -1.30(0.67)^{\cdot} & -0.27(0.28) & -0.11(0.26) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-3} \\ \Delta V_{t-3} \\ \Delta P_{t-3} \end{pmatrix}$$

$$+ \begin{pmatrix} 0.03(0.19) & -0.02(0.07) & 0.11(0.07) \\ 0.33(0.54) & 0.43(0.19)^{*} & 0.62(0.20)^{**} \\ -0.74(0.76) & -0.12(0.27) & -0.22(0.28) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-4} \\ \Delta V_{t-4} \\ \Delta P_{t-4} \end{pmatrix}$$

$$+ \begin{pmatrix} -0.15(0.19) & -0.04(0.07) & 0.02(0.07) \\ 0.29(0.55) & 0.68(0.19)^{**} & 0.75(0.19)^{***} \\ 0.10(0.78) & -0.04(0.26) & -0.20(0.26) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-5} \\ \Delta V_{t-5} \\ \Delta P_{t-5} \end{pmatrix}$$

$$+ \begin{pmatrix} -0.23(0.19) & -0.06(0.07) & -4.4\text{e-}03(0.07) \\ 1.81(0.55)^{**} & 0.73(0.20)^{**} & 0.07(0.20) \\ -0.93(0.79) & -0.06(0.29) & -0.26(0.28) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-6} \\ \Delta V_{t-6} \\ \Delta P_{t-6} \end{pmatrix}$$

$$+ \begin{pmatrix} 0.15(0.21) & -0.01(0.06) & -0.02(0.06) \\ 2.27(0.61)^{**} & 0.45(0.18)^{*} & 0.65(0.16)^{***} \\ -0.51(0.87) & 0.12(0.26) & -0.08(0.23) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-7} \\ \Delta V_{t-7} \\ \Delta P_{t-7} \end{pmatrix}$$

$$+ \begin{pmatrix} -0.13(0.23) & -0.12(0.06)^{*} & 1.9\text{e-}03(0.07) \\ 2.08(0.64)^{**} & 0.52(0.16)^{**} & 0.60(0.19)^{**} \\ 0.33(0.91) & 0.15(0.22) & -0.10(0.26) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-8} \\ \Delta V_{t-8} \\ \Delta P_{t-8} \end{pmatrix}$$

$$+ \begin{pmatrix} -0.60(0.22)^{*} & -0.06(0.05) & 0.04(0.06) \\ -0.59(0.63) & 0.36(0.15)^{*} & 0.46(0.18)^{*} \\ 0.32(0.89) & 0.11(0.21) & 4.3\text{e-}03(0.25) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-9} \\ \Delta V_{t-9} \\ \Delta P_{t-9} \end{pmatrix}$$

ROBUSTNESS CHECKS

Table C.5: Checks for model 1

Test	Chi-squared	df	p-value
Portmanteau Test (asymptotic)	53.12	3	1.72e-12
ARCH (multivariate)	96	1080	1
JB-Test (multivariate)	1.61	6	0.95
Skewness only (multivariate)	0.33	3	0.95
Kurtosis only (multivariate)	1.28	3	0.73

Table C.6: Shapiro-Wilk normality test for the residuals of the model 1 and for each variable

