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Community reconstruction of biocultural landscapes. Application in the Kokonuko Indigenous Territory

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ABSTRACT

To reverse the socioecological impacts derived from the Green Revolution in the indigenous territory of Puracé (Colombia), an agroecological transition proposal elaborated by the Kokonuko community through participative action research is presented with a respectful approach to the indigenous knowledge of this community and their *Cabildo*. Reversing the detrimental consequences of industrial agriculture requires reducing dependence on non-renewable energy inputs and their replacement with nature-based solutions based on biocultural heritage of the community. This study compares traditional agricultural management based on ethnobotanical characterization, biophysical energy analysis, and landscape evaluation, describing the different agricultural systems that compose the basis of the proposal for this agroecological transition carried out with the Kokonuko people. The results show that traditional management from socially integrated polyculture of some pilot farms is multifunctional, high agro-diverse, food-sovereignty and traditional medicine oriented. Besides, it has a high energy efficiency compared to industrial monoculture management more related to agrochemicals and direct production to the market. The performance of traditional management in the indigenous territory, previously optimized in pilot farms, would facilitate the reconstruction of biocultural landscapes, strengthen indigenous governance, and recover traditional multifunctionality that assured food sovereignty of the community that was the depository of indigenous knowledge. The conservation of seeds by the community is essential to generate a global transformative change towards sustainability.

1. Introduction

The Green Revolution, which began in the 1960s, promoted agricultural intensification based on plant breeding, leading to the reduction of crop diversity to a few high-yield commercial varieties and the homogenization of agrarian landscapes (Sietz et al., 2022). At global level, this has entailed the most remarkable transformation of cultivated lands in recent centuries, evidenced in a rapid and deep landscape simplification (Tilman et al., 2001). These changes generated loss of forests and land degradation worldwide (Steffen et al., 2015) and have also been detrimental for many indigenous and local communities, producing loss of cultural identity and indigenous knowledge for management of their territories, reducing their sacred sites and practice of traditional agriculture (Toledo, 2013; Loh and Harmon, 2014; Martínez Alier, 2023).

Currently, the difficulty in sustaining global patterns of production, energy supply, and consumption is affecting 3200 million people in the world, producing economic effects that put indigenous-peasant communities and the planet's biodiversity at risk (IPBES, 2018; Otero et al., 2024). Consequently, it is necessary to generate agroecological models that allow the reconstruction of biocultural landscapes, moving away from the development model based on infinite growth (Hickel, 2019; United Nations, 2021; Slameršak et al., 2022) to face the challenge of guaranteeing the food production required by a growing population (Tilman et al., 2011) while conserving biodiversity and attaining sustainability (IRP, 2019).

Two nature conservation strategies are confronted with addressing this challenge (Perfecto and Vandermeer, 2010; Balmford et al., 2012; Kremen and Merenlender, 2018). The 'land sparing' strategy has been

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implemented in the declaration of more than 25,000 nature conservation areas in the world from 1950 onwards (Cifuentes et al., 2000), by expelling in most cases the indigenous communities from the land that they inhabited, while at the same time industrial agriculture is promoted in other areas through the extractivist expansion of uniform monocultures with high-yield patented seeds and agrochemicals (Infante-Amate et al., 2022). Despite the proven detrimental impacts of these agro-industrial ways of farming for biodiversity, the land-sparing approach keeps promoting them under the premise that this agricultural intensification allows setting aside more land for nature conservation (Picado-Umaña, 2013). The effectiveness for biodiversity conservation of this land-sparing paradigm has been widely put into question (Casas et al., 2014; Agnoletti et al., 2015; Marull et al., 2018), together with the unjust green land grabs exerted over indigenous and peasant communities (Ojeda, 2013; Fairhead et al., 2013; Urrego-Mesa, 2021a).

Conversely, the 'land sharing' is an alternative conservation paradigm that has shown how traditional food-producing systems, based on polycultures and landscape mosaics, can maintain biodiversity with high productive yields (Altieri, 1999; López García and Guzmán, 2012; Nicholls and Altieri, 2012). Land-sharing complex matrices can host a great deal of farm-associated biodiversity, while providing ecological connectivity among nature protected sites and indigenous sanctuaries and, at the same time, food provisioning to farmers, communities and societies (Tscharntke et al., 2005; Phalan et al., 2011; Duru et al., 2015; Tittonell, 2023). This is shown by a great variety of biocultural landscapes such as the rice terraces in the Philippines, the agro-silvo-pastoral systems in Portugal and Spain, the Milpa Maya and the Chinampas in Mexico, the traditional crops of Chilóe in Chile (Venegas and Lagarrigue, 2014), the rooftops of Afro-descendant communities or the conventional production systems of indigenous communities such as Tul Nasa or Trau Misak in Colombia (Sanabria Diago, 2003; Sanabria Diago et al., 2022a), to cite just a few relevant examples.

