Energy efficiency of extractive agriculture in Colombia, 1916-2015

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Agriculture lies between ecological and social systems and plays a critical role by transforming energy and materials into goods and ecosystem services. Over the course of history, however, agriculture has transitioned from being a solar-based system to a fossil fuel-based system. This socio-ecological transition (SET) of agriculture has led the sector to become a sink of energy instead of a source. Therefore, in the current crossroads of a new transition towards more sustainable agriculture, energy analysis of the past changes becomes relevant.

Energy analysis in agriculture began in the wake of the oil crisis in the 1970s and has surged again on the eve of the threats of climate change and peak oil (Hercher-Pasteur et al. 2020). Within this renaissance, conventional and agroecological approaches offer different ways to understand energy efficiency in agriculture. First, conventional energy analysis usually provides a sectoral approach focusing on socioeconomic inputs and outputs. Though traditionally the main results have highlighted sharp efficiency losses during agricultural industrialization, recent works offer contradictory results due to the differences in the scales and methods to estimate the energy returns (Hall et al. 2011). Second, with the lens of bioeconomic and agroecological approaches, Agroecological Energy Analysis (AEA) focusses on the role of internal biomass reinvested versus the dependence on external inputs in agriculture to assess the sustainable reproduction of agroecosystems in the long run. The results of the AEA highlight the increasing dependence on external inputs during this transition, but these conclusions are grounded on the analysis of temperate agricultures of the developed countries, except the case study of coffee plantations in Costa Rica. Many aspects are still unclear, such as the role of external inputs during the early stages of agricultural industrialization or the implications of livestock and land tenure structure on energy efficiency and sustainability.

This work contributes to these discussions by introducing the case study of Colombian agriculture in the long run. We rise two main questions: What are the main changes in energy efficiency and sustainability of Colombian agriculture during the SET? Do follow these changes the same path as the temperate agriculture of developed countries? To answer these questions, we aim to measure the main energy flows involved in Colombian agroecosystem throughout the twentieth century, to compare with the results of the temperate agriculture, and to set up a periodisation of changes. Our results highlight the energy efficiency gains of the blending use of internal and external inputs during the first stages of industrialization, while also stressing the extractive profile of extensive livestock breeding of Colombian tropical agriculture as a feature threatening the agroecosystem sustainability.

The adoption of an agroecological methodology allows us to evaluate the changes of the energy flows going to and coming from the society to measure energy efficiency, but it also includes the energy flows devoted to keep the reproductive functions of the agroecosystem which relate to sustainability. The basic model accounts for three living funds which transform energy or materials into goods and ecosystems services: the associated biodiversity, the soil fertility of farmland, and the livestock. These funds are linked by a set of flows going in and out of the agroecosystem to meet the societal needs and reproduce the productive live funds, like fertile soils or livestock heads (figure 1).

These flows include the actual net primary productivity (NPP) of plants composed by Unharvest Biomass (UhB), which goes directly to feed wild biodiversity, and the extraction of harvests which are split into Biomass Reused (BR) and Vegetal Produce (VP). The BR are the internal inputs recycled to feed the soil biota and the livestock, whereas the VP meets the Animal Produce (VP) at the boundaries of the systems to provide food, energy and raw materials to the society through what we label Final Produce (FP). Finally, from society comes a set of External Inputs (EI) such as human labour, tools, fertilizers, or machinery to maintain the ongoing extractive process. With these flows, we first account for the returns of each unit of energy invested into the agroecosystem (EI, BR and UhB) relative to the entire biomass output (FP or NPP), so as to assess efficiency and sustainability by mean of bioeconomic and agroecological EROIs, respectively (Table 1). Then we stablish a periodisation of the transition grounded on the structural breaks of the times series of these indicators.