	Statistic	P-Value
Model 1	0.98	0.05
SP	0.97	0.39
V	0.98	0.71
P	0.98	0.80

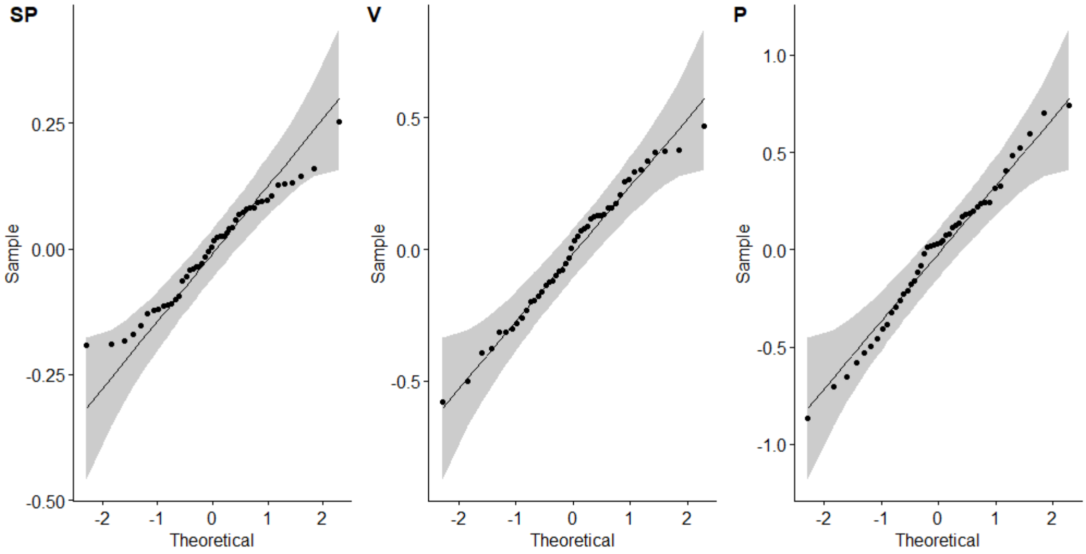


Figure C.1: Model 1: distribution for the residuals os SP, V, and P

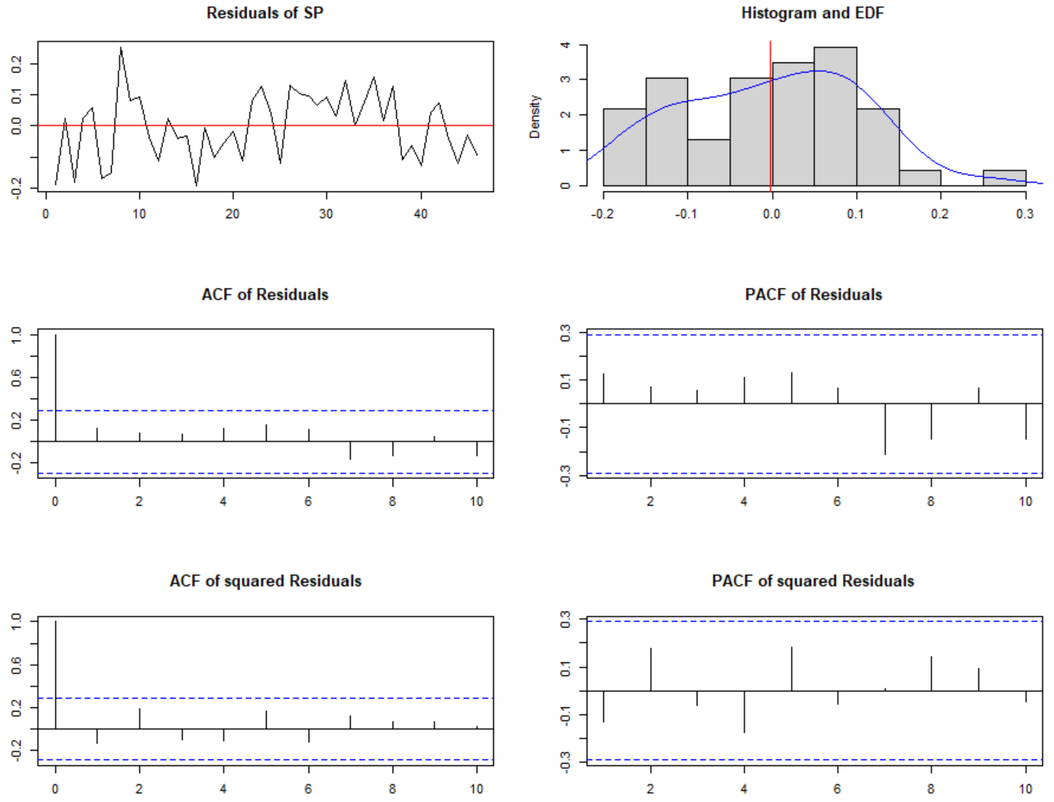


Figure C.2: Model 1: ACF and PACF of the residual of SP

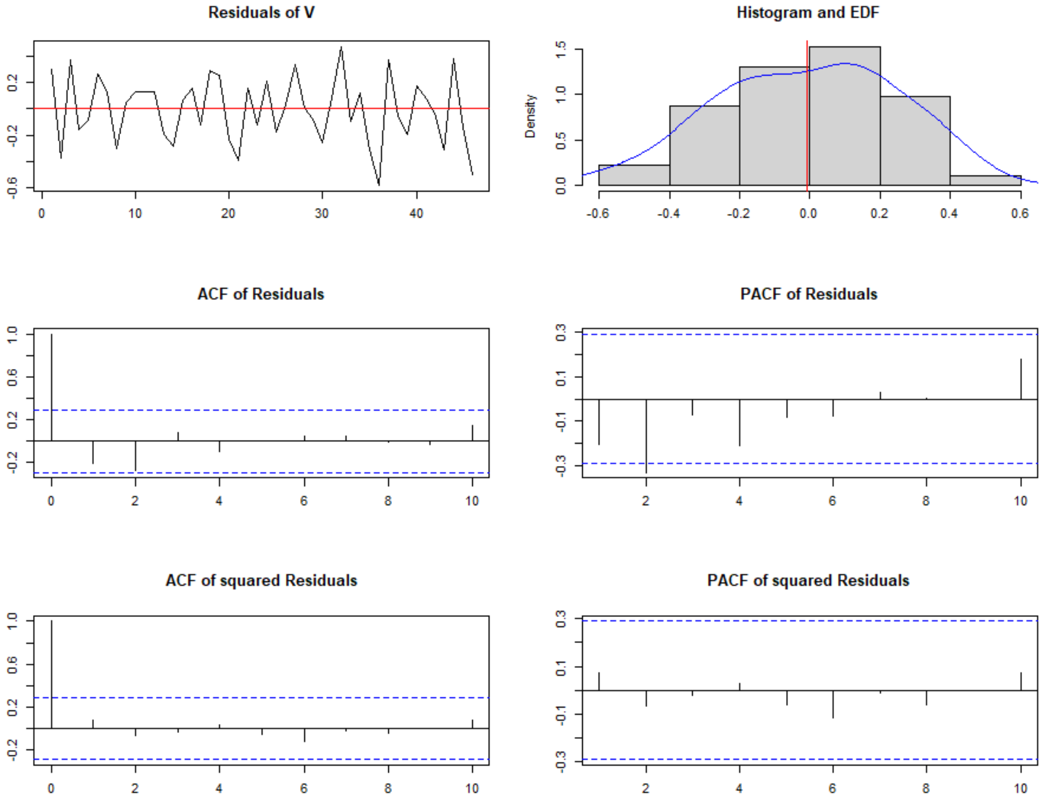


Figure C.3: Model 1: ACF and PACF of the residual of V

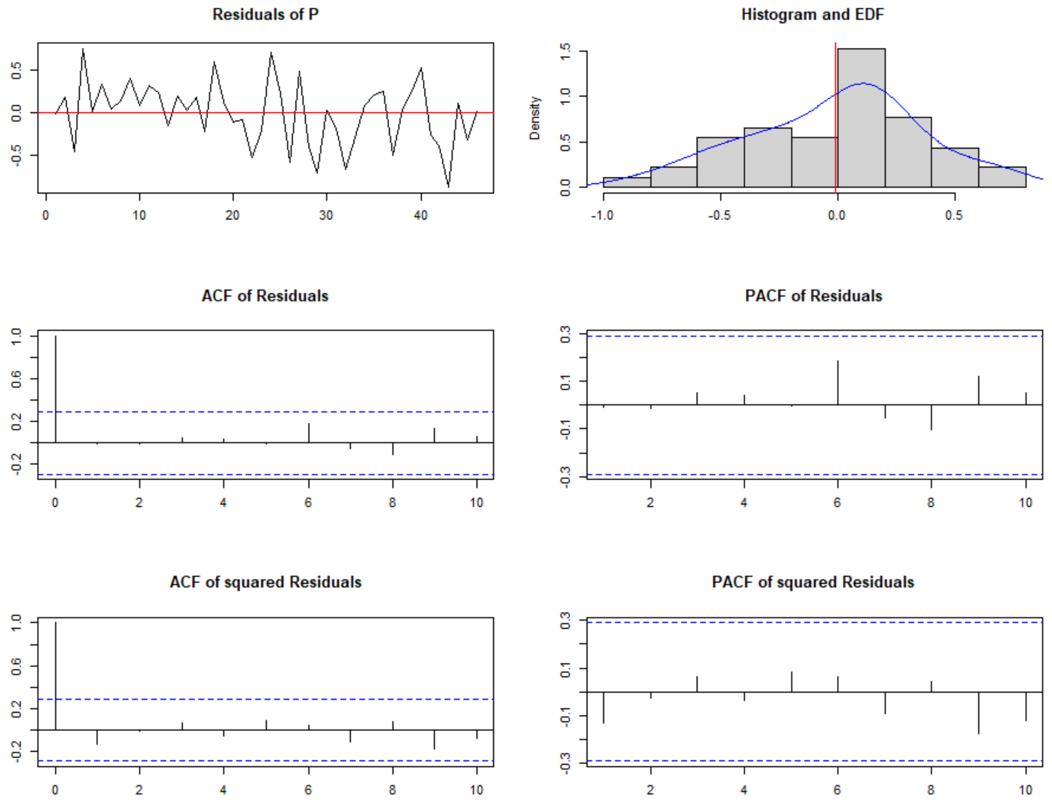


Figure C.4: Model 1: ACF and PACF of the residual of P

C.3.2 Model 2

NOTATION

$$\Delta SP_t = \theta_1 + \sum_{i=1}^{p} + [\alpha_{1i}\Delta SP_{t-i} + \beta_{1i}\Delta\overline{V}_{t-i} + \psi_{1i}\Delta P_{t-i}] + \mu ECT_{t-1} + \epsilon_{1t} \tag{C.1}$$

$$\Delta\overline{V}_t = \theta_2 + \sum_{i=1}^{p} + [\alpha_{2i}\Delta SP_{t-i} + \beta_{2i}\Delta\overline{V}_{t-i} + \psi_{2i}\Delta P_{t-i}] + \mu ECT_{t-1} + \epsilon_{2t} \tag{C.2}$$

$$\Delta P_t = \theta_3 + \sum_{i=1}^{p} + [\alpha_{3i}\Delta SP_{t-i} + \beta_{3i}\Delta\overline{V}_{t-i} + \psi_{3i}\Delta P_{t-i}] + \mu ECT_{t-1} + \epsilon_{3t} \tag{C.3}$$

OUTPUT

$$\begin{pmatrix} \Delta SP_t \\ \Delta\overline{V}_t \\ \Delta P_t \end{pmatrix} = + \begin{pmatrix} -0.30(0.18) \\ -0.99(0.32)^{**} \\ -0.67(0.58) \end{pmatrix} ECT_{-1} \begin{pmatrix} 10.68(6.55) \\ 35.07(11.42)^{**} \\ 24.00(20.76) \end{pmatrix}$$

$$+ \begin{pmatrix} -0.08(0.24) & 0.34(0.20)^{\cdot} & -0.04(0.09) \\ 0.72(0.42) & 0.43(0.34) & -0.02(0.15) \\ 0.16(0.76) & 0.39(0.62) & -0.07(0.28) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-1} \\ \Delta\overline{V}_{t-1} \\ \Delta P_{t-1} \end{pmatrix} + \begin{pmatrix} -0.04(0.22) & 0.25(0.18) & -0.08(0.08) \\ 0.83(0.39)^{*} & 0.51(0.31) & -0.13(0.15) \\ 0.13(0.71) & 0.31(0.56) & -0.58(0.27)^{*} \end{pmatrix} \begin{pmatrix} \Delta SP_{t-2} \\ \Delta\overline{V}_{t-2} \\ \Delta P_{t-2} \end{pmatrix}$$

$$+ \begin{pmatrix} -0.13(0.24) & 0.19(0.14) & -0.08(0.09) \\ 0.70(0.41) & 0.80(0.24)^{**} & -0.13(0.16) \\ -0.55(0.75) & 0.16(0.43) & -0.08(0.30) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-3} \\ \Delta\overline{V}_{t-3} \\ \Delta P_{t-3} \end{pmatrix} + \begin{pmatrix} 0.02(0.23) & 0.13(0.13) & -0.05(0.10) \\ 0.78(0.40)^{\cdot} & 0.81(0.22)^{**} & -0.03(0.18) \\ -0.65(0.73) & 0.13(0.40) & -0.57(0.33) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-4} \\ \Delta\overline{V}_{t-4} \\ \Delta P_{t-4} \end{pmatrix}$$

$$+ \begin{pmatrix} -0.05(0.23) & 0.15(0.12) & -0.09(0.09) \\ 0.53(0.40) & 0.56(0.21)^{*} & 0.09(0.15) \\ 0.51(0.73) & 0.12(0.38) & -0.16(0.27) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-5} \\ \Delta\overline{V}_{t-5} \\ \Delta P_{t-5} \end{pmatrix} + \begin{pmatrix} -3.8\text{e-}03(0.23) & 0.09(0.10) & -0.06(0.09) \\ 0.69(0.41) & 0.47(0.17)^{*} & -0.23(0.16) \\ -0.36(0.74) & -0.15(0.31) & -0.39(0.29) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-6} \\ \Delta\overline{V}_{t-6} \\ \Delta P_{t-6} \end{pmatrix}$$

$$+ \begin{pmatrix} -0.05(0.23) & 0.08(0.08) & -0.14(0.09) \\ 1.08(0.40)^{*} & 0.24(0.15) & -0.16(0.16) \\ 0.23(0.73) & 0.02(0.27) & -0.18(0.29) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-7} \\ \Delta\overline{V}_{t-7} \\ \Delta P_{t-7} \end{pmatrix} + \begin{pmatrix} 0.01(0.26) & 0.12(0.06)^{\cdot} & -0.02(0.08) \\ 0.06(0.46) & 0.16(0.11) & -0.28(0.14)^{\cdot} \\ 1.05(0.84) & -0.20(0.20) & -0.18(0.25) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-8} \\ \Delta\overline{V}_{t-8} \\ \Delta P_{t-8} \end{pmatrix}$$

$$+ \begin{pmatrix} -0.17(0.28) & 0.07(0.06) & -0.01(0.08) \\ -0.84(0.49) & 0.07(0.10) & -0.25(0.13)^{\cdot} \\ 0.06(0.89) & 0.07(0.18) & -0.14(0.24) \end{pmatrix} \begin{pmatrix} \Delta SP_{t-9} \\ \Delta\overline{V}_{t-9} \\ \Delta P_{t-9} \end{pmatrix}$$

ROBUSTNESS CHECKS

Table C.7: Checks for model 2

Test	Chi-squared	df	p-value
Portmanteau Test (asymptotic)	71.54	3	1.99e-16
ARCH (multivariate)	96	1080	1
JB-Test (multivariate)	8.93	6	0.18
Skewness only (multivariate)	4.9	3	0.18
Kurtosis only (multivariate)	4.03	3	0.25

Table C.8: Shapiro-Wilk normality test for the residuals of the model 2 and for each variable

	Statistic	P-Value
Model 2	0.96	0.001
SP	0.98	0.85
$\overline{V}$	0.96	0.13
P	0.97	0.34