These traditional agroecosystems have, thanks to their complexity, an inherent biodiversity value (Koohafkan et al., 2011; Koohafkan and Aliteri, 2011; Sietz et al., 2022). It has been shown that they maintain a strong association between cultural diversity and biodiversity and, ultimately, offer more sustainable production models (Ellis et al., 2021). Therefore, they are sustainable alternatives to the currently prevailing industrial agriculture model (Pretty et al., 2009; Maffi and Dilts, 2014; Toledo et al., 2019). However, traditional systems are being endangered by political, economic, and social factors that have caused the reduction of their territory, the removal of biodiversity, and the risk of loss of ancestral knowledge (Scheidel et al., 2020; Fletcher et al., 2021; Reyes-García et al., 2022; Reyes-García et al., 2023).

The agricultural development during the Green Revolution has greatly degraded the management and functionality of agricultural production systems all over the world, making them unsustainable (Tello et al., 2016; González de Molina et al., 2020; Picado and Infante, 2020). Agroecology, on the other hand, has sought to collect the legacy of traditional systems, focusing its objective on the optimization of interrelated ecological, socioeconomic, and political processes (González de Molina, 2012; Wezel et al., 2020; Gliessman et al., 2023) to generate actions of improvement and conservation of biodiversity (Altieri, 2001; Barrios et al., 2020) by regenerating the biocultural landscape patterns that guarantee the provision of ecosystem services to society, including food production (Sietz et al., 2022).

Agroecology recognizes that the keys to biodiversity conservation and food production are found in traditional production systems (González de Molina, 2012; Gliessman, 2018; Altieri and Nicholls, 2019). To that aim, it is essential to understand the cultural processes on which traditional production systems are based, to guarantee the interrelated conservation of culture and biodiversity (Altieri, 1999; López García and Guzmán, 2012; Reyes-García et al., 2023). Therefore, in the most important biodiversity hotspots like the ones in Latin America agroecological transitions must start from the worldview of indigenous communities, revitalizing the agro-diversity indigenous knowledge (in terms of spirituality, organizational dynamics of community work, and relationship with nature), to propose processes aimed at the community reconstruction of biocultural landscapes, which restore the relationship of culture with nature, contributing to the socio-metabolic efficiency (*i.e.*, energy, water, food), and increasing the territorial sustainability (Koohafkan and Aliteri, 2011; Moreno Calles et al., 2017; La Rota Aguilera and Marull, 2023).

At the global level, indigenous communities maintain an ancestral and collective link with their territory that has allowed them to keep a sustainable way of life for very long periods of time (Barthel et al., 2013). This biocultural relationship between communities and territories has preserved 80 % of the world's biodiversity within a wide variety of productive systems with high agro-diversity (United Nations, 2021). The land grabbing exerted to these indigenous communities is putting their productive, economic, social, and cultural system at risk, that is, their own identity. In Latin America, where almost every biome in the world appears according to CEPAL (Barrera and Sanchéz, 2002) and six of the most megadiverse countries in the world are there, indigenous communities represent between 8 and 10 % of the population (Barragán-Alvarado, 2008), 14 % of them poor and 17 % extremely poor. A fifth of these communities have even lost their native indigenous language (Freire et al., 2015).

To reverse this situation, indigenous people's worldview and ancestral knowledge constitute valuable elements in the overall framework of a desirable agroecological transition aimed at a transformative change in their territory. In this context, the Kokonuko indigenous community of Colombia started in 1999 a process to recover their biocultural heritages through an agroecology transition in their Puracé reservation. Our research team has been invited to assess and monitor this collective process, and, to that aim, our research questions are: How can this indigenous community advance towards an improved agroecology landscape based on the recovery of the ancestral biocultural heritages that ensure the best conditions of their territorial sustainability? How can alternative scenarios be scientifically designed to improve landscape sustainability by scaling up best agroecological practices based on indigenous knowledge? To answer these questions, participatory action research combining indigenous and scientific knowledges has been applied to a case study in the Puracé reservation, located in the high-Andean zone of Colombia. This is a territory whose biocultural landscape has been seriously damaged by the landowners and mining activities before the process of recovery of these lands through a long fight by the Kokonuko people from 1961 to 1981. The community, which has even lost its language, intends to restore the landscape as a means to recover their own destiny based on a sustainable way of life.

