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LCA Towards Sustainable Agriculture: The Case Study Of Cupuaçu Jam From Agroforestry

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Abstract

Appropriate design of agricultural systems for the regeneration of deforested lands in critical areas, like the Amazon, may be an effective action to restore forest ecosystem functions and to mitigate biodiversity loss and climate change. Among the possible strategies, agroforestry may represent a viable trade-off between economic and environmental aspects. In this study, the production of a jam made of fruits from agroforestry was analysed from a Life Cycle Assessment (LCA) perspective. The agroforestry system investigated was implemented in a reforested area of the Peruvian Amazon. A *cradle-to-grave* approach, from the cultivation phase to the end-of-life of the jam, was adopted. Additionally to LCA, the focus is on the agricultural phase and, in particular, on the comparison of alternative agro-ecosystems from an environmental viewpoint. Therefore, LCA indicators are integrated with biodiversity indicators to account for the ecological dimension. Preliminary results highlight the benefits of producing jam from fruits harvested in an area of the Amazon reforested via agroforestry, as well as the high variability of environmental impacts due to the differences in the alternative agricultural systems considered.

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Keywords: LCA, Agroforestry, Biodiversity, Agro-ecosystems

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1. Introduction

Agriculture is responsible for more than 25% of global greenhouse gas emissions [1], for the majority of water consumption and contamination [2, 3] and it is among the main causes of deforestation [4]. When agricultural systems are located in ecological hotspots (e.g., the tropical forests), the impacts on the environment become even more crucial. Nevertheless, the magnitude of those impacts may depend on the adopted agricultural approaches and practices. Indeed, agricultural ecosystems characterized by reduced external inputs (e.g., fertilizers, pesticides) and by the presence of perennial crops might be an effective action to mitigate climate change and to maintain important ecosystem services at the base of human well-being. Moreover, the critical role of the agricultural phase clearly emerges when the environmental performances of processed food are evaluated along their entire life cycle [5, 6] through the Life Cycle Assessment (LCA) methodology. Among the major challenges of LCA studies in the agri-food sector, the multi-functionality (i.e., the simultaneous food provisioning and maintenance of ecosystem services) and the heterogeneity of agro-ecosystems emerge as crucial elements [7]. In addition to the material and energy balances considered in LCA, it is thus necessary to broaden the scope of the analysis in order to encompass the whole production system of agricultural products and to extend the set

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of indicators in order to include the ecosystem's structure and services. For these reasons, an agri-food life cycle analysis was here integrated with (i) a sensitivity analysis considering alternative agro-ecosystems practices and (ii) ecological indicators. In this preliminary analysis, two standard biodiversity indicators (i.e., Simpson and Shannon [17]) were considered to enlarge the perspective from the agricultural product to the whole agro-ecosystem. As a case study, the environmental dimension of a Peruvian cupuaçu (*Theobroma grandiflorum*) jam was assessed.

1.1. The case study: cupuaçu (Theobroma grandiflorum) jam from agroforestry

Cupuaçu is a tropical rainforest tree belonging to the same genus of cacao (*Theobroma cacao*), and it is an emerging marketable product [8]. The tree is quite common throughout the Amazon basin and widely cultivated in Colombia, Bolivia, Peru and in the north of Brazil. It is often planted in agroforestry systems to produce both seeds (similar to cocoa beans) and pulp's derivatives, such as juice and jam. This latter is obtained by mixing sugar cane and the white fruit pulp, which has a unique fragrance. The present study investigates the supply chain of a cupuaçu jam from agroforestry, realized by Agroindustria Delicia Ecológica ADE S.R.L (ADE from now on) in the Madre de Dios Region (Peru), until the commercialization of the product in Italy by Equo Mercato [9]. The analysed raw material is cultivated in an agro-ecosystem, created over a deforested and degraded land and that includes several plant species (up to 15) as well as a cover crop (Kudzu, *Pueraria phaseoloides*).