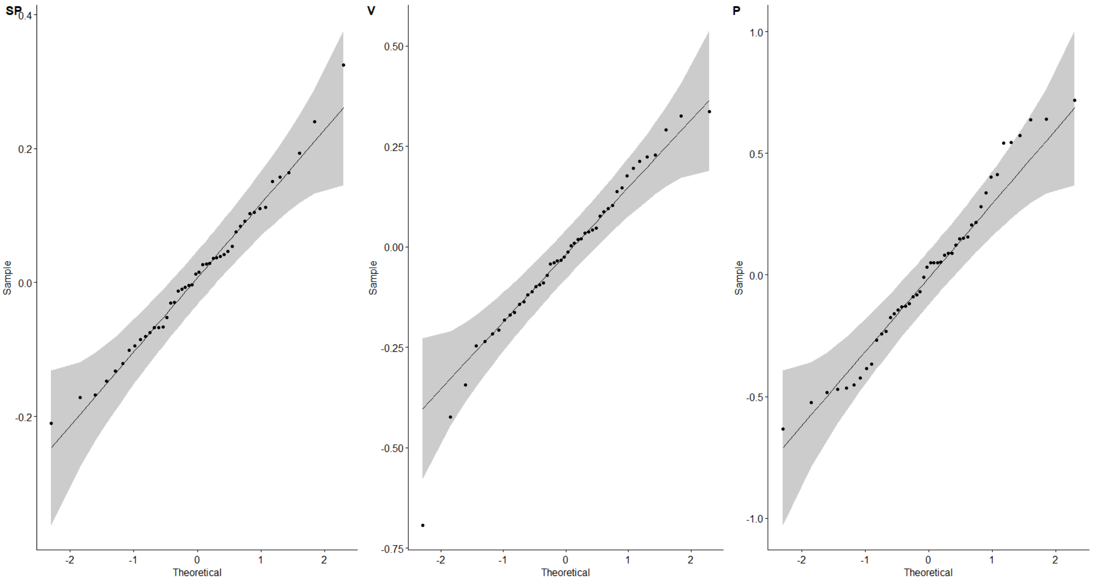


Figure C.5: Model 2: distribution for the residuals os SP, $\overline{V}$, and P

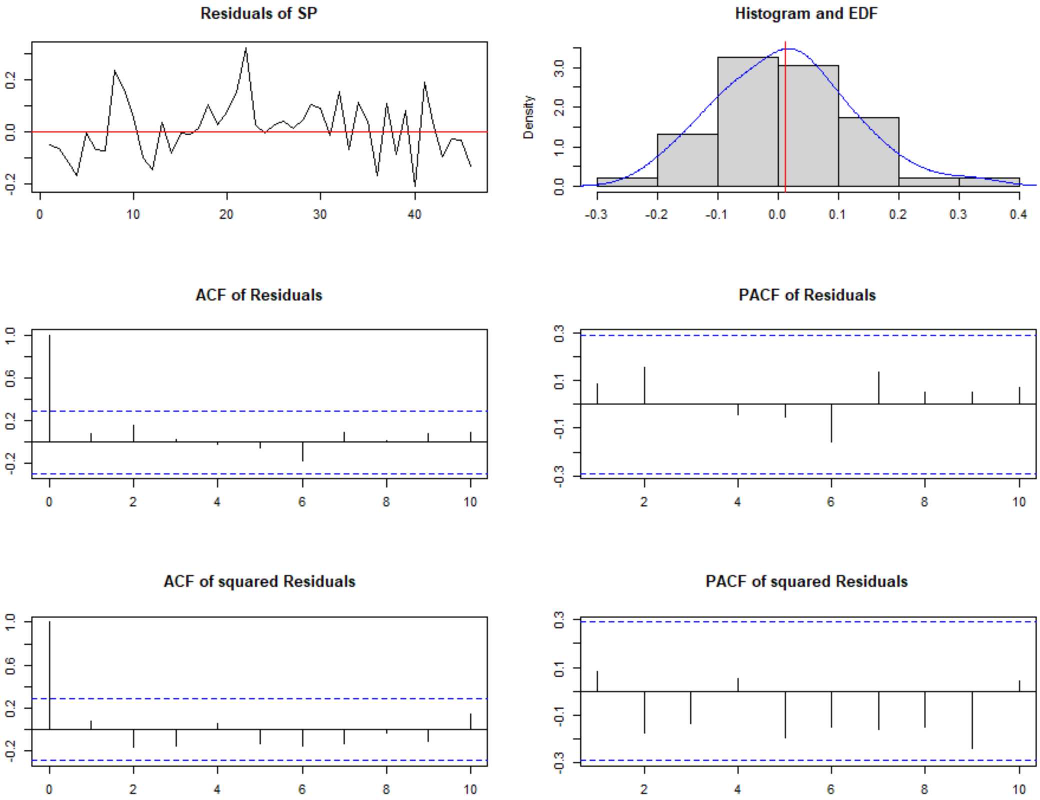


Figure C.6: Model 2: ACF and PACF of the residual of SP

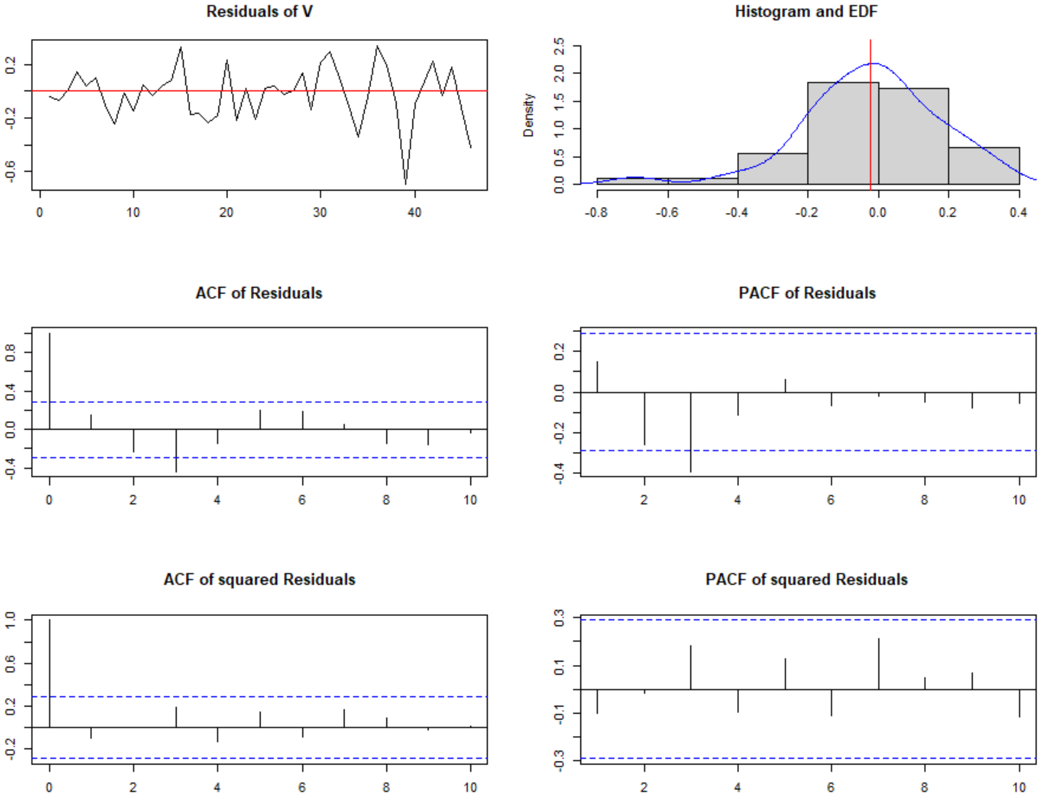


Figure C.7: Model 2: ACF and PACF of the residual of $\overline{V}$

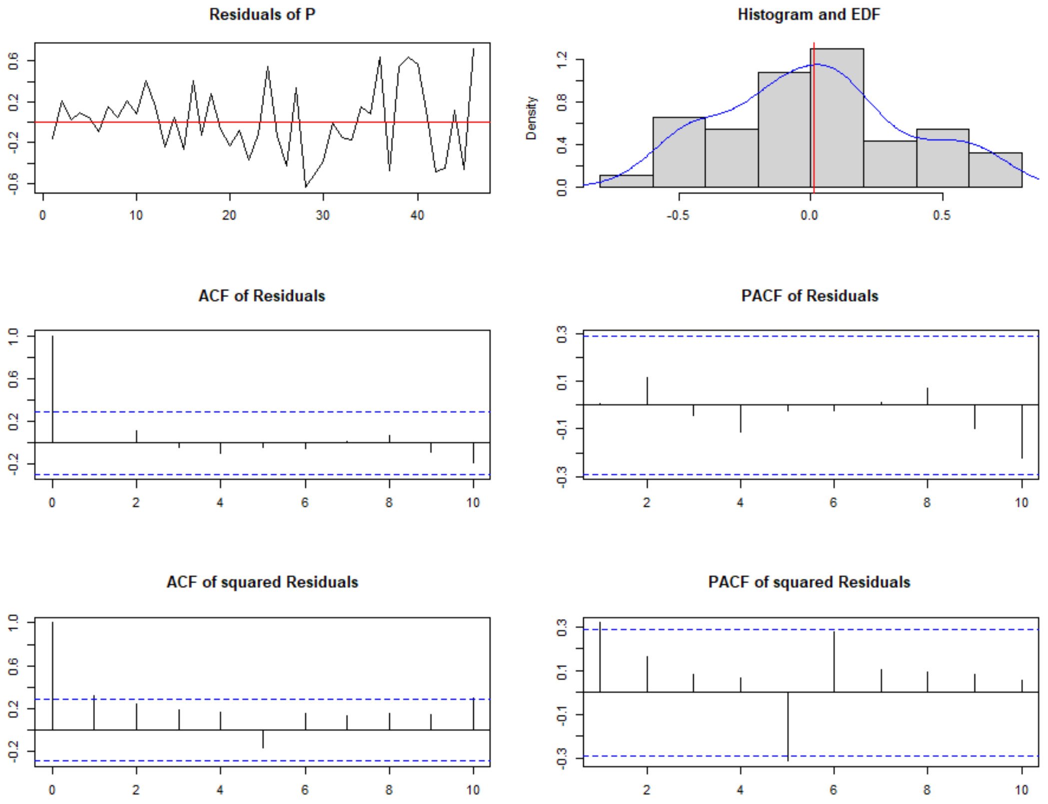


Figure C.8: Model 2: ACF and PACF of the residual of P

Appendix D

Energy Efficiency and Sustainability in Twentieth Century Colombian Agriculture

D.1 INTRODUCTION

This supplementary material reports is organized in three pieces. First, the information for the sources and data processing to build the biomass flows and external inputs time series; here we also provide information on the share of seed and feed used to adjust biomass reused and the standardization of the trade year books products to nutrients in the same way as FAOSTAT (2021) and Aguilera et al. (2015) databases. Second, the methodological approach of the periodisation which is complemented with the time series database as "Energy_SM.csv" file, and the R code to run the exercises of structural breaks. Finally, we provide the average performance of the main variables according to the defined periods.

D.2 SOURCES AND PROCESSING

In this section we offer the historical factors used to adjust the final production and obtain the quantity of seed and feed; the equivalences among the Trade Year Books, FAOSTAT (2021), and Aguilera et al. (2015) nomenclatures of the fertilizers; the main assumptions to figure the time series of machinery and the equivalences between the Trade Year Book nomenclatures and FAOSTAT (2021) databases; and finally, the disaggregated average, share, and the rates of change of the external inputs by the four periods of its structural breaks.

Figure D.1 plots the work flow from the gathering of information in the sources until the obtaining of the main flows necessary to the fund–flow model and the multi-EROI analysis. We build the mains times series of vegetal production, animal output, and internal and external inputs from the data collection of crops, pastureland, forestland, livestock and animal production, and agricultural inputs available in historical records (Trade Yearbooks, U.S. reports, agricultural magazines), current monographs (Bejarano, 2011; Flórez Nieto & Méndez, 2000; Kalmanovitz & López, 2006; Tafunell, 2013), and previous works (Urrego-Mesa, in press; Urrego-Mesa et al., 2019) for the period before 1960 and digital databases (DANE, 2018; FAOSTAT, 2021; MoxLAD, 2020; UPME, 2017) thereafter. We completed the biophysical series applying historical factors of roots, by-products, weeds, uses, yields by types of forest and pastures, wood and firewood consumption, nutritional requirements of herds, and embodied energy in external inputs among others (Guzmán et al., 2014; Krausmann, Erb, et al., 2008; Montero, 2018; Scurlock & Olson, 2013; Urrego-Mesa et al., 2019). Finally, from the combination of these times series we got the main flows to fit the fund–flow model and the multi-EROI analysis.

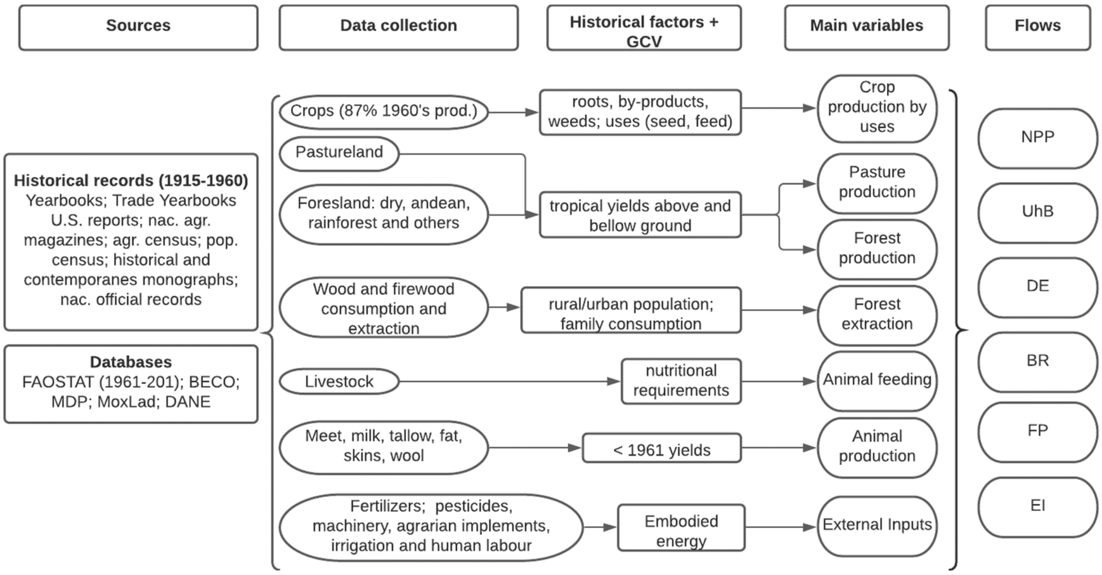


Figure D.1: Work flow from the sources to the main flows and throughout the data processing

D.2.1 Historical factors for seed and feed

Table D.1: Share of seed and feed in domestic supply for 1916-60

Cod.	Item aggregation 1	Seed	Feed
44	Barley	4.7%	2.3%
108	Cereals, nes	0.0%	16.4%
56	Maize	2.7%	9.8%
27	Rice, paddy	7.8%	0.0%
15	Wheat	4.1%	0.0%
176	Beans, dry	11.3%	0.0%
211	Pulses, nes	7.6%	0.0%
125	Cassava	0.0%	3.9%
116	Potatoes	10.9%	10.0%
149	Roots and tubers, nes	2.7%	8.2%
17350	Vegetables, total	0.0%	2.6%
2625	Fruits, other	0.0%	0.0%
486	Bananas	0.0%	15.0%
489	Plantains and others	0.0%	10.0%
257	Oil, Palm	0.0%	0.0%
2570	Oilcrops, Other	0.3%	63.6%
249	Coconuts	0.0%	0.0%
328	Seed cotton	3.0%	0.0%
800	Agave fibres nes	0.0%	0.0%
821	Fibre crops nes	0.0%	0.0%
661	Cocoa, beans	0.0%	0.0%
656	Coffee, green	0.0%	0.0%
826	Tobacco, unmanufactured	0.0%	0.0%
2922	Stimulants nes	0.0%	0.0%
156	Sugar cane	1.2%	0.4%
15600	Sugar, Other	0.0%	2.1%
9999	Others	0.0%	5.9%

Note: This is the average share of seed and feed to domestic supply during 1961–63 in FAOs' balance sheets. From 1961 onwards we used the percentage resulted in each year. See the methodology section in the main document for details.