2. Methodology

To this end, and the Kokonuko's will of moving forward with a process of more than 20 years reconstructing their biocultural landscape, the local authorities of the *Cabildos* requested advice from Olga Lucía Sanabria, leader of the Colombian group of Latin American Ethnobotanists (GELA), and founder of the PhD in Ethnobiology and Biocultural studies at the University of Cauca. Marta Elena Montaño, who has a personal recognition of this indigenous community in the Puracé reservation, started her doctoral thesis in this PhD program co-supervised by Olga Lucia Sanabria and Joan Marull, director of the Laboratory of Ecology and Territory at the Autonomous University of Barcelona. The participatory action research was coordinated by Marta Elena Montaño from the scientific side, and the leader Oswlado Quilindo from the Kokonuko's community side. Together with the two PhD supervisors, the research team counted with the participation of Enric Tello at the University of Barcelona, and Alex Urrego-Mesa at the University of Granada (Spain). Marta Elena Montaño carried out the field work and the rest of the research team collaborated with her in processing the collected data to help identify the best agroecological practices to scale up. Through a dialogue of knowledges with community leaders and authorities, an alternative scenario has been jointly raised for the agroecological reconstruction of the biocultural landscape in the Kokonuko Indigenous Territory.

To assess and monitor the sustainability performances of the current scenario, compared to a future alternative scenario based on scaling up the best agricultural practices now existing in the Kokonuko's coffee polyculture and organic cultivation of potatoes, we have applied the circular material and energy flow accounting of agroecosystems using different Energy Returns on Energy Inputs instead of a single one (multi-EROI; Tello et al., 2016 and Tello et al., 2023), in line with the recent FAO's report *From nature-negative to nature-positive production. A conceptual and practical framework for agriculture based on thermodynamics* (Ferri and Arnes Garcia, 2023).

2.1. Study area

This research was carried out in the indigenous territory of Puracé (SW Colombia, 22,487 ha) located inside the *páramos* and high Andean Forest ecosystems (Fig. 1). It is a volcanic area at an altitudinal range from 2000 to 4650 masl, with a cold climate between 2 °C and 15 °C and an average precipitation of 1870 mm/year for the period 1986–2016 (IDEAM, 2016). It is part of the Andean Belt Biosphere Reserve, of great importance for biodiversity due to the existence of fauna, flora, and fungi characteristic of the Andean zone (Unidad de Parques Naturales Nacionales, 2004; Valencia Rojas et al., 2017). It is also a region of great archeological importance due to findings demonstrating ancestral communities dating back more than 1800 years (Patiño and Mosalve, 2015). It is inhabited by 5061 indigenous belonging to the Kokonuko people, with an economy based on the production of milk, commercial potatoes, and to a lesser extent, coffee and products from the traditional production plots made up of vegetables, tubers, and corn.

In the 1960s, 3336 ha were in the hands of landowners, 2536 ha were part of the overlap of the area established in 1961 as a Natural Park on indigenous territory, and more than 1000 ha were affected by the mining exploitation of natural sulfur (Patiño, 1991), which weakened the use of the territory by the indigenous communities and the biocultural relationship of the community with the landscape. The departmental agriculture secretariat starting in 1960 promoted the transition from traditional productive systems to industrialized agricultural systems, exacerbating the situation, which reduced the traditional productive systems from 2206 ha in 1960 to 22.94 ha in 2019 (Fig. 1). The traditional biocultural landscape had been reduced and fragmented in the territory, generating socio-environmental degradation and reducing territorial resilience (Figueroa Casas et al., 2010; Joaqui, 2017; Valencia Rojas et al., 2017).