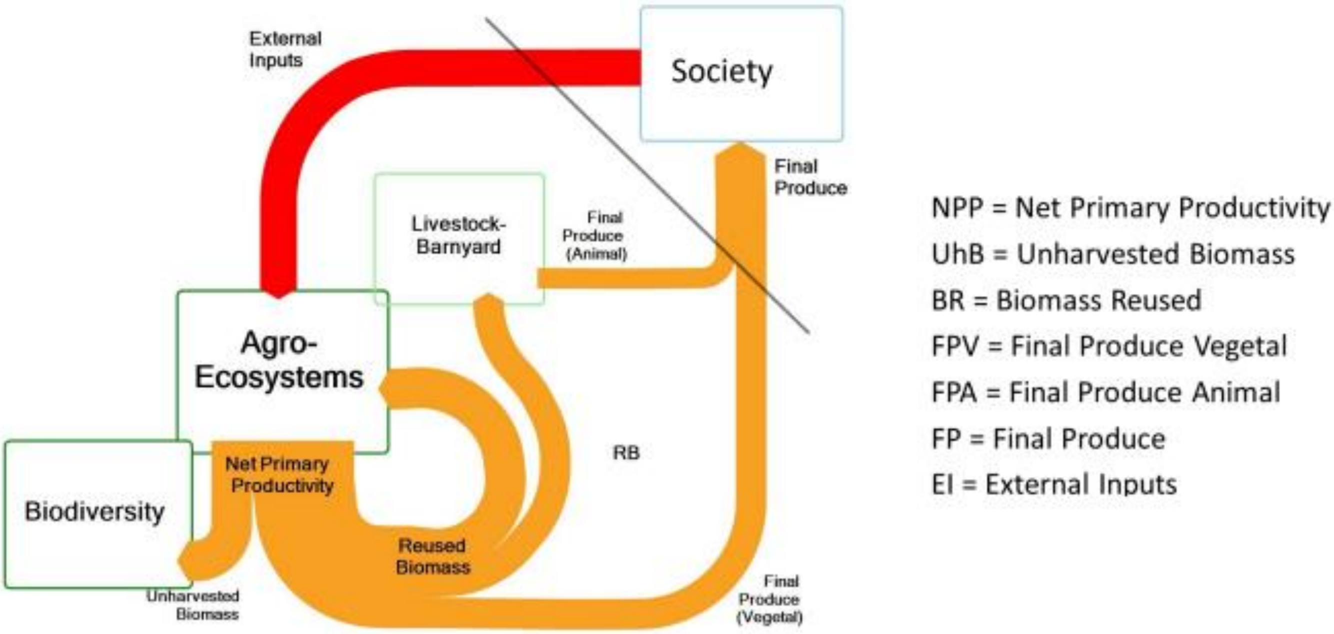

Figure 1: *Energy flows in agroecosystem model*

Bioeconomic EROIs

$$FEROI_t = \frac{FP_t}{EI_t + BR_t} \quad (1)$$

$$EFEROI_t = \frac{FP_t}{EI_t} \quad (2)$$

$$IFEROI_t = \frac{FP_t}{BR_t} \quad (3)$$

$$FEROL_t = \frac{FP_t}{HL_t} \quad (4)$$

Agroecological EROIs

$$NPPEROI_t = \frac{NPP_t}{EI_t + BR_t + UhB_t} \quad (5)$$

$$AFEROI_t = \frac{FP_t}{EI_t + BR_t + UhB_t} \quad (6)$$

$$BFEROI_t = \frac{UhB_t}{EI_t + BR_t + UhB_t} \quad (7)$$

Table 1: *Bioeconomic and agroecological Energy Returns On Investment (EROIs) ratios*

To fit the model, we gathered information from historical official records before 1960 and current databases, specially FAOSTAT from 1961 onwards, to collect data on land uses, agrarian production (agriculture, livestock, and forestry), and external inputs such as fertilizers, machinery, and human labour. To get the main variables we use historical factors of roots, weeds, by-products, nutritional requirements, weight changes of the livestock, gross calorific value, and embodied energy among others.

The main results show that the NPP fell by 10% moving from 32 million of TJ in 1916 to 29 in 2015. UhB almost shared the entire NPP in 1916 and it was 92% in 2015, being forest biomass 75% which stresses the potential to store carbon and to feed wild species of the country's ecosystems (figure 3 a and b). Though extraction seems a thin piece of the NPP, since it moved from 2% to 7.5%, this portion is two and three times larger than the current extraction in Spain (Guzmán et al. 2017) and Austria (Gingrich & Krausmann, 2018), respectively.