2. Goal and scope definition of the LCA of cupuaçu jam

The LCA of cupuaçu was performed following the Product Category Rules (PCR) for *Jams fruit jellies and marmalades* [10], in compliance with the General Programme Instruction of the International EPD System and the ISO standards [11, 12, 13]. The PCR were developed for the Central Product Classification (CPC) Group 21494, which includes jams, fruit jellies, marmalades, fruit or nut puree and fruit or nut pastes. Considering the PCR guidelines, the production system was modelled following the flow chart reported in Fig.1. A *cradle-to-grave* LCA was performed and the considered unit processes were grouped into upstream, core and downstream. The upstream processes comprise the cultivation and the transportation of the fruits from the field to the jam production plant, the production of the ancillary ingredients (i.e. sugar cane) and the primary (i.e., glass pots and caps), secondary, and tertiary packaging production. The in-field practices are carried out by operators without using any machine and any pesticides. Only a self-produced fertilizer is applied on the field (the direct field emissions due to fertilization, e.g., N_2O or NO_3, were not considered in this first assessment). It is composed of 46% of water, 4% of humus, 45% of manure and animal urine, and the remaining 5% of additives like calcium (1%), phosphate rock (2%), zinc (1%), and the Island guano (1%). The core processes include jam manufacturing, thermal treatment for sterilization, and packaging processes. Both upstream and core processes are located in the Madre de Dios region in Peru. Finally, transportation to Italy and delivery to retailers distributed over the Italian peninsula were considered as downstream processes. The study was conducted with the SimaPro 8.4 software and the Ecoinvent 3.3 database. The impact assessment method selected was CML-IA baseline and the impact categories considered were: abiotic depletion (AD), global warming (GW), ozone layer depletion (OD), photochemical ozone creation (POC), acidification (AC) and eutrophication (EU).

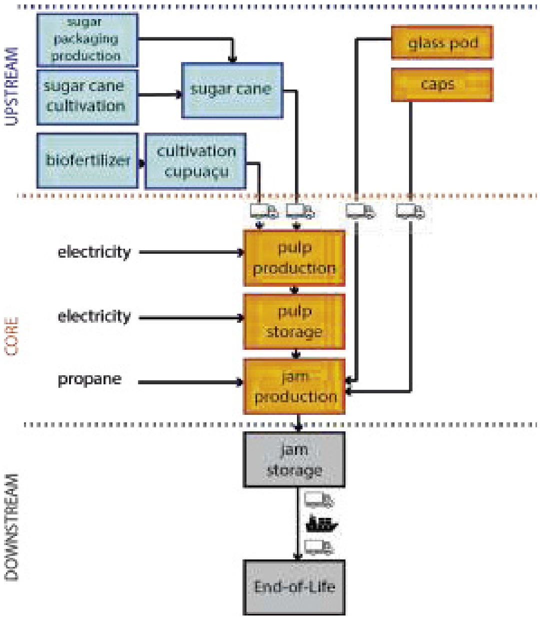

Fig. 1. Flow chart of the cupuaçu jam production, from the cultivation of the ingredients in Peru to the end-of-life of packaging materials in Italy.

The declared unit (DU) of the study was 1 kg of jam including packaging (packaging weight not included in this 1 kg). Since the cupuaçu jam is sold in pots containing 212 g of product, the DU corresponded to 4.72 pots. The ingredients of the cupuaçu jam are fruit pulp (57%) and sugar cane (43%), without any use of additives or preservatives.

The allocation procedure regarded the four saleable products obtained from the cupuaçu fruit: jam, juice, soft drink and seeds. Specifically, economic allocation factors (λ_i) obtained through Eq. 1 were applied. In the equation m_i is the mass and δ_i is the economic value of each considered product, which were both provided as primary data by the ADE company.

$$\lambda_i = \frac{\delta_i m_i}{\sum_i \delta_i m_i} \qquad (1)$$

The Life Cycle Inventory (LCI) was built in collaboration with the producer (ADE) and Simbio, an Italian partner of the producer. Data were collected between 2015 and 2017 in the Peruvian region of Madre de Dios.

3. Life Cycle Inventory

The majority of data was directly provided by the jam producer. The average weight of a cupuaçu fruit is 896 g divided into pulp (35.9%), seeds (16.9%), shell (43%), and placenta (4.2%). 70% of the pulp (i.e. 25% of the fruit) is used for jam production and, therefore, 2.26 kg of fruits are required to produce the considered DU. The amount of fruits necessary to produce 1 kg of jam requires the occupation of 11.3 m^2 year of agricultural land considering a yield of about 2000 kg of fruit per hectare per year. A peculiar characteristic of the cultivation is the fertilization strategy: the presence of leguminous species like Pacae (*Inga brachyptera*) guarantees low fertilization dosages, which is entirely satisfied with a self-produced fertilizer. This latter is mainly composed of ingredients with animal or plant origin (i.e., 86% in weight from manure and grass). Additional primary data concern:

- upstream processes: dosage (0.84 kg tree^{-1} year^{-1}) and recipe of the self-produced fertilizer, water and ancillary products inputs (no irrigation required for cupuaçu), transportation and packaging;
- core processes: electrical and thermal energy required for pulp and jam production;
- downstream processes: distances from the Peruvian production plant to the Italian retailers.

On the other hand, secondary data were used for the environmental exchanges of sugar cane and packaging production.

4. Life Cycle Impact Assessment

The results obtained through the CML-IA method are reported in Table 1 (absolute values) and in Fig. 2, divided into upstream, core and downstream processes.