The lands of Puracé, which were in the hands of landowners due to

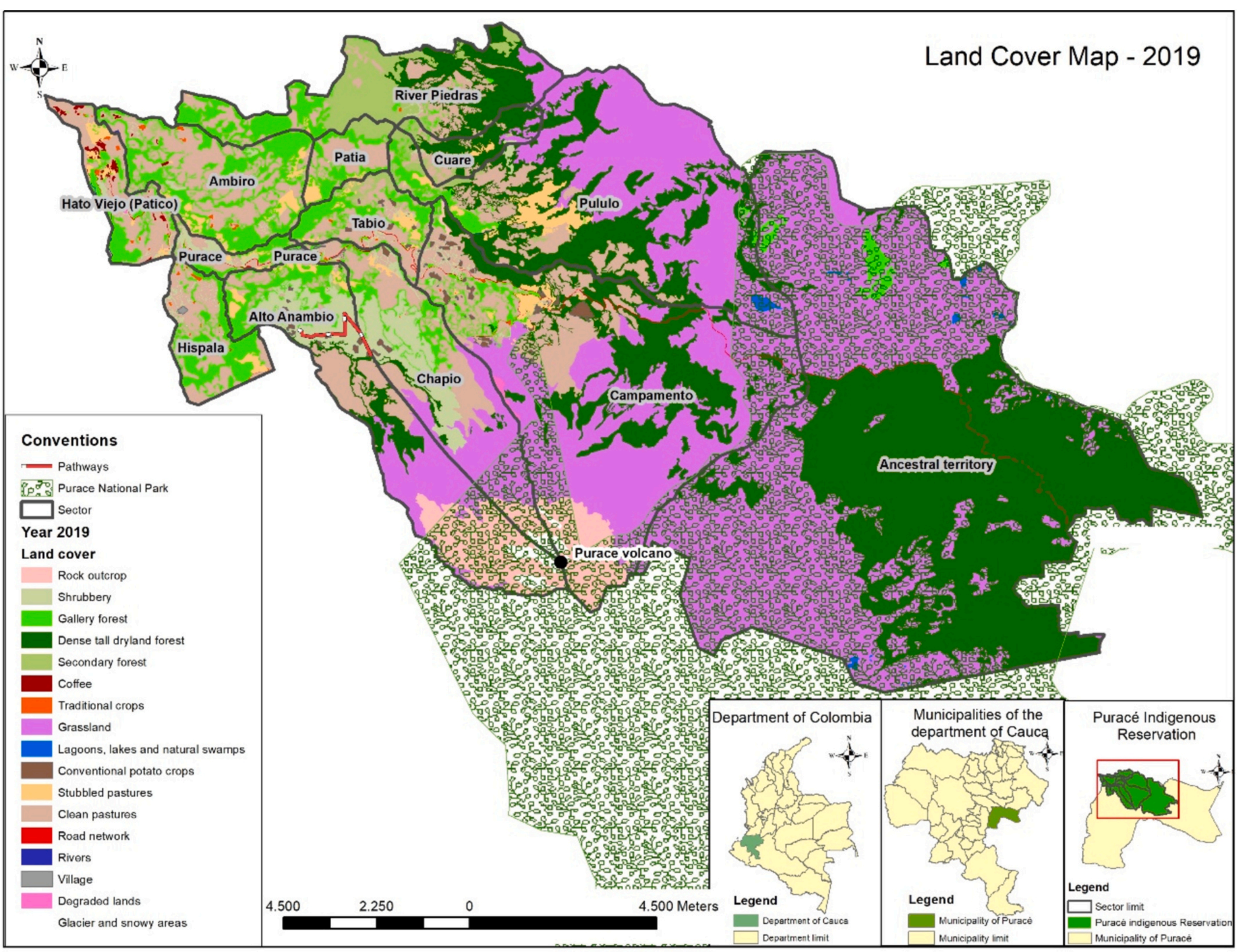

Fig. 1. Current land cover map of the indigenous territory of Puracé. Source: our own elaboration with GIS from Landsat satellite images and aerial photographs (IGAC).