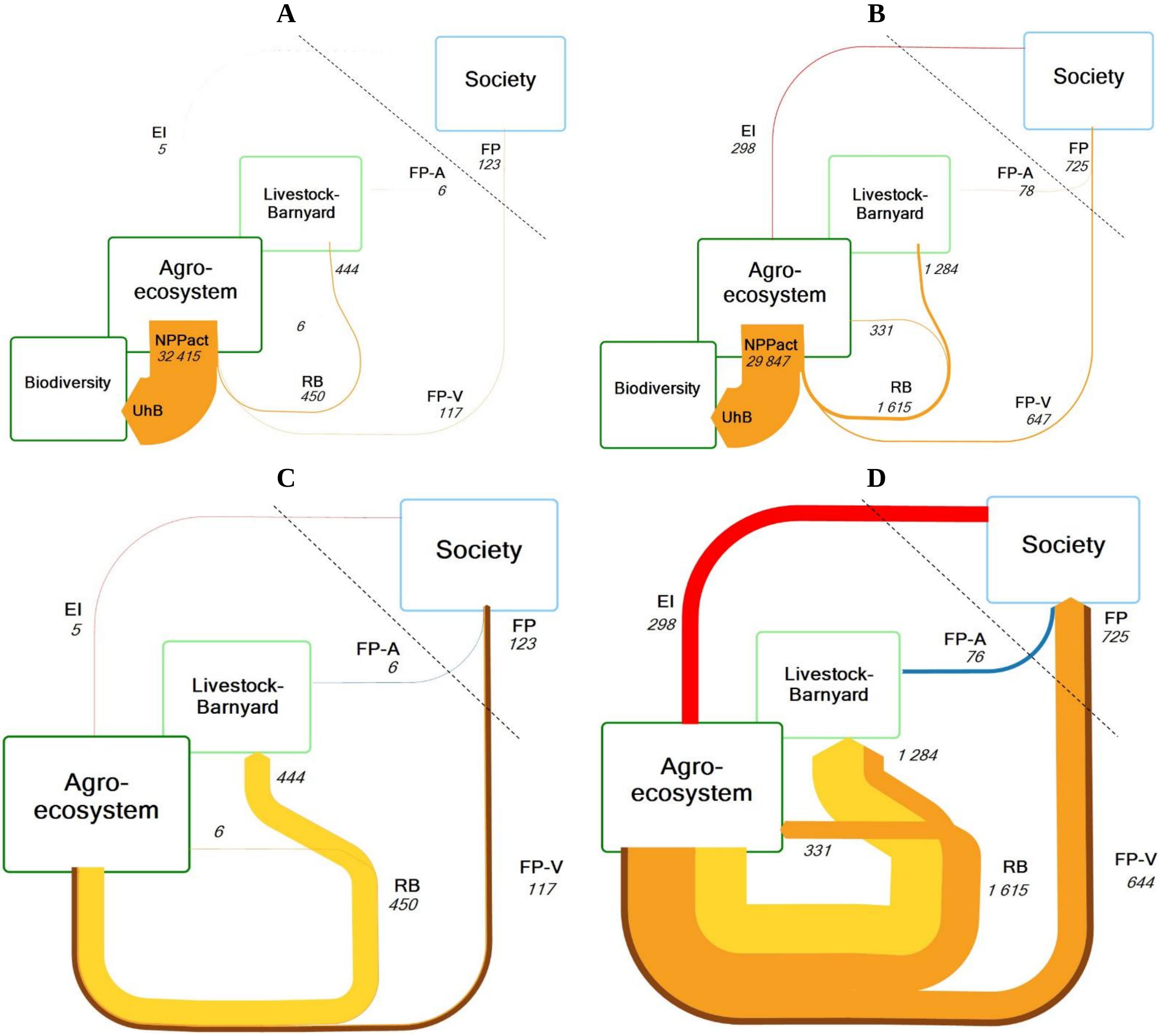

Figure 2: *Main flows of Colombian agroecosystem (A and B) and the zoom of its extraction (C and D) in 1916 and 2015*

If we focus on domestic extraction of biomass (figure 2 c and d) two main changes arise. First, the displacement of pasture as the main source of animal feeding which moved from 80% of the BR in 1916 to 40% in 2015, and second, the reduction of forest share into the FP from 76% to 17% along the analysed period. These changes are in accordance with the intensification of livestock breading and the energy transition during the urbanization process, but they are also related to the agricultural production take-off of cash crops, especially of fodder and tropical crops with high yields, residues, and energy intensity such as sugarcane, banana, and oil palm.