D.2.2 Standardization for fertilizers

Table D.2 deploys the equivalences among the items in the Trade Year Books in Spanish, FAOSTAT (2021) and Aguilera et al. (2015) nomenclatures.

Table D.2: Trade Year Book items and its equivalences to FAOSTAT (2021) and Aguilera et al. (2015) nomenclatures

TYB code	Items TYB (1916-60)	Equivalence to FAO	Equivalence to Aguilera	Main nutrient
498	Abonos naturales,etc	Natural	Average NPK averages	Organic
498	Abonos químicos para la agricultura	Fertilizers n.e.c.	N fertilizers average	Nitrogenous fertilizers
89	Abonos químicos como los superfofatos de cal y de potasa y demás que se emplean en el abono de la tierra	PK compounds	PK 22-22	Phosphate fertilizers
90	Desechos de procedencia animal y vegetal y abonos naturales, tales como el salitre no purificado y el guano	Natural	Average NPK averages	Organic
243	Abonos químicos nitrogenados	Other nitrogenous fertilizers, n.e.c.	N fertilizers average	Nitrogenous fertilizers
244	Abonos químicos fosfatados	Other phosphatic fertilizers, n.e.c.	P fertilizers average	Phosphate fertilizers
245	Abonos potásicos	Other potassic fertilizers, n.e.c.	K fertilizers average	Potash fertilizers
246	Otros abonos químicos	Fertilizers n.e.c.	N fertilizers average	Nitrogenous fertilizers
243.1	Salitre no purificado	Other NK compounds	N fertilizers average	Nitrogenous fertilizers
243.2	Nitrato de sodio sintético, importado en cantidades mayores de 10 kilos	Sodium Nitrate	N fertilizers average	Nitrogenous fertilizers
243.3	Nitrato de sodio, importado en cantidades menores de 10kilos	Sodium Nitrate	N fertilizers average	Nitrogenous fertilizers
243.4	Nitrato de calcio como abono	Calcium Nitrate	N fertilizers average	Nitrogenous fertilizers

243.7	Nitrato de amonio como abono	Ammonium nitrate	N fertilizers average	Nitrogenous fertilizers
243.1	Sulfato de amonio como abono	Ammonium sulphate	AS	Nitrogenous fertilizers
243.14	Sulfonitrato de amonio	Ammonium SulphateNitrate	AS	Nitrogenous fertilizers
243.16	Abonos químicos nitrogenados (otros)	Other Nitrogenous Fert	N fertilizers average	Nitrogenous fertilizers
243-17	Ciamida de calcio o cal nitrogenada	Calcium Cyanamide	Cyanamide	Nitrogenous fertilizers
244.1	Escorias de desfoforación para abono	Basic Slag	Slag	Phosphate fertilizers
244.2	Superfosfatos de cal y potasa	Superphosphates, other	P fertilizers average	Phosphate fertilizers
244.4	Fosfatos de cales precipitadas	Superphosphates, other	P fertilizers average	Phosphate fertilizers
244.5	Sulfato de potasio, como abono	Potassium sulphate (sulphate of potash) (SOP)	P fertilizers average	Phosphate fertilizers
244.6	Fosfato de amoniaco	Monoammonium phosphate (MAP)	DAP, MAP	Nitrogenous fertilizers
245.1	Sales brutasde potasio	Potassium sulphate	P fertilizers average	Phosphate fertilizers
245.2	Cloruro de potasio como abono	Potassium chloride (muriate of potash) (MOP)	P fertilizers average	Phosphate fertilizers
245.3	Cloruro de potasio en cantidades mayores	Potassium chloride (muriate of potash) (MOP)	P fertilizers average	Phosphate fertilizers
245.6	Sulfato de potasio, como abono	Potassium sulphate (sulphate of potash) (SOP)	P fertilizers average	Phosphate fertilizers
245.7	Sulfato de potasio en envases menores de 10 kilos	Potassium sulphate (sulphate of potash) (SOP)	P fertilizers average	Phosphate fertilizers
245.6	Sulfato de potasio en cantidades mayores de 10 kilos	Potassium sulphate (sulphate of potash) (SOP)	P fertilizers average	Phosphate fertilizers

246.1	Fosfato de amonio bibásico, como abono	Diammonium phosphate (DAP)	DAP, MAP	Nitrogenous fertilizers
246.5	Fosfatos solubles, como abonos	Other phosphatic fertilizers, n.e.c.	P fertilizers average	Phosphate fertilizers
246.3	Nitrato de potasio, como abono	Potassium nitrate	P fertilizers average	Phosphate fertilizers
246.6	Residuos quimicos como abonos	Fertilizers n.e.c.	N fertilizers average	Nitrogenous fertilizers
246.7	Nitrato de sodi , como abono	Sodium nitrate	N fertilizers average	Nitrogenous fertilizers
342.1 (246.6)	Abonos de origen animal o vegetal, sin elaboración química	Natural	Average NPK averages	Organic
343.1 (243.1)	Nitrato de sodio (Salitre)	Sodium nitrate	N fertilizers average	Nitrogenous fertilizers
343.2 (243.4/ 243.7)	Nitratos de amonio y de calcio	Calcium ammonium nitrate	CAN	Nitrogenous fertilizers
343.3 (243.10/13)	Sulfato de amonio y sulfonitrato de amonio	Other nitrogenous fertilizers, n.e.c.	N fertilizers average	Nitrogenous fertilizers
343.4	Cianamida cálcica	Calcium Cyanamide	Cyanamide	Nitrogenous fertilizers
343.5 (243.16/ 243.18)	Otros abonos minerales o químicos nitrogenados	Other nitrogenous fertilizers, n.e.c.	N fertilizers average	Nitrogenous fertilizers
344.1 (244.2)	Fosfatos naturales aún molidos	Phosphate rock	Ground rock	Phosphate fertilizers

344.2 (244.1)	Escorias de desfoforación	Basic Slag	Slag	Phosphate fertilizers
344.3 (244.2)	Superfosfatos	Superphosphates, other	P fertilizers average	Phosphate fertilizers
344.4 (246.5)	Fosfatos precipitado (fosfato bicálcico) y otros abonos minerales o químicos fosfatados	Other phosphatic fertilizers, n.e.c.	P fertilizers average	Phosphate fertilizers
345.1 (245.1)	Sales de potasio en bruto	Potassium sulphate	P fertilizers average	Phosphate fertilizers
345.2 (245.2)	Cloruro de potasio	Potassium chloride (muriate of potash) (MOP)	P fertilizers average	Phosphate fertilizers
345.3 (245.1)	Sulfato de potasio	Potassium sulphate (sulphate of potash) (SOP)	P fertilizers average	Phosphate fertilizers
345.4 (245.2)	Otros abonos potásicos	Other potassic fertilizers, n.e.c.	K fertilizers average	Potash fertilizers
346.1 (246.6)	Mezclas de abonos	Fertilizers n.e.c.	N fertilizers average	Nitrogenous fertilizers
346.2 (246.3)	Otros abonos minerales compuestos por lo menos de 2 elementos fertilizantes	Fertilizers n.e.c.	N fertilizers average	Nitrogenous fertilizers
347.1 (243.1)	Mezclas de abonos no denominados ni comprendidos en otra parte	Fertilizers n.e.c.	N fertilizers average	Nitrogenous fertilizers
347.2 (243.1)	Otros abonos no denominados ni comprendidos en otras partes	Fertilizers n.e.c.	N fertilizers average	Nitrogenous fertilizers

D.2.3 Standardization for machinery

As machinery we introduce tractors, soil machinery, harvesters, milking machines, and others composed especially by agricultural tools (see table D.3). In the case of tractors between 1950 and 1975, we used the information in Araya and Ossa (1976) on the stock of tractors in units and power. The unitary weight of 2.7 tonnes of tractors in imports served to figure the stock in physical weight. We estimated the stock between 1935 and 1949 based on a 15-year lifetime at a depreciation rate of 13% (obtained as 100/15*2) and adding the annual inflow from imports.

The stock of machinery in use in the "Machinery" (1961-2009) database (FAOSTAT, 2021) have the same value between 1995 and 2005. Therefore, we match this information to the data of "Machinery Archive" data base (1961-2005). Although the information on stock is less consistent in this latter database, there are data on trade. After 1995 we add the net imports of harvesters and tractors with the same 15-year lifetime to compute the stock and between 2010-16, we use the 2005-10 average rate of growth (0.15 for harvesters and 0.061 for tractors) to complete the series.

FAOSTAT (2021) does not report soil machinery and milking machinery in use and the trade information is only available since the year 2005. Therefore, we model the growth of this kind of machinery according to the growth of tractors, harvesters and fertilizers for the case of the soil machinery. If we look carefully, the capitalization of the agricultural sector regarding tractors, harvesters and soil machinery evolved quite similar during 1916-60. However, this kind of machinery is also useful during the intensification, not only to plough the soil, but to spread fertilizers. For the case of milking machinery there are data of imports for 1959 and 1960, but we know that the milk industry developed during the eighties (Kalmanovitz & López, 2006). Therefore, to model the growth of this machinery we use the 1960 value and assumed that its use is associated to the production of whole and skimmed milk.

Finally, the agricultural implements powered by human force relevant in trade information during 1916-60, does not have a continuation into the "Agricultural Machinery n.e.s" category since 1961 nether in use and trade. To solve this lack of information, we modelled the series of agrarian implements as a function of the population working in agriculture. Once we settled milking machinery and agricultural implements, we added them into a same category labelled as others.