the configuration of the colonial *hacienda* model, were recovered in 1974 by the communities through a long and hard indigenous struggle. In 1981 the State established the indigenous territory of Puracé, which is the territorial figure of legal recognition of collective property to the community; this allowed the Kokonuko people to exercise their government through the *Cabildo* (an organization that legally represents the autonomous assembly on the indigenous people and is the traditional authority in the territory), and generate guidelines and policies of community consensus, called mandates, allowing the recovery cultural importance's conservation areas and traditional production systems. In this way, in 1999, the life plan of the reserve was established as a priority for the recovery of the traditional systems. In 2005, the Cauca Indigenous Environmental Plan (PAI) implemented by the *Cabildo* strengthened the traditional orchards, and together with the Cauca Regional Indigenous Council (CRIC), as the regional indigenous organization, proposed environmental and productive projects to strengthen the traditional production from now on. In 2009, the Puracé *Cabildo*, together with other indigenous *Cabildos* from the upper Cauca River basin, reached an agreement with the United Nations to carry out the joint climate change adaptation program, which concluded that traditional production systems are the ones with significant adaptability, laying the foundations for the constitution in 2010 of the network of seed custodians of the *Cabildo* to recover and preserve native and creole seeds. In 2018, the territory's network of seed custodians, made up of 15 traditional production plots, was declared as an object of biocultural conservation through an internal and collective process.

2.2. Methodological procedures

Based on the long indigenous struggle for the land's recovery and the gradual reestablishment of a sustainable way of life, the *Cabildo* has currently the mandate to move towards the agroecological transition to allow the recovery of the ancestral biocultural landscapes. In this context, a procedure is proposed, which combines traditional and scientific knowledges with a shared methodology applied through four execution phases (Fig. 2): In the first phase, a diagnosis of the current conditions of the territory has been made from the point of view of the rural metabolism to assess its degree of sustainability; In the second phase, based on the analysis and evaluation of the previous results, a proposal for the recovery of the biocultural heritage through the retrieval of traditional varieties are generated; In the third phase, pilot tests are carried out in the field to evaluate the best agricultural practices using the recovered traditional varieties; Finally, the fourth phase elaborates and promotes a future scenario for the reconstruction of the biocultural landscapes through an agroecological transition based on a dialogue of knowledges with the community and the scientific and practical results of the previous research and action phases.

Following this procedure, three scenarios are analyzed: The Current Scenario corresponds to the current conditions of the agroecosystems of the territory, involving both the productive and the conservation areas; The Pilot Scenario of 'best agricultural practices' that represent the biocultural heritage of the indigenous community, includes two farm systems of organic management, which use traditional varieties, the first with a productive management of potatoes and the second with coffee polyculture; The Alternative Scenario represents a potential agroecological transition process in the territory, simulated from the two traditional production systems of organic management, which allows evaluation of the effects of an eventual reconstruction of the biocultural landscape. As put forward by Pablo Tittonell (2023, 361), the visioning of the desired scenario opens the way to a back-casting process of prioritization, piloting and system co-innovation towards the future envisioned through a community process of "*understanding and then acting, but also understanding through acting, or even while acting,*" This community process makes the desirable future feasible and viable.

In its life plan, the conservation of nature is fundamental for the Kokonuko's people, who have identified in their own landscape spaces the difficulties that the current productive model is generating in the territory. Acknowledging them, the community has decided to elaborate a proposal for agroecological transition, and this is why a mixed team composed of external and community researchers has been formed for carrying out the initial steps for this purpose. The research and action team has defined the proposed procedure (Fig. 2), which consists of performing a diagnosis of the territory to evaluate the degree of sustainable efficiency of the agroecosystems in the Current Scenario, and figuring out the necessary steps to assess a possible Alternative Scenario through the recovery of traditional varieties, the experimentation of their organic management in an experimental farm, and the study of the best practices, through two productive pilot systems at the family unit scale (Pilot Scenario). The diagnosis started with the elaboration of a land cover map (Fig. 1) through the GIS digital processing of satellite images to identify the agroecosystems of the territory, which were characterized by Ethnobotanical methods (Sanabria Diago et al., 2022b), combining the Participatory Action Research (or IAP for the Spanish acronym) (Fals-Borda, 1999), field trips with the voluntary company of seed custodians, and ethnographic methods (Restrepo, 2018), which were used to characterize the traditional productive systems.