Table 1. Impacts on six categories referred to the DU

Impact Category	Units	Total	upstream	core	downstream
AD	kg Sb eq	2.6E-05	2.5E-07	2.6E-05	2.3E-08
GW	kg CO2 eq	3.6E+00	1.5E-01	1.9E+00	1.6E+00
OD	kg CFC11eq	5.3E-07	2.3E-08	2.0E-07	3.1E-07
POC	kg C2H4 eq	1.2E-03	4.0E-04	5.1E-04	3.2E-04
AC	kg SO2 eq	2.0E-02	8.0E-04	1.1E-02	8.2E-03
EU	kg PO4^{3-}eq	3.0E-03	3.2E-04	1.5E-03	1.2E-03

The contributions of the agricultural phase (green bars) range between 1% for abiotic depletion (AD) and 32% for photochemical oxidation (POC), mainly due to pre-harvest burning in sugar cane cultivations. It must be reminded that the field emissions due to fertilization of cupuaçu were not considered in this first assessment of the environmental impacts of jam production. Core processes are responsible for 51% of the GW potential and almost entirely for the abiotic depletion (99%), both related to the use of fossil fuels (i.e., propane) during the jam production process. Finally, the long transportation distances covered for the distribution of the product in Italy represent an important cause of impact for the six considered environmental categories. Analyzing the existing literature [14], it emerges that the life-cycle GW emissions (i.e., 3.6 kg CO_2 eq. per kg of jam) are comparable to the ones of strawberry jam and nut cream (2.93 kg CO_2 eq. and 3.76 kg CO_2 eq., respectively). Nevertheless, the contribution of upstream processes in this case study is significantly lower than what found in the literature [14]: in the case of cupuaçu jam, upstream processes cause 4% of total GW, while this contribution increases up to 83.6% in the case of nut cream and up to 61.1% in the case of strawberry jam.

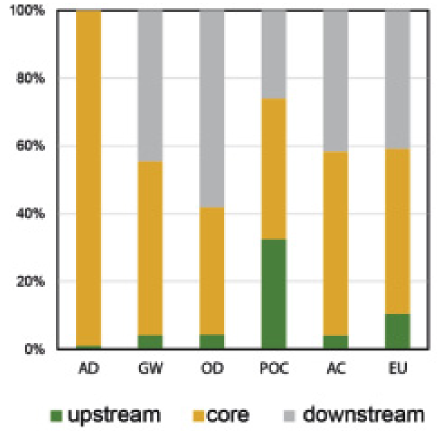

Fig. 2. Life Cycle Impact Assessment (LCIA) results obtained through the CML-IA baseline method, considering the impact categories required by the EPD system. Results are grouped into upstream, core and downstream, according to the flow chart reported in Fig.1.

Nevertheless, the outcomes of this comparison may be affected by an additional evaluation of direct field N_2O emissions: while in the present study these emissions were not considered, it is unclear if and how they were accounted for in the literature study [14].

5. From product back to agroecosystem: how the agroecosystem influence the environmental impacts

To investigate how differences in agricultural practices can influence the environmental impacts of a product, the LCI of four additional alternative agro-ecosystems for the cupuaçu production was built using literature data [15, 16]. The four systems considered are the combination of two crop mixes (A and B) and two fertilization strategies (full and low). In particular, configuration A includes, together with cupuaçu, Brazilian nut, peach palm and annatto, while configuration B includes cupuaçu, peach palm and rubber tree. As for fertilization, the “full” fertilization strategy was defined according to the tentative recommendations for each crop in the region [18], while “low” fertilization corresponds to the application of approximately 30% of the “full” doses (detailed information about the fertilization strategy are reported in [15, 16]). Fig.3 shows the impacts of 1 kg of cupuaçu produced through the five agro-ecosystems compared, pointing out that agricultural practices vary widely in terms of environmental burdens. The cupuaçu produced by ADE is characterized by the lowest impacts, mostly due to the lower fertilization rates (0.6 g_N tree^{-1}) with respect to the alternative agro-ecosystems (B full: 194 g_N tree^{-1}, B low: 48 g_N tree^{-1}, A full: 71 g_N tree^{-1}, A low: 12 g_N tree^{-1}). When the alternative agro-ecosystems are compared with the ADE one, the range of impacts for 1 kg of fresh cupuaçu fruit increased from +17% (EU and GW) to +98% (OD). The role of the fertilization strategy clearly emerges from the results, since the agroecosystems with a “full” fertilization strategy (i.e., AF B Full and AF A Full) are characterized by the highest impacts. Referring to the whole life cycle, the contribution of the upstream phase increased in all four alternative systems: AD (the smallest impact category) increased from 1% to 5%, while POC (the highest contribution of upstream processes) increased from 32% to 35% with respect to the ADE case.