Table D.3: Trade Year Book items, its equivalences to Machinery Archive database (FAOSTAT, 2021) and our classification

Code	**TYB items (1916-60)**	**Equivalence to FAO**	**Our items**
110	Arados, sus rejas y repuestos. Until 1935: "máquinas para el cultivo"	Soil machinery	Tillage
111	Arietes hidráulicos	Agr Machinery nes	Others
112	(Herramientas agricultura) Aqüinches, azadas, azadones, barras, barretones, hachas, hachuelas, azuelas, martillos, calabozos, hoces, púcoras, taladros y hoyadoras	Agr Machinery nes	Others
114	Irrigadoras	Irrigation	Others
119-1	Carretillas de mano	Agr Machinery nes	Others
119-2	Herramientas, utensilios e instrumentos para la agricultura y mineria	Agr Machinery nes	Others
119-3	Herramientas, utensilios e instrumentos no mencionados para la agricultura y mineria	Agr Machinery nes	Others
121	Malacates y motores de fuerza animal	Soil machinery	Tillage
122	Máquinas para destruir hormigueros	Soil machinery	Tillage
123-1	Desmotadoras	Harvesters-Threshers	Harvesters
123-2	Máquinas para beneficiar arroz	Harvesters-Threshers	Harvesters
123-3	Máquinas para beneficiar cacao	Harvesters-Threshers	Harvesters
123-4	Máquinas para beneficiar azúcar	Harvesters-Threshers	Harvesters
123-5	Máquinas para beneficiar café	Harvesters-Threshers	Harvesters
123-6	Molinos de trigo, beneficiar maíz, trigo	Harvesters-Threshers	Harvesters
123-7	Trapiches y sus repuestos	Harvesters-Threshers	Harvesters
123-8	Máquinas y útiles mecánicos para la agricultura	Agr Machinery nes	Others
124-1	Máqunas y repuestos para la agricultura, no especificados	Agr Machinery nes	Others
124-2	Máquinas para moler granos	Harvesters-Threshers	Harvesters
125	Máquinas y trenes hidráulicos para regadíos	Agr Machinery nes	Others

127	Rueda hidráulica	Irrigation	Others
130	Rastras y rastrillos	Harvesters-Threshers	Harvesters
131	Segadoras, sembradoras y distribuidoras de a abonos	Soil machinery	Tillage
147	Máquinas para apicultura,sericicultura, avicultura	Agr Machinery nes	Others
362	Alambre de púas para cercas y sus grapas	Agr Machinery nes	Others
369	Herramientas de hierro o acero para agricultura, minería y otras grandes industrías	Agr Machinery nes	Others
375-5.3	Llantas de caucho exteriores, neumáticas de cualquier peso, para tractores o implementos agrícolas	Tractors Agric Total	Tractors
416	Accesorios de cobre o latón para máquinas de agricultura, como trilladoras, pilas de vapor y engrsadores automáticos	Agr Machinery nes	Others
489	Máquinas y útiles mecánicos para la industria y agricultura. Arados, sus rejas y repuestos	Harvesters-Threshers	Harvesters
490	Rastras y rastrillos	Harvesters-Threshers	Harvesters
491	Segadores, sembradores y distribuidores de abono	Soil machinery	Tillage
491a	Todas las máquinas para agricultura, no mecionadas en otra parte de la Tarifa	Agr Machinery nes	Others
496	Arietes hidráulicos	Irrigation	Others
496b	Máquinas y trenes hidráulicos para regadío	Irrigation	Others
513bis	Carretillas de mano para remover materiales	Agr Machinery nes	Others
768-2(362bis)	Alambre de púas para cercas	Agr Machinery nes	Others
790(369)	Palas, barras, azadas, picos, rastrillos, tenedores, zapapicos	Soil machinery	Tillage

790-1(369)	Palas y garlanchas, de hierro o acero	Soil machinery	Tillage
790-2(369)	Barras, barretones, regatones y recatones de hierro o acero	Soil machinery	Tillage
790-3(369	) Azadas y gambias de hierro o acero	Soil machinery	Tillage
790-4(369)	Azadones de hierro o acero	Soil machinery	Tillage
790-5(369)	Picos, zapapicos y picos de punta y pala, de hierro o acero	Soil machinery	Tillage
790-6(369)	Rastrillos y tenedores de hierro o acero	Harvesters-Threshers	Harvesters
791(369)	Hachas, hachuelas, machetes, hoces, guadañas y similares	Agr Machinery nes	Others
791-1	Machetes, rulas, peinillas, tacisos, de hierro o acero	Agr Machinery nes	Others
791-1(369)	Hachas y hachuelas de hierro o acero	Agr Machinery nes	Others
791-3(369)	Azuelas de hierro o acero	Soil machinery	Tillage
791-3	Podones, rozaderas, tajaderas de mano, etc., de hierro o acero	Harvesters-Threshers	Harvesters
791-3	Guadañas y hoces; cuchillas para heno y para paja, de hierro o acero	Harvesters-Threshers	Harvesters
798-2(369)	Herramientas para agricultura y minería (otras)	Agr Machinery nes	Others
791-2(369)	Hoces y guadañas de hierro o acero	Harvesters-Threshers	Harvesters
791(369)	Azuelas de hierro o acero	Soil machinery	Tillage
823-4.1	Motores de explosión y de combustión interna para tractores	Tractors Agric Total	Tractors
823-4.2	Partes y piezas sueltas reconocibles y no denominadas en otras partes, para motores de explosión y de combustión interna, para tractores	Tractors Agric Total	Tractors
829-1	Pulverizadores y rociadores agrícolas, de un peso menor de 20 kilos por unidad	Irrigation	Others

829-2	Pulverizadores y rociadores agrícolas, de un peso menor de 20 kilos por unidad	Irrigation	Others
834-1	Distribuidoras de abonos	Soil machinery	Tillage
834-2	Sembradoras y máquinas de plantar	Soil machinery	Tillage
834-3	Arados de rejas o vertederas, de tracción animal, y rastrillos de dientes o púas	Soil machinery	Tillage
834-3.2	Rastrillos de dientes o puas	Harvesters-Threshers	Harvesters
834-4	arados para tracción mecánica	Soil machinery	Tillage
834-5.1	Cultivadoras, arrancadoras, gradas, rodillos y otras máquinas para la preparación y el cultivo del suelo	Soil machinery	Tillage
834-5.2	Cavadoras	Soil machinery	Tillage
834-5.3	Cultivadoras	Soil machinery	Tillage
834-5.4	Zanjadoras	Soil machinery	Tillage
834-5.5	Sub-soladoras	Soil machinery	Tillage
834-5.6	Aporcadoras	Soil machinery	Tillage
834-5.7	Rotavators	Soil machinery	Tillage
834-6	Otras maquinas para el trabajo, la preparacion y el cultivo del suelo, asi como sus partes y piezas sueltas	Soil machinery	Tillage
835-1	Segadoras y segadoras trilladoras	Harvesters-Threshers	Harvesters
835-2	Rastrillos mecánicos	Harvesters-Threshers	Harvesters
835-3	Guañadadoras, removedoras de heno, y otras similares	Harvesters-Threshers	Harvesters
835-4	Trilladoras para café	Harvesters-Threshers	Harvesters
835-5.1	Desmotadoras de algodón	Harvesters-Threshers	Harvesters
835-5.2	Trilladoras de cereales	Harvesters-Threshers	Harvesters
835-5.3	Trilladoras y desgranadoras para otros granos	Harvesters-Threshers	Harvesters
835-5.5	Limpiadoras de arroz	Harvesters-Threshers	Harvesters
835-5.6	Otras trilladoras de cereales	Harvesters-Threshers	Harvesters
835-5.7	Despulpadoras de café	Harvesters-Threshers	Harvesters
835-5.8	Otras destrilladoras y desgranadoras	Harvesters-Threshers	Harvesters
835-6	Clasificadoras de café	Harvesters-Threshers	Harvesters

835-7	Otras clasificadoras y aparatos para escoger los granos y las frutas	Harvesters-Threshers	Harvesters
836-3.1	Máquinas de ordeño	Milking machines	Others
836-4	Trapiches	Harvesters-Threshers	Harvesters
836-5	Cortadoras y picadoras de forraje	Harvesters-Threshers	Harvesters
836-6	Molinos de grano, con peso hasta 100 kg	Harvesters-Threshers	Harvesters
836-7	Máquinas y aparatos para avicultura	Agr Machinery nes	Others
836-8	Máquinas y aparatos para apicultura	Agr Machinery nes	Others
836-9	Máquinas y aparatos agrícolas, no denominados en otra parte	Agr Machinery nes	Others
836-10	Maquinas y apartos para el tratamiento y benificio del fique	Harvesters-Threshers	Harvesters
837-1	Máquinas y aparatos para la molinería	Harvesters-Threshers	Harvesters
837-1.1	Máquinas y aparatos para la producción de semolas de cereales y de harinas y almidones de tubérculos	Harvesters-Threshers	Harvesters
837-1.2	Partes y piezas sueltas para máquinas y aparatos, para la producción de sémolas y almidones	Harvesters-Threshers	Harvesters
837-1.3	Otras máquinas y aparatos para la molinería	Harvesters-Threshers	Harvesters
837-1.4	Partes y piezas sueltas para máquinas y aparatos, para la molinería,N.E.P.	Harvesters-Threshers	Harvesters
880-1(489)	Arados, sus rejas y repuestos. Hasta 1935: Máquinas para el cultivo	Soil machinery	Tillage
880-2(490)	Rastras y rastrillos	Harvesters-Threshers	Harvesters
880-3(491)	Sembradoras y sus accesorios	Soil machinery	Tillage
880-4(491)	Distribuidoras de abonos y sus accesorios	Soil machinery	Tillage

880-5(501)	Tractores para la agricultura, y accesorios	Tractors	Tractors
880-7(491 and 504)	Accesorios para tractores	Tractors Agric Total	Tractors
880-6(491)	Máquinas para el cultivo de la tierra, y accesorios (otras)	Soil machinery	Tillage
881-1(491)	Segadoras y accesorios. Hasta 1935: Máquinas para la recolección	Harvesters-Threshers	Harvesters
881-2(491)	Trilladoras y accesorios	Harvesters-Threshers	Harvesters
882-13(491)	Maquinaria para la recolección, no designada, y accesorios	Harvesters-Threshers	Harvesters
882-1(491	Maquinaria agrícola, no designada, y accesorios	Agr Machinery nes	Others
883-3(500)	Maquinaria para la molinería de granos (otras) y sus acc esorios	Harvesters-Threshers	Harvesters
884 (491)	Trilladoras de grano y sus accesorios	Harvesters-Threshers	Harvesters
884-1(491)	Maquinaria para beneficiar café, y sus accesorios	Harvesters-Threshers	Harvesters
884-2(491)	Maquinaria para beneficiar arroz, y sus accesorios	Harvesters-Threshers	Harvesters
884-3(491)	Maquinaria para la avicultura, y sus accesorios	Agr Machinery nes	Others
884-4(491)	Maquinaria para la cericultura, y sus accesorios	Agr Machinery nes	Others
884-5(491)	Maquinaria para la apicultura, y sus acc esorios	Agr Machinery nes	Others
885-2(500)	Máquinas para la molinería de aceites, y accesorios	Harvesters-Threshers	Harvesters
886-1(500)	Trapiches y accesorios. Hasta 1935: Maquinaria para el beneficio de la caña de azúcar	Harvesters-Threshers	Harvesters
886-3(500)	Tachos, pailas, calderas, etc., para el beneficio de la caña de azúcar	Harvesters-Threshers	Harvesters

886-4(500)	Maquinaria para el beneficio de la caña de azúcar (otras), y accesorios	Harvesters-Threshers	Harvesters
889-1	Tractores agrícolas	Tractors	Tractors
889-3	Partes y piezas sueltas para tractores (incluidas las chuchillas o bulldozers)	Tractors Agric Total	Tractors
893-2.1	Partes y piezas sueltas trabajadas para transmisión y dirección de tractores	Tractors Agric Total	Tractors
893-3.1	Otras partes trabajadas, como ruedas, ejes, rotadores de grasa, radiadores, etc. para tractores	Tractors Agric Total	Tractors
898-1	Vehículos no automotores, agrícolas y similares, sin resortes	Tractors	Tractors

Note: The TYB code and Items contend the nomenclatures in the records from 1916 to 1960. As the classification suffered changes there are repeated items under different codes. We added Irrigation nomenclature to the original classification of FAOSTAT (2021)

D.3 PERIODIZATION

We defined five periods in the processes of the SET of agriculture in Colombia: 1916–32, 1933–54, 1955–75, 1976–97 and 1998–2015 (See the main document for its characterization). To divide the SET process into these periods, we look for the structural breaks in 17 of our time series. In table D.4, we present the summary statistics of these series.

To deal with the time pattern changes of the mean in the non-stationary variables we fit a trend-lineal model in this way:

$$Y_t = X_t \tag{D.1}$$

Y is the time series involved, $_t$ denotes time, and the independent variable X is a time index into the regression model (see Nau (2020) for details on the model). To date the breaks and to choose the optimal segment partition for each time series we use the breakpoints function in strucchange package implemented by Zeileis, Kleiber, Hornik, and Leisch (2002) into the R Core Team (2020) system. Optimal partition is selected on the base of the bayesian information criterion (BIC) and the residual sum of squares also provided into the same function (see Zeileis (2006) for some examples). We provide the R code, the plots of the selection process and the breakpoints together with the confident intervals for the time series in subsections D.3.1 and D.3.2.