The EI moved from 5.4 PJ in 1916 to 298 PJ in 2015 (figure 3). During this process we identify three structural breaks in the time series which allow us to characterize four waves of agricultural industrialization. First, the changing of organic system period (1916-48), featured by low average consumption of external inputs (10.3 PJ), mainly human labour (73%) and agricultural implements on the rise (13%). During the second period (1949-85), the consumption of "modern" inputs such as synthetic fertilizers (N, P, K), pesticides, fuel, machinery, and tractors reached 69% of the EI. This spread of the green revolution package went deeper during the third period (1986-2000) when the use of fertilizers and pesticides experienced a threefold increase (from 11.3 PJ to 32.5 PJ). However, the new feature of this period was the entering of feed from international markets which led to the dominance of the land saving inputs during the process of intensification, reaching 45% of the EI. Finally, the agricultural intensification that began during the previous stage moved up quickly in the last wave of industrialization

(2001-15). The use of energy in agricultural land climbed from 4 GJ per ha in 1985 to 10 GJ per ha in 2015, featuring the main growth of all sort of inputs including the more traditional ones, such as human labour.

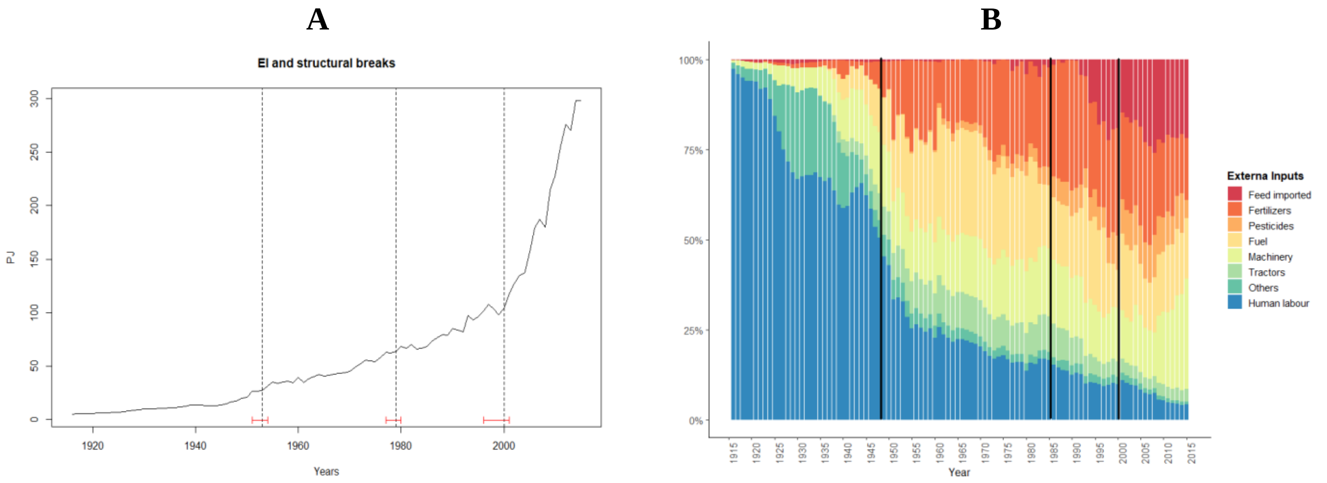

Figure 3: *Structural breaks for external inputs (A) and its composition (B)*

The comparative assessment of the energy efficiency of Colombian agriculture in figure 4 highlights, first, that the Colombian levels of final energy returns (FEROI) are among the lowest in the AEA sample, and second, that there were efficiency improvements. In levels, the Colombian case matches some current cases with high livestock components like the Vallès County in Spain, the Grünburg village in Austria, and Quebec Province in Canada. The only comparable case in Europe from the very beginning is Manacor municipality (Mallorca Island) in 1860, where latifundia-led farming predominated (Tello et al., 2018). Despite the low levels, there were some gains in efficiency and Colombian trend moved in the opposite way to the rest of the cases until the mid-1960s, from 0.27 to 0.44. However, thereafter energy efficiency dropped to 0.36 and stalemated from the early 1980s. The only comparable cases in trend are the late-colonizing counties of the arid Great Plains in the US, which shifted from livestock colonization to intensive grain production during the First Globalization such as Chase, Nemaha and Decatur counties.