The biophysical analysis of these different farm systems relies on the energy flow-fund approach proposed by Georgescu-Roegen (1971) and adopted in ecological economics, which considers three biophysical funds: agricultural land, livestock, and biodiversity; the agrarian community is a social fund that coproduces with nature by driving the external energy flows applied to and combined with the natural ones of the three previous funds. The analysis of the flows of matter and energy,

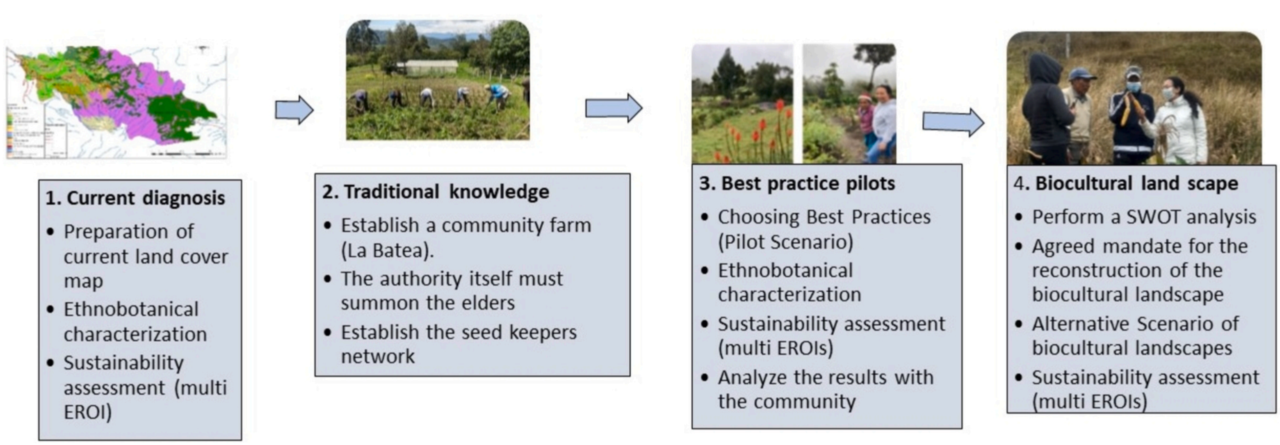

Fig. 2. Methodological steps for the reconstruction of Kokonuko's biocultural landscapes. Source: our own, from the participatory action research carried out.

uses the Energy Return on Investment (EROI) method, relying on the Net Primary Productivity (NPP; Haberl et al., 2007), which is split into the Unharvested Biomass (UhB) directly taken by the wildlife, the Biomass Reused (BR) that farmers actively return to the reproduce the other natural funds of the agroecosystem, and the Final Produce (FP) delivered to meet the needs of Kokonuko people and/or traded outside their community (Tello et al., 2015, 2016). The relationship between what is taken from the natural funds of the agroecosystem (FP) relative to what is returned to them for their healthy reproduction (UhB + BR) provides a key sustainability indicator (Tello et al., 2023; Shiva, 2016). Data measurements in the field at harvest time determined the production yields. The destination of biomass and inputs have been estimated from surveys and interviews (Annex 2). The analysis of the different EROIs was carried out both in the entire indigenous territory of Puracé (Current Scenario and Alternative Scenario) and in two traditional farm systems (Pilot Scenario), involving three bioeconomic and three agroecological EROIs:

The External Final EROI (EFEROI) is a ratio that relates the energy content of the Agricultural Final Produce (AFP) and Livestock Final Produce (LFP) to the sum of the Agricultural External Inputs (AEI) and Livestock External Inputs (LEI) used to obtain them:

$$EFEROI = \frac{AFP + LFP}{AEI + LEI}$$

The Internal Final EROI (IFEROI) is a ratio that relates the Final Produce (FP = AFP + LFP) to the Agriculture Biomass Reused (ABR) and Livestock Biomass Reused (LBR) driven by farmers.

$$IFEROI = \frac{AFP + LFP}{ABR + LBR}$$

The Final EROI (FEROI) is a ratio that relates the FP to both the External Inputs (EI = AEI + LEI) and internal Biomass Reused (BR = ABR + LBR).