Table D.4: Summary statistics of the time series for structural breaks

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Crop production [PJ]	100	161.2	122.7	16.4	51.3	277.9	418.9
FP [PJ]	100	410,732.2	202,001.3	122,769.3	221,004.0	614,026.2	758,449.0
BR [PJ]	100	1,054.540	436.830	449.945	663.369	1,555.881	1,704.582
UhB [PJ]	100	29,325.620	1,484.912	27,513.100	27,712.390	30,609.490	31,848.210
NPP [PJ]	100	30,763.1	881.1	29,636.5	29,895.4	31,484.8	32,415.2
EI [PJ]	100	64.7	69.6	5.4	13.4	82.8	298.0
CCRA yields [GJ/ha][1]	100	19.335	12.748	4.441	8.856	29.090	51.515
Intensification [GJ/ha][2]	100	2.661	2.285	0.591	0.944	2.968	10.558
Energy prod. [GJ][3]	100	7.854	1.367	4.334	7.094	8.819	10.466
Monetary prod. [GJ][4]	94	0.893	0.244	0.477	0.706	1.116	1.441
FEROI	100	0.36	0.05	0.25	0.33	0.38	0.44
EFEROI	100	11.06	5.63	2.43	7.34	15.96	22.55
IFEROI	100	0.37	0.06	0.25	0.34	0.41	0.45
Labour FEROI	100	41.59	14.08	23.02	26.62	53.52	65.87
NPP EROI	100	1.011	0.005	1.003	1.006	1.015	1.018
AFEROI	100	0.014	0.007	0.004	0.007	0.021	0.026
BFEROI	100	0.963	0.017	0.934	0.944	0.978	0.986

Note: [1]Crop and animal production yields including crop residues as output. [2]External inputs per hectare. [3] External inputs per output including crop residues. [4]External input per agricultural GDP in million ($ 1970 LCU).

Once obtained the break points for each time series, we grouped the information by decades and got the account, average, and standard deviation as a way to stablish the main periods (see table 5.1). In addition, we base the periodization choices on the economic history of the region (Cárdenas et al., 2000a, 2000b; Thorp, 2000) and the food regimes framework (McMichael, 2009).

D.3.1 R code

The supplementary (.csv) file contains the variables to run the code into the R Core Team (2020) system. Note that we do not provide the series on Crops, Energy productivity (nether physical and monetary), Yields, and Intensification due to the data on land, crops and agricultural GDP come from Urrego-Mesa et al. (2019) and the MoxLAD (2020) project.

```
#"Energy_SM" refers to the database available in
#the supplementary .csv file

tseries_break <- function(x){
        #Get the values from the data base
        serie <-  Energy_SM%>%
        filter(Item == x)%>%
        mutate(Value = ifelse(Element != "erois",
        Value/1000, Value))%>%
        select(Value)

        #Set the time series
        Tserie <- ts(serie, start = c(1916),
        end= c(2015), frequency = 1)
        plot(Tserie,
        main = "Time␣series",
        xlab = "Years",
        ylab = "PJ")

        #Compute the breaks
        bf_Tserie <- breakpoints(Tserie ~ time(Tserie))
        plot(bf_Tserie,
        main =   "BIC␣and␣Residual␣Sum␣of␣Squares")

        #Compute the confidence intervals
        ci_Tserie <- confint(bf_Tserie)

        #Plot the time series with structural breaks
        plot(Tserie,
        main = "Stracutural␣breaks",
        xlab = "Years",
        ylab = "PJ")
        lines(bf_Tserie)
        lines(ci_Tserie)

        #See the optimum breaks
        return(bf_Tserie)
}

#Energy flow times series ----
tseries_break("FP")
tseries_break("RuB")
tseries_break("UhB")
tseries_break("TNPP")
```

```
tseries_break("Total_EI")
#Energy returns time series ----
tseries_break("FEROI")
tseries_break("IFEROI")
tseries_break("EFEROI")
tseries_break("Labour_FEROI")
tseries_break("NPPEROI")
tseries_break("AFEROI")
tseries_break("BFEROI")
```

D.3.2 Breakpoint selection

This subsection deploys the BIC and RSS plots together with the plots of the time series and its breakpoints.

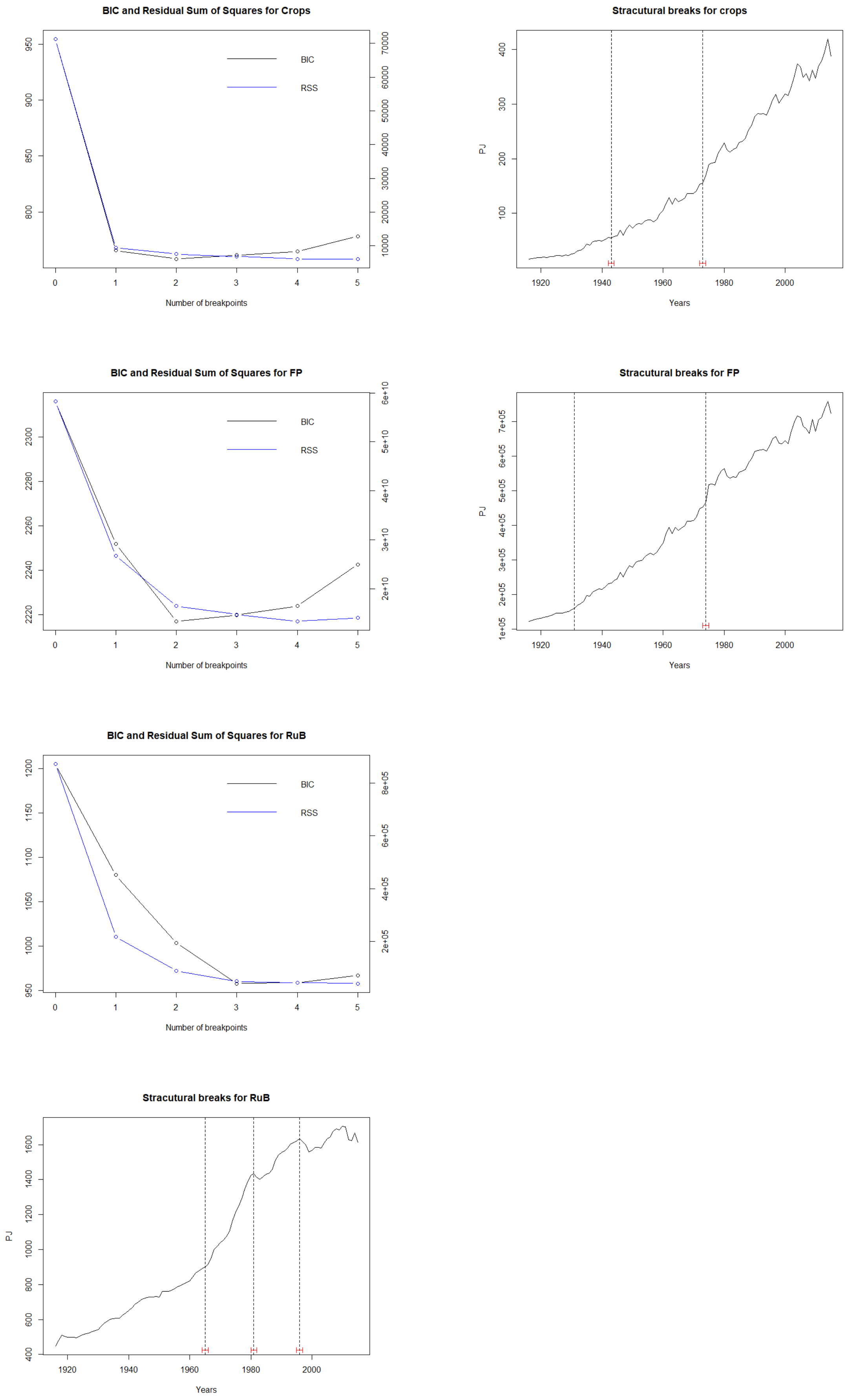
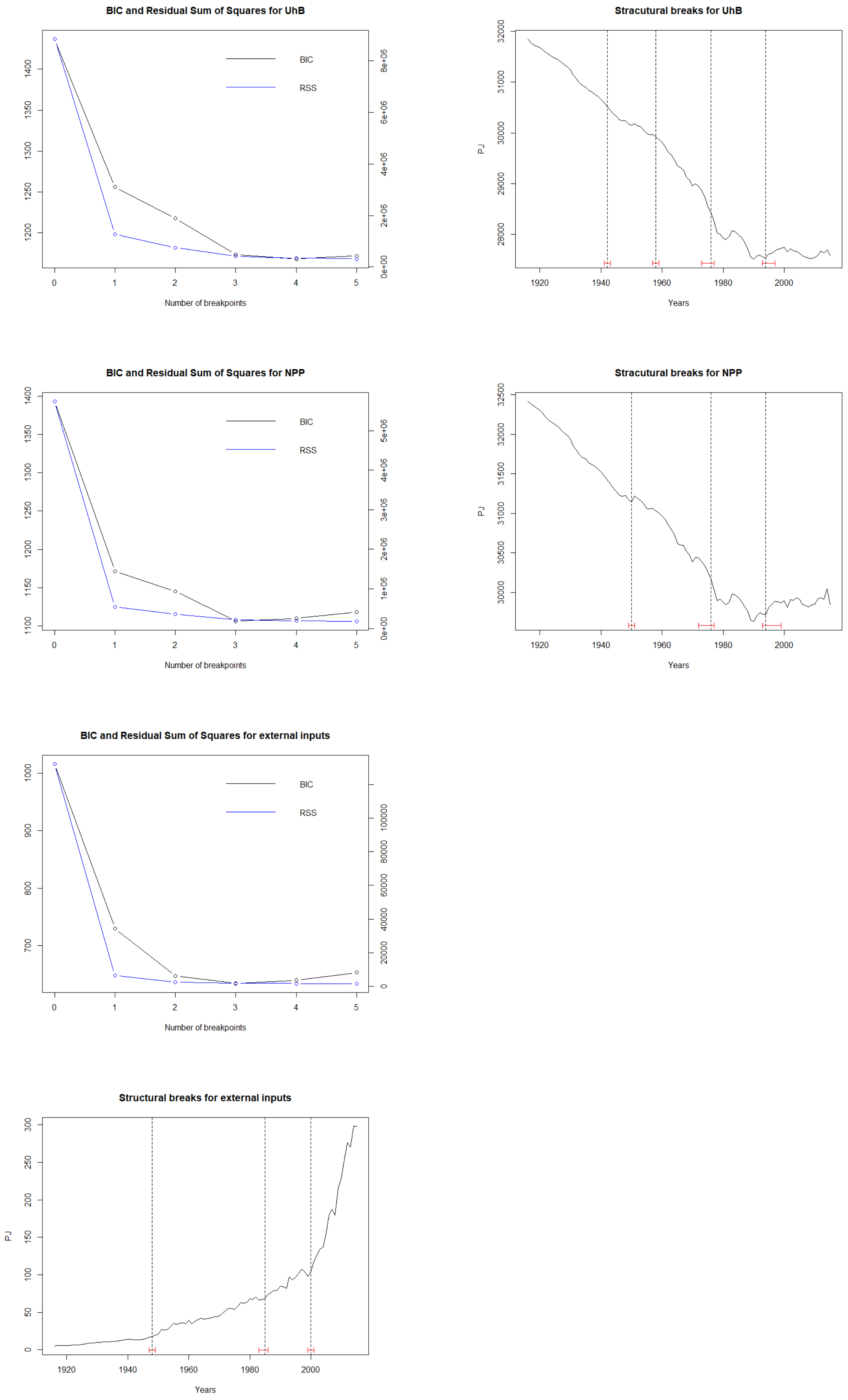