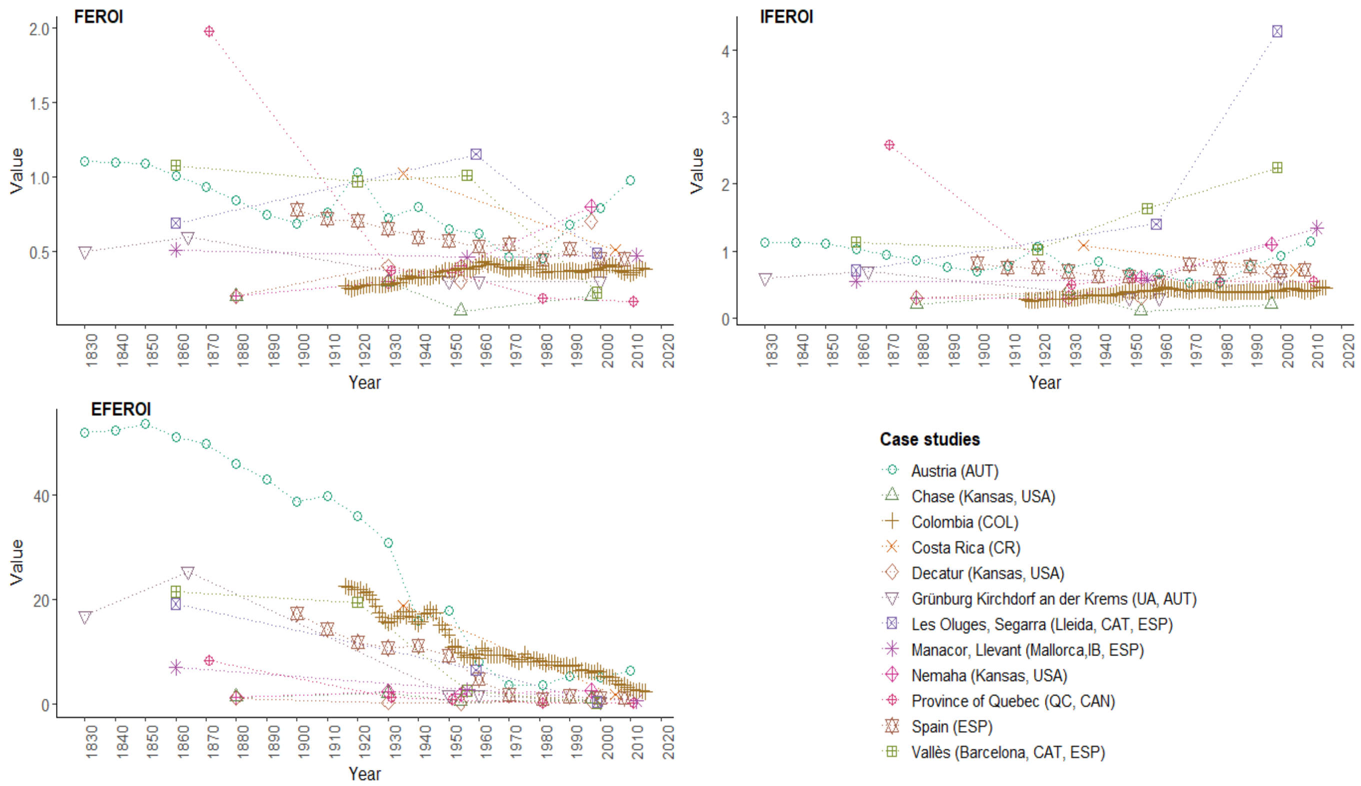

Figure 4: *International comparison of energy efficiency of Colombian agriculture: final energy returns (**FEROI**), internal returns (**IFEROI**), and the external returns (**EFEROI**), 1830-2015*