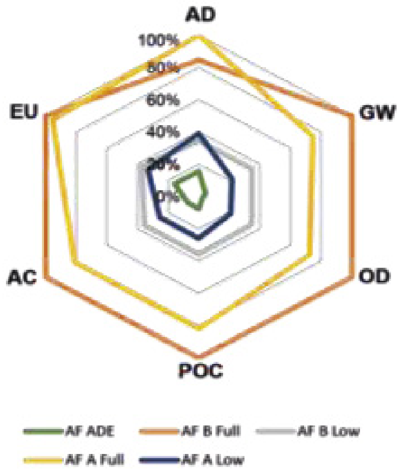

Fig. 3. LCA sensitivity analysis on cupuaçu production. Each line represents an alternative agricultural practice. For each impact category, the product with the highest environmental impact is characterized by a value of 100%. (the product under study is labelled as “AF ADE”, where AF means “AgroForestry”, while the other alternatives (AF) are labelled by combining species composition (B and A) and level of fertilization (Full or Low)).

As a second step, the alternative cupuaçu agro-ecosystems were compared in terms of biodiversity, which can be considered as a proxy of agro-ecosystems multi-functionality [19, 20]. Two standard biodiversity indicators, Simpson and Shannon [17], were estimated to assess the plant species diversity in the systems considered. These indices are based on the frequency of each species in the plant community. The biodiversity results for the five agro-ecosystems analysed are shown in Fig. 4. According to the Shannon index, the ADE system is the best alternative (light green bar); conversely, agroforestry A is the best option according to the Simpson index (yellow bar). The different results depend on the nature of the biodiversity indices: AF ADE ranks first for the Shannon index because it is characterized by the highest species richness (12 vs. 4 and 3 species for AF A and AF B, respectively). On the other hand, AF A ranks first for the Simpson index because species frequencies are closer to an even distribution compared to those of AF ADE and AF B. The values of the two indices have been calculated also for a virgin rainforest to provide a benchmark. Simpson and Shannon indicators for a virgin forest in the Peruvian Amazon would be on average 0.88 (+19% than the average of agroforestry systems) and 2.50 (+40% than the average of agroforestry systems), respectively. For the sake of completeness, by contrast, both indicators would be null in the case of cupuaçu monoculture.

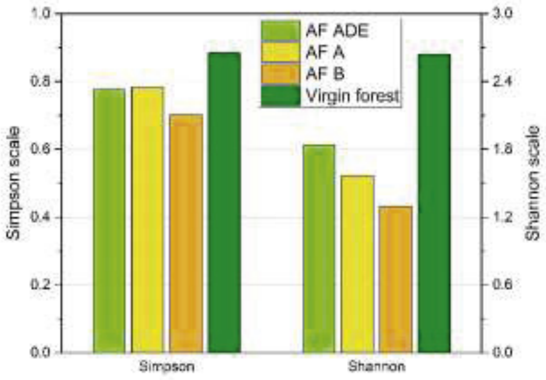

Fig. 4. Biodiversity indices of different cupuaçu production systems. Each bar represents the value of the indexes (Simpson and Shannon) calculated on the basis of the relative abundance of each tree species for a given agroecosystem. The maximum value of the Simpson index is equal to 1, while for Shannon it depends on the number of species involved (*n*) and it is achieved when species are uniformly distributed (probability equal to *1/n*). The values of the two indices for a virgin rainforest in Madre de Dios are also reported for the sake of benchmarking.

6. Discussion

The performed LCA allowed us to highlight the unit processes that mainly contribute to the environmental impacts of a cupuaçu jam, as well as the role of the agricultural phase at the base of this supply chain. The agro-ecological approach adopted by ADE minimized the environmental impacts of the produced jam, making it comparable with jams manufactured from fruits cultivated in the same country where the product is sold [14]. Nevertheless, improvements in the methodological approach and in the production process could influence the results. In particular, regarding the assessment, future research will focus on the estimation of field emissions due to the application of fertilizers (e.g., N_2O and NO_3) and land use change, which can strongly influence the overall results. On the production side, given the results of this study, ADE has planned interventions regarding the jam manufacturing, especially with regard to the energy supply.

The analysis of the environmental sphere of the analyzed agricultural product was improved by broadening the perspective from the single product to the whole agroecosystem and integrating the LCA approach with other ecological indicators, to compare alternative agro-ecosystems aimed at cupuaçu production. The results obtained from both the LCA and the biodiversity assessment performed in this study confirmed the high variability of impacts depending on agricultural practices. Moreover, the comparison with the virgin rainforest gives an idea of the magnitude of plant species biodiversity loss due to deforestation. The performed assessment could be further improved with additional ecological indicators regarding the multi-functionality of agro-ecosystems (e.g., ecosystem services like carbon storage), as well as social aspects regarding both the production (e.g., work conditions) and the nutritional sphere (e.g., diet diversification). Finally, production systems like the one proposed by ADE foster the regeneration of forest-like agro-ecosystems and the consequent sustainable coexistence between humans and natural forests, and this benefit should be captured by future assessments.

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