Figure D.2: Segment selections (BIC and RSS) and break points for the time series of crops, final produce, and biomass reused. The dotted lines are the structural breaks, and the red lines depicts the IC at 95%



BIC and Residual Sum of Squares for UhB

Stracutural breaks for UhB

BIC and Residual Sum of Squares for NPP

Stracutural breaks for NPP

BIC and Residual Sum of Squares for external inputs

Structural breaks for external inputs

Figure D.3: Structural breaks for selected time seriesof unharvested biomass, net primary productivity, and external inputs. The dotted lines are the structural breaks, and the red lines depicts the IC at 95%

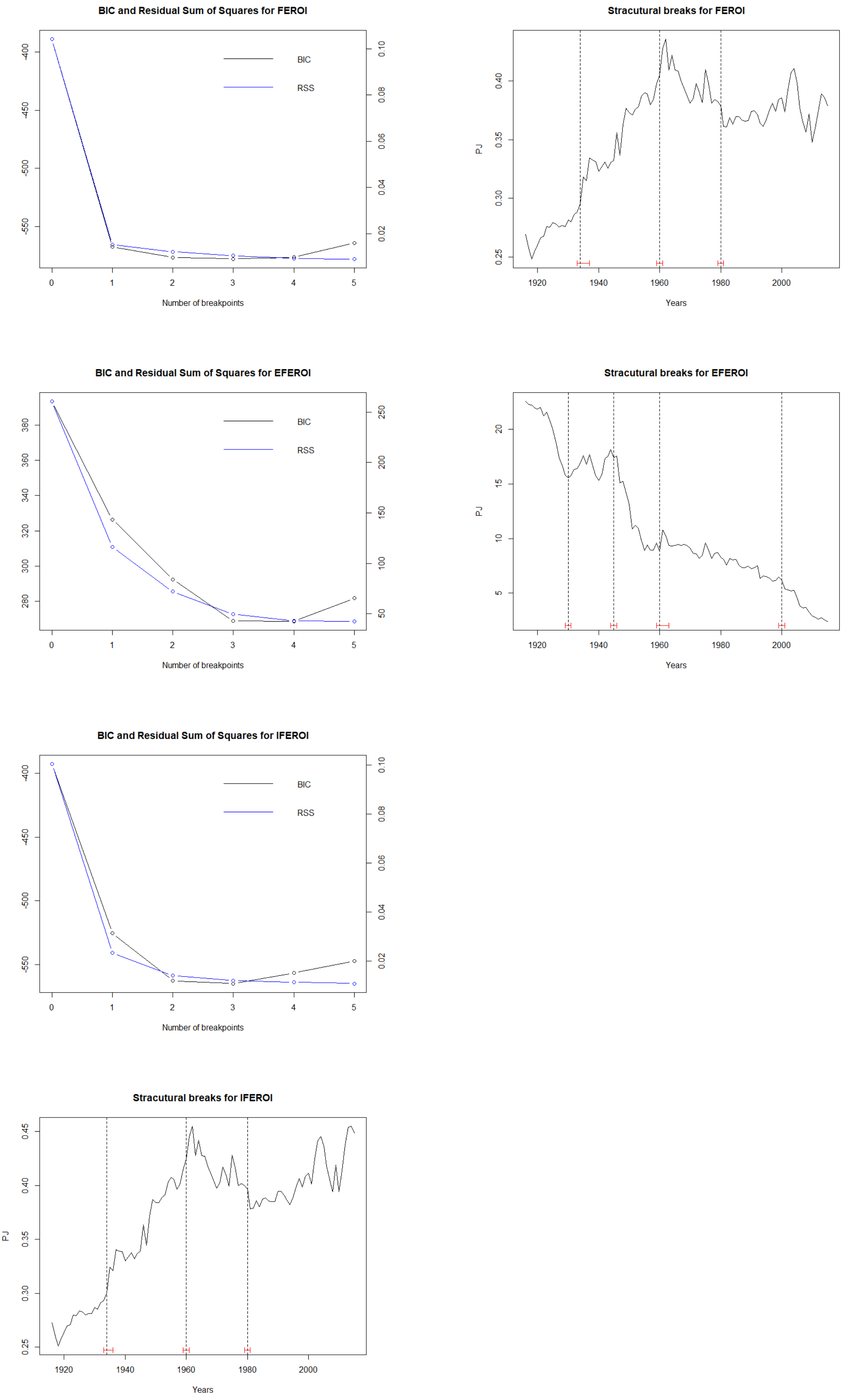


Figure D.4: Segment selections (BIC and RSS) and break points for the time series of the bioeconomic energy returns. The dotted lines are the structural breaks, and the red lines depicts the IC at 95%

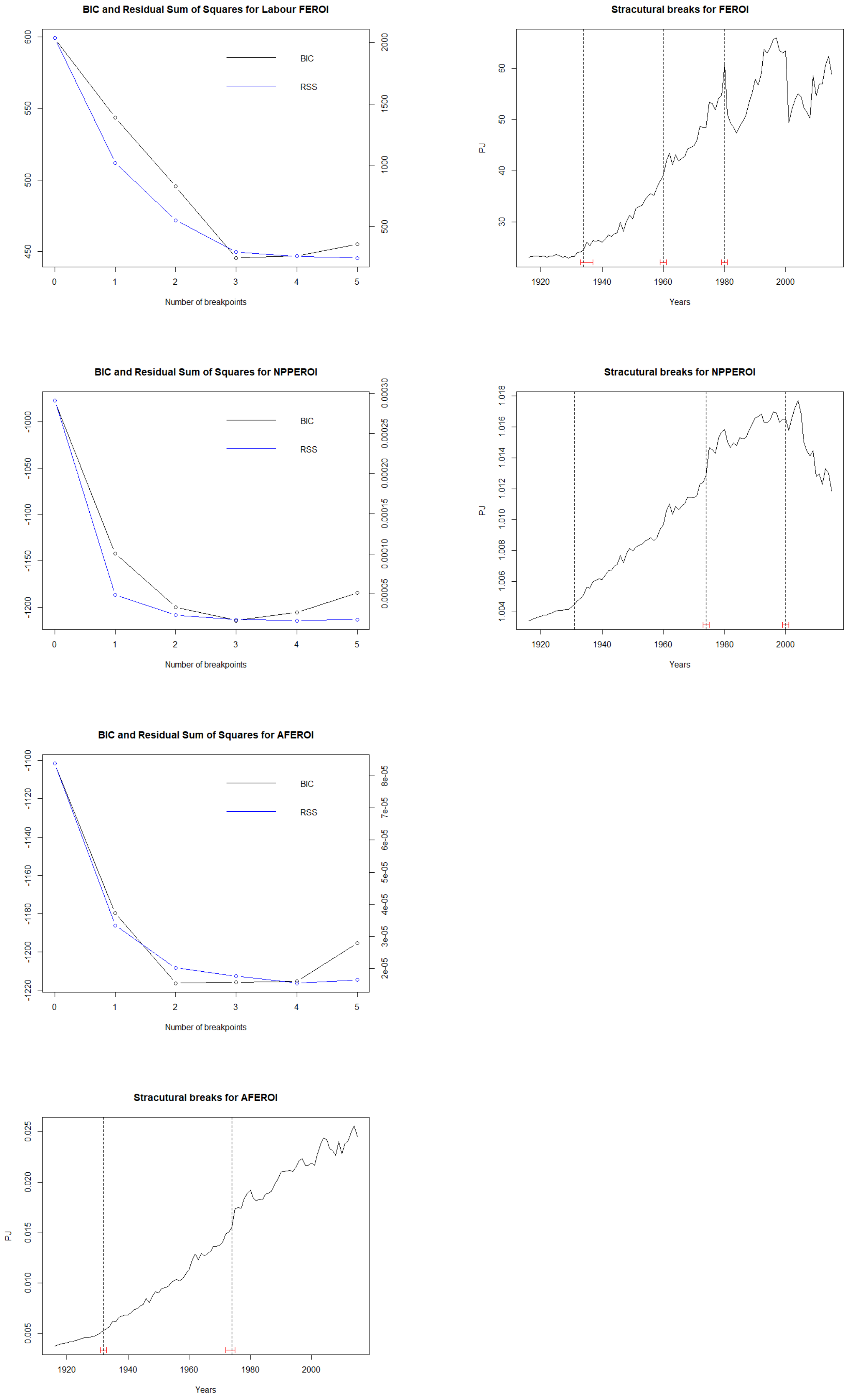


Figure D.5: Segment selections (BIC and RSS) and break points for the time series of the agroecological energy returns. The dotted lines are the structural breaks, and the red lines depicts the IC at 95%

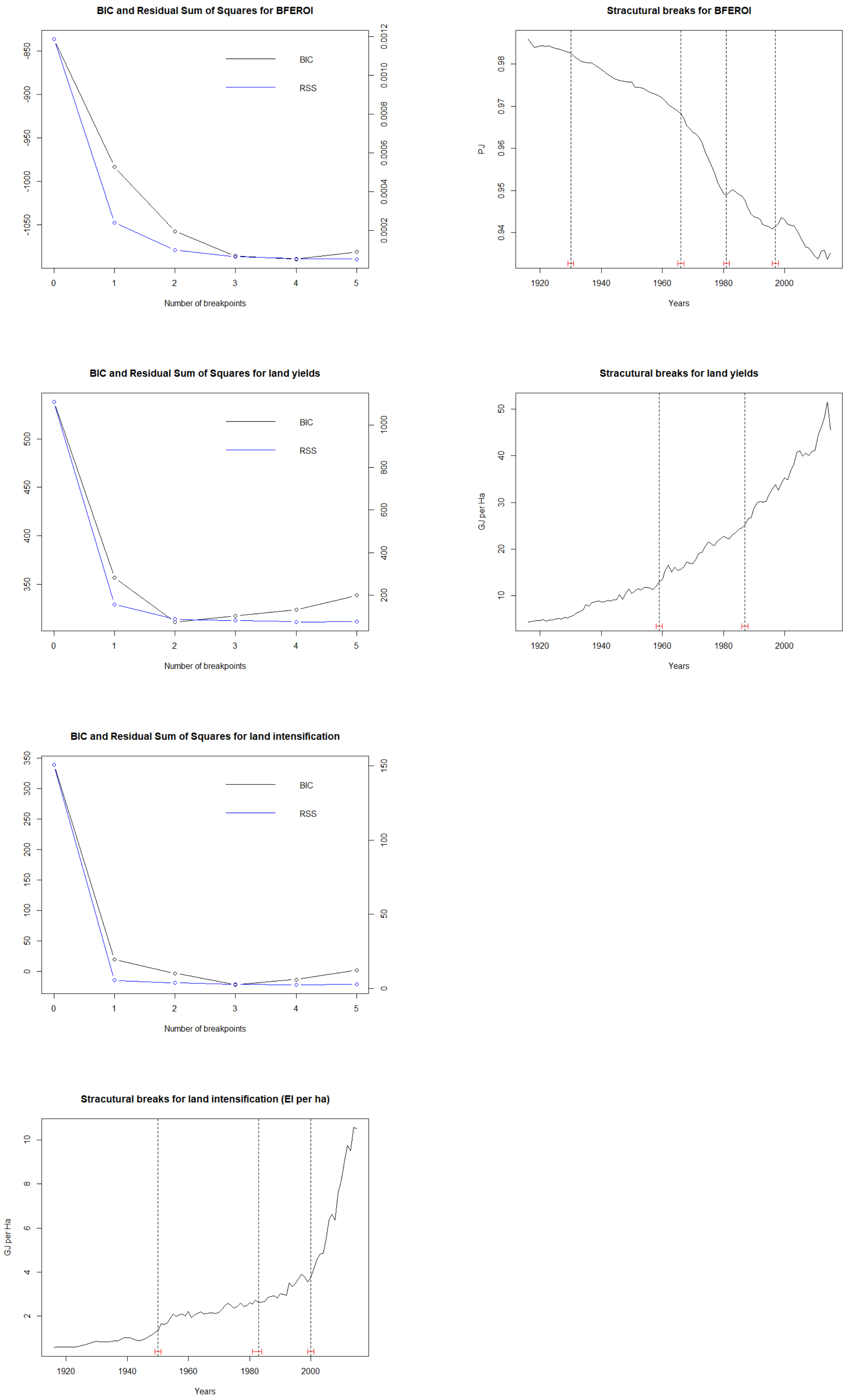


Figure D.6: Segment selections (BIC and RSS) and break points for the time series of socio-economic indicators. The dotted lines are the structural breaks, and the red lines depicts the IC at 95%