The internal returns (figure 6 IFEROI) show that the low levels of the total efficiency were driven by the high biomass reuse in these areas of early agricultural colonization under extensive livestock breeding and latifundia structures, namely the Great Plains and Manacor, but these two features also fit well the Colombian case. Although the increase of internal energy returns up to the 1960s gives the impression of BR abandonment as industrialization advanced, as occurred in Europe, this growth did not follow the European path. There was a dynamic growth of BR together with a faster increase of FP up to 1975, and only from the 1980s onwards, when agricultural and livestock sectors began to intensify, the BR abandonment pattern took place. Just as grain intensification in the Great Plains led to the end of energy efficiency improvements, so intensification in Colombia did under tropical agriculture during the Second Globalization leading to a reduction of internal energy reuses and a loss of efficiency.

Eventually, the returns on external energy inputs (figure 6 IFEROI) are similar in trend and level to the other cases, which confirms the increasing dependence on fossil fuel-based inputs of tropical agriculture. However, this process differs in the timing. Though advanced organic agriculture developed latter in Colombia than in temperate agricultures, the stagnation during the shocks of the Great Depression, the Spanish civil war and the Second War World was a common trend. After that, industrial intensification spread in temperate agricultures, but this process was slower in Colombia; the path of increasing external inputs dependence in the country began with the Second Globalization.

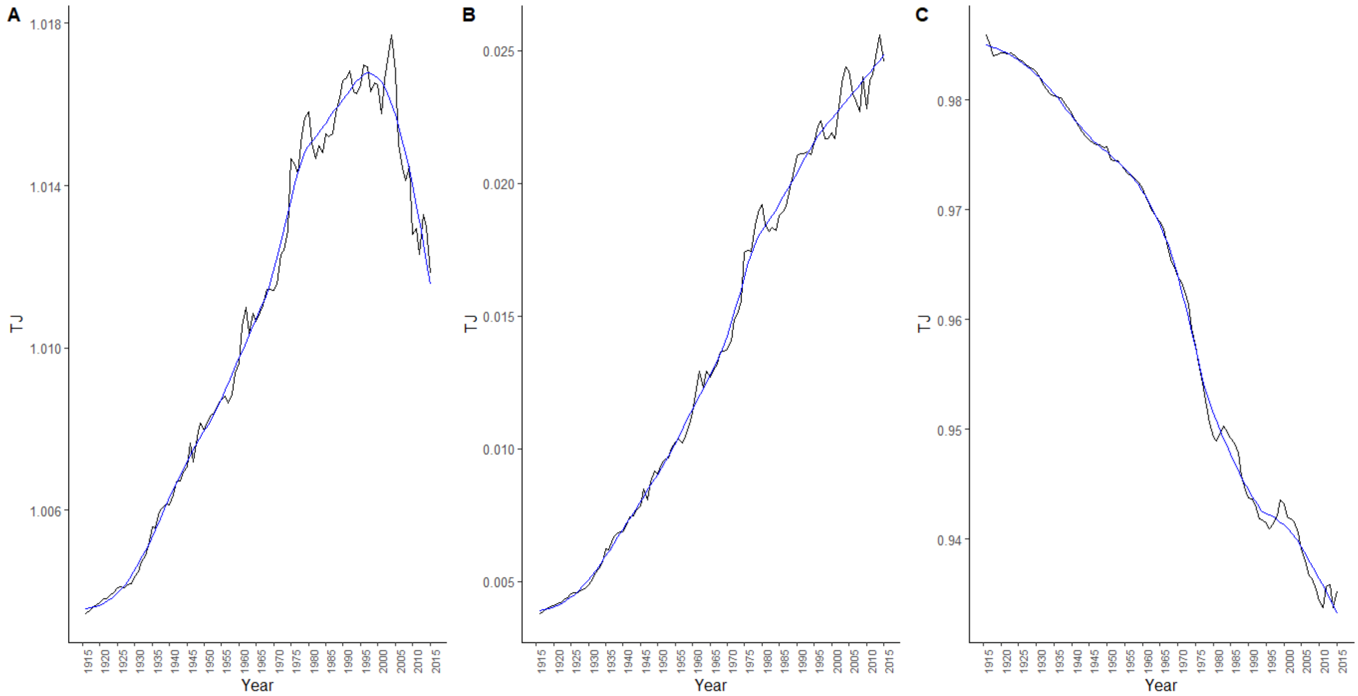

Figure 5:*Energy returns on sustainability for the net primary productivity -**NPP EROI**- (A), the agroecosystem -**AFEROI**- (B), the ecosystem colonisation -**BFEROI**- (C) in Colombia, 1916-2015*

Regarding the assessment of the agroecosystems' sustainability, first, the energy returns in terms of NPP (figure 7a) performed slight but with continued gains until 1975. It seems that there was a positive effect of the blended use of internal and external inputs on the reproductive capacity of the system. However, as shown before, the 1980s agrarian change also led to stagnation and fall since 2000 indicating a new pattern of loss of the agroecosystem sustainability. Secondly, the agroecological energy returns (figure 7b) grew more than 8 times between 1916 and 2015 which indicates an improvement of the energy productivity of FP conceived as a coproduction with nature. Different to the NPP returns, there was not a significant fall in energy efficiency, but a gradual slowdown in the rates of growth since 1998. Thirdly, the proportion of inputs addressed to sustain biodiversity (figure 7c), which gives information on the colonization of agriculture on natural ecosystems, is very close to 1 faithfully reflecting the weight of natural systems in the country. Despite its reduction, the Colombian agroecosystem has diverted the largest portion of its energy NPP in form of UhB used to sustain and reproduce the associated biodiversity.

Lastly, we tested for structural breaks on the times series and related them with the timing process according to the role of the state policies, peasants' protests, and the reactions of agrarian elites on the configuration of the agriculture in each of the five periods defined by the agrarian and economic history literature of the country and the region (Bejarano, 2011; Kalmanovitz & López, 2006; Bértola & Ocampo, 2012). During the export-led growth (1916-32), advanced organic agriculture expanded under the coffee economy. The increasing demand for land, labour, and agricultural tools eroded the traditional tides of the Hacienda system while rising a dilemma between the international oriented interests of the landlords and the subsistence of the family farming, which led to several food crises and increasing peasant unrest.

Thereafter (1933-54) the shocks of the Great Depression and World War II boosted the state intervention. Despite the state made some attempts to redistribute land to the peasants, and coffee production expanded under the family farming colonization process, the support to the export sector favoured the commercialization and the promotion of domestic commercial farming under producer associations. Some redistribute land policies took place again during the 1960s, but the main approach during the following period (1955-75) was to increase agricultural output by modernization. This aim achieved with the promotion of the import of agricultural inputs, sectoral credits, technical advice from abroad, experimentation centres, and the expansion of the road network to integrate the domestic market.

Although for a while agriculture became the main provider of food and raw materials, during the period of deregulation and the setting of the new agro-export model (1976-1997), the lack of access to land and capital of the small farmers and its radicalization under guerrillas groups went in parallel to the agrarian elites appropriation of green revolution technologies and the capture of the state to helps its entering in international markets with the Chicoral pact of 1972. A new colonization stage of the lowlands of the southern helped to reduce the social unrest for a while, but it was at the expense of increased deforestation in the rainforest which ended in new pastures for landlords and coca crops expansion under small family farming. Finally, agrarian intensification and expanding agricultural trade since the beginning of the new century have led to tropical specialization and food dependence; a process achieved with the use of violence as a tool for land dispossession and the state support to the tropical export sector (Vargas & Uribe, 2017).

To conclude, this work shows that compared to the AEA of the temperate agricultures of developed countries, the energy efficiency and sustainability indicators of the tropical agriculture in Colombia improved with the blended use of internal and external inputs until c.1980. However, agricultural intensification under the tropical export model led to a trend of decline in efficiency thereafter. The early frontier expansion under livestock, such as in the Great Plains, and the unequal land tenure structure like in Manacor, seem to be behind the low levels of final energy returns in the beginning of the series, and its subsequent gains with intensification. In the case of Colombia, during this process of intensification the agrarian elites appropriated the benefits of the green revolution technologies and shaped trade and domestic policies to boost its international market-oriented interests. Thus, the extractive metabolism of Colombian agriculture has gone hand in hand with the extractive traits of its social and political institutions.

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