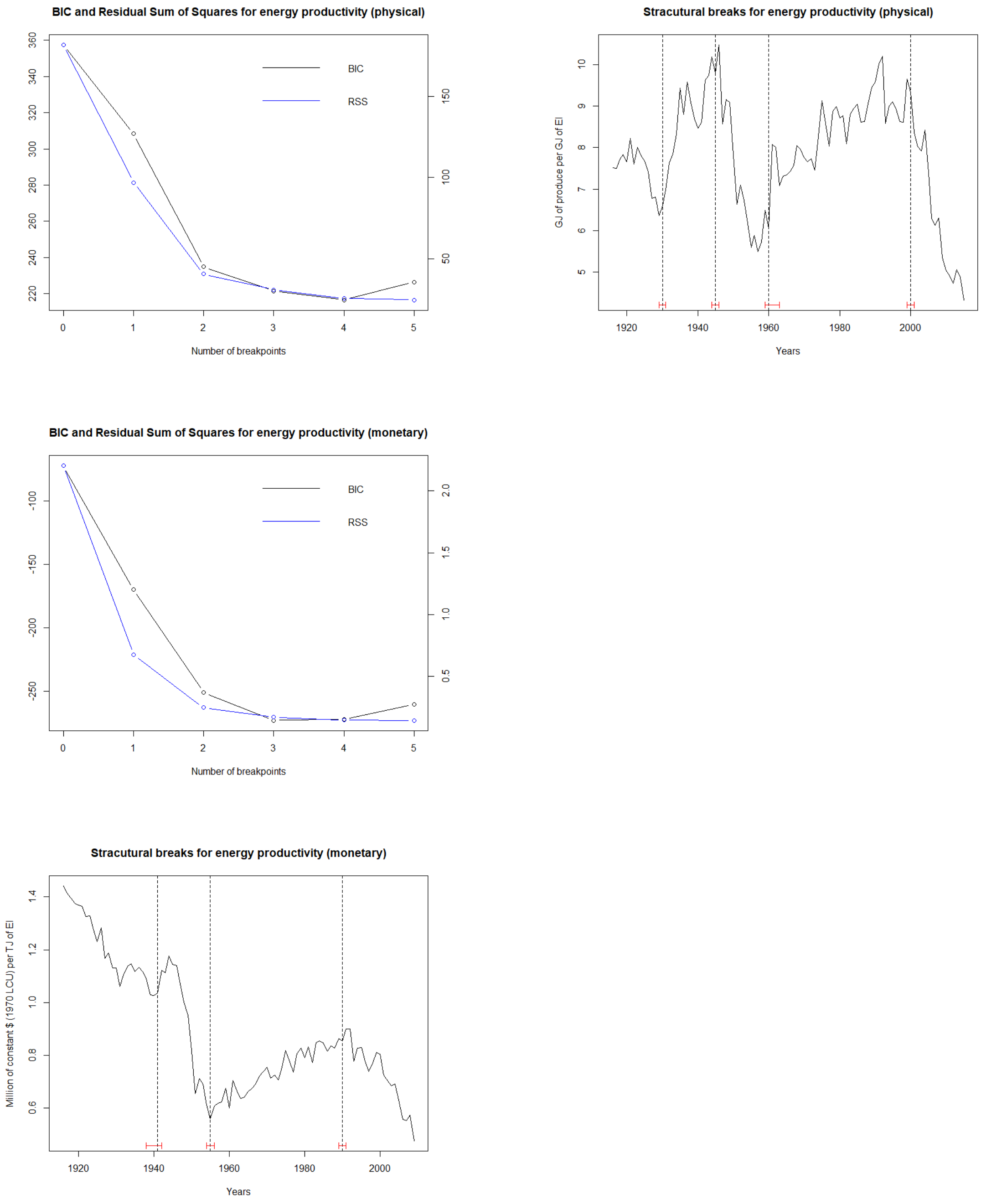


Figure D.7: Segment selections (BIC and RSS) and break points for the time series of energy productivity indicators. The dotted lines are the structural breaks, and the red lines depicts the IC at 95%

D.3.3 Average performance and rates of change by periods

This subsection shows the main results and the rates of change by using the proposed preriodisation.

Table D.5: Average performance of socioeconomic indicators, energy flows (% of NPP) and Energy Returns On Investment (EROIs) by main periods

Socioeconomic indicators		1916-32	1933-54	1955-75	1976-1997	1998-2015
1	Population [M]	6.9	10.6	19.3	32.0	44.0
2	Agr. labour [PJ]	6.1	8.4	9.2	10.4	12.3
3	Density [pop/km2]	6.2	9.5	17.4	28.8	39.6
4	Pastureland [Mha]	9.8	12.2	16.1	22.3	24.1
5	Area harvested [Mha]	0.9	2.3	3.3	4.3	4.0
6	VAA[1] (M $ 1970 LCU)	9281.0	15682.2	29287.4	63773.2	92733.3
7	GDPpc [2011US$]	1718.9	2683.9	3956.2	6739.5	9202.2
8	FP pc [GJ/pc/y]	20.6	22.8	20.4	18.2	15.7
9	Intensification [GJ/ha][2]	0.7	1.1	2.2	2.9	6.6
10	CCRA yields [GJ/ha][3]	5.1	9.4	15.9	26.1	40.7
11	Energy Prod. [GJ][4]	7.4	8.6	7.2	8.9	6.7
11	Energy Prod. [VAA$/EI]	1.3	1	0.7	0.8	0.7 [6]
Energy flows						
12	FP [PJ]	141.8	241.4	391.4	578.5	689.2
	(FP)	(0.44)[5]	(0.77)	(1.28)	(1.94)	(2.31)
13	BR [PJ]	514.5	686.8	938.6	1478.5	1631.1
	(BR)	(1.6)	(2.19)	(3.06)	(4.95)	(5.46)
14	UhB [PJ]	31495.4	30474.3	29383.8	27831.6	27630.5
	(UhB)	(97.98)	(97.07)	(95.73)	(93.24)	(92.45)
15	NPP [PJ]	32144.8	31392.3	30693.5	29849.9	29886.5
16	External inputs [PJ]	7.5	16.7	42.6	79.0	192.0
EROIs						
	Socioeconomics					
17	$FEROI$ [TJ]	0.271	0.341	0.399	0.372	0.380
18	$IFEROI$ [TJ]	0.275	0.349	0.417	0.391	0.423
19	$EFEROI$ [TJ]	19.58	15.34	9.24	7.57	4.16
20	$LabourFEROI$ [TJ]	23.36	28.45	42.62	55.64	56.51
	Agroecologics					
21	$NPP_{act}EROI$ [TJ]	1.004	1.007	1.011	1.016	1.015
22	$AFEROI$ [TJ]	0.004	0.008	0.013	0.020	0.023
23	$BFEROI$ [TJ]	0.984	0.977	0.968	0.947	0.938

[1] Aggregate value in agriculture (agricultural GDP). [2] External inputs per hectare. [3] Crop and animal production yields including crop residues as output. [4] External inputs per output including crop residues. [5]In main flows the addition does not return 100 due to rounding. [6] 1998–2009 average **Source:** GDP is from MPD (2018) for the rest see section 2.2

Table D.6: Rates of change of socioeconomic indicators, energy flows and Energy Returns On Investment (EROIs) by main periods

	Socioeconomic indicators	1916-32	1933-54	1955-75	1976-97	1998-2015
1	Population	2.01	2.49	2.81	2.05	1.24
2	Agr. labour	1.76	1.14	0.37	0.21	1.37
3	GDP pc	3.24	2.20	2.65	1.25	3.13
4	VAA	2.42	2.51	4.03	2.74	2.17
5	FPpc	-0.01	0.35	-0.26	-0.93	-0.63
6	Pastureland	1.45	1.08	1.64	0.97	0.12
7	Area harvested	5.51	2.96	1.37	0.14	0.46
8	Yields (inc. residues)	2.38	3.03	3.03	2.10	1.79
9	Yields	1.78	3.15	2.33	1.67	1.19
10	Land intensification	2.25	4.02	1.17	2.46	5.89
11	Energy prod.	0.23	-0.59	2.28	-0.09	-3.48
11	Energy prod [VAA/EI].	-1.53	-2.67	2.09	-0.06	-3.99
	Energy flows					
12	FP	2.0	2.8	2.5	1.1	0.6
13	BR	1.6	1.3	2.2	1.3	0.0
14	NPP	-0.12	-0.10	-0.13	-0.05	-0.01
15	UhB	-0.16	-0.15	-0.24	-0.14	-0.02
16	EI	4.1	5.4	2.7	3.3	6.0
	EROIs					
	Socioeconomics					
17	FEROI	0.40	1.43	0.32	-0.31	0.03
18	IFEROI	0.44	1.58	0.33	-0.29	0.77
19	EFEROI	-1.95	-2.09	0.14	-1.90	-4.78
20	Labour FEROI	0.24	1.69	2.17	1.09	-0.34
	Agroecologics					
21	NPPEROI	0.01	0.02	0.03	0.01	-0.03
22	AFEROI	2.14	2.97	2.72	1.17	0.58
23	BFEROI	-0.03	-0.03	-0.08	-0.08	-0.04

D.3.4 The disaggregated performance of the external inputs during the waves of industrialization

Table D.7: Disaggregated average, share and rates of change of the external inputs by periods

Average		1916-48	1949-85	1986-2000	2001-15
1	Feed imported	0.06	0.46	8.80	42.96
2	Fertilizers	0.25	10.11	26.38	44.35
3	Pesticides	0.00	1.23	6.26	19.38
4	Human labour	7.11	9.49	10.36	12.70
5	Machinery	0.94	7.63	14.11	40.53
6	Tractors	0.23	4.24	5.54	6.82
7	Fuel	0.36	11.48	17.34	34.84
8	Others	1.36	1.38	2.10	2.49
9	Total EI	10.31	46.02	90.90	204.07
Share on the total of the EI					
10	Feed imported	0.57	0.79	8.79	20.55
11	Fertilizers	1.82	20.79	29.40	22.64
12	Pesticides	0.01	2.21	6.85	9.74
13	Human labour	73.42	22.66	11.63	6.90
14	Machinery	7.51	16.30	15.71	18.32
15	Tractors	1.56	9.22	6.32	3.36
16	Fuel	2.46	24.69	18.97	17.15
17	Others	12.66	3.35	2.33	1.35
Rates of change					
18	Feed imported	12.9[1]	197.1	127.4	8.9
19	Fertilizers	33.4	13.8	3.7	4.4
20	Pesticides		24.5	7.8	5.2
21	Human labour	1.7	0.7	-0.7	1.5
22	Machinery	17.1	4.0	1.3	14.2
23	Tractors		4.7	-2.7	6.0
24	Fuel		5.5	3.3	13.9
25	others	9.5	1.8	2.9	0.8
26	Total EI	3.8	3.9	3.0	7.4

Note:[1] This figure is of low confidence due to we use the 1961 to estimate the imported feed between 1916–60.

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