$$FEROI = \frac{AFP + LFP}{AEI + LEI + ABR + LBR}$$

FEROI is related to EFEROI and IFEROI according to the following function (Tello et al., 2016; Tello et al., 2023):

$$FEROI = \frac{EFEROI^{*}IFEROI}{EFEROI + IFEROI}$$

Considering the whole photosynthetic Net Primary Productivity over a year (NPPt), and the fraction of this biomass that remains unharvested (UhB) and available for non-domesticated species living in the agroecosystem, three other agroecological EROIs are accounted. NPP-EROI is the ratio of the NPPt to all external, internal, and unharvested energy flows:

$$NPP - EROI = \frac{NPPt}{ABR + LBR + AEI + LEI + UhB}$$

The degree of human colonization of the agroecosystem is measured by the ratio between the share of biomass energy that remains unharvested (UhB) and to the total energy throughput circulating into the agroecosystem (EI + BR + UhB), called BFEROI. The values approaching to 0 represents agroecosystems with such and extremely high human intervention that leaves almost nothing to the rest of non-domesticated species, while the ones approaching to 1 would have a low human intervention close to natural of natural ecosystems (Guzmán Casado and González de Molina, 2017; González de Molina et al., 2020).

$$BFEROI = \frac{UhB}{(EI + BR + UhB)}$$

Finally, AFEROI is the ratio of the FP to the total energy recirculation, which accounts for Total Inputs Consumed (TIC = EI + BR = AEI + LEI+ABR + LBR) plus the UhB that sustains the non-domesticated species that inhabit the agroecosystem:

$$AFEROI = \frac{FP}{TIC + UhB}$$

Both the biomass actively reused by farmers (BR) and the unharvested biomass (UhB) taken directly by non-domesticated species play a key role for the sustainable reproduction of all the living funds of the agroecosystem: fertile soils and their biota, forests and trees, livestock, associated biodiversity, and the farming community. According to the fund-flow bioeconomic analysis, a living fund can only provide a flow of products and services to society if they receive the flows of energy-matter required for their own self-reproduction over time (Couix, 2020). This basic sustainability criterion is embedded in the cosmovision of indigenous and peasant cultures as a 'Law of Return' (Shiva, 2016) or 'Honourable Harvest' (Kimmerer, 2020): you must not take everything from nature, and always leave something for someone else; and whenever you take something, you must give nature something in return. The agroecosystem sustainability requires keeping a wise balance between how much energy-matter farmers extract as product (FP), how much external input invest from outside (EI), and how much biomass recirculates within (BR and UhB).

Using these criteria and indicators to differentiate the more sustainable ways of farming, the four steps to develop the Alternative Scenario were the following (Fig. 3): Creation by the traditional authority of a network of 15 seed custodians, identifying with the *Cabildo* and the community elders the families with traditional productive systems; define an experimental farm (*La Batea*) to evaluate traditional varieties and organic management based on ethnobotanical characterization and analysis, which allows optimizing agricultural practices shared by farmers; selection of two traditional production systems considered 'best practices' at the family unit level, the first with potatoes as its productive organic management (PTP1) and the second with coffee polyculture (PTC1), two systems that stand out for their integrated management of agroforest landscapes; inter-scientific dialogue for the definition of a mandate scheme to rebuild an agroecological biocultural landscape, which starts from the Participative Action Research (IAP) and 'learning by doing', to define with the indigenous authorities of the territory, and with the participation of the elders, an agreed scheme that includes the criteria to generate the Alternative Scenario.

An analysis of Strengths, Weaknesses, Opportunities and Threats (SWOT) of the indigenous territory of Puracé has been carried out, from which the *Cabildo* and custodians make a mandate which researchers participate to establish the reconstruction of biocultural landscapes, and to determine the areas of conservation, incorporating a proposal for the agroecological transition from extensive livestock farming to agroforestry systems, the reconversion of commercial potato areas to the traditional PTP1 potato system and from monocultural, unshaded coffee to traditional shaded coffee PTC1, making a land use map for the Alternative Scenario. The sustainability of each system is evaluated with the multi-EROI method, comparing the results with the Current Scenario and, consequently, generating recommendations for the reconstruction of the landscapes of the territory that considers biocultural heritage. The proposal is submitted to the cultural steps of 'opening the way', carried out by the traditional doctor, who consults through signs if the proposal is positive for the territory.

Although this research proposes a scenario for the reconstruction of biocultural landscapes, which includes traditional agroecological practices and knowledge, the proposed systems only include some of the possibilities that high agrodiversity can allow, in which perhaps better options could be found than those proposed. The research has considered summary information related to the adaptation capacity that traditional systems have to climate variability and change, and about the species that can be fed through the UhB and are important to contribute to the conservation of wildlife. Now the analysis must continue researching these agroecological transition by including in the future scenarios the capacity of adaptation to climate change and its impact on socioecological resilience beyond the four first steps included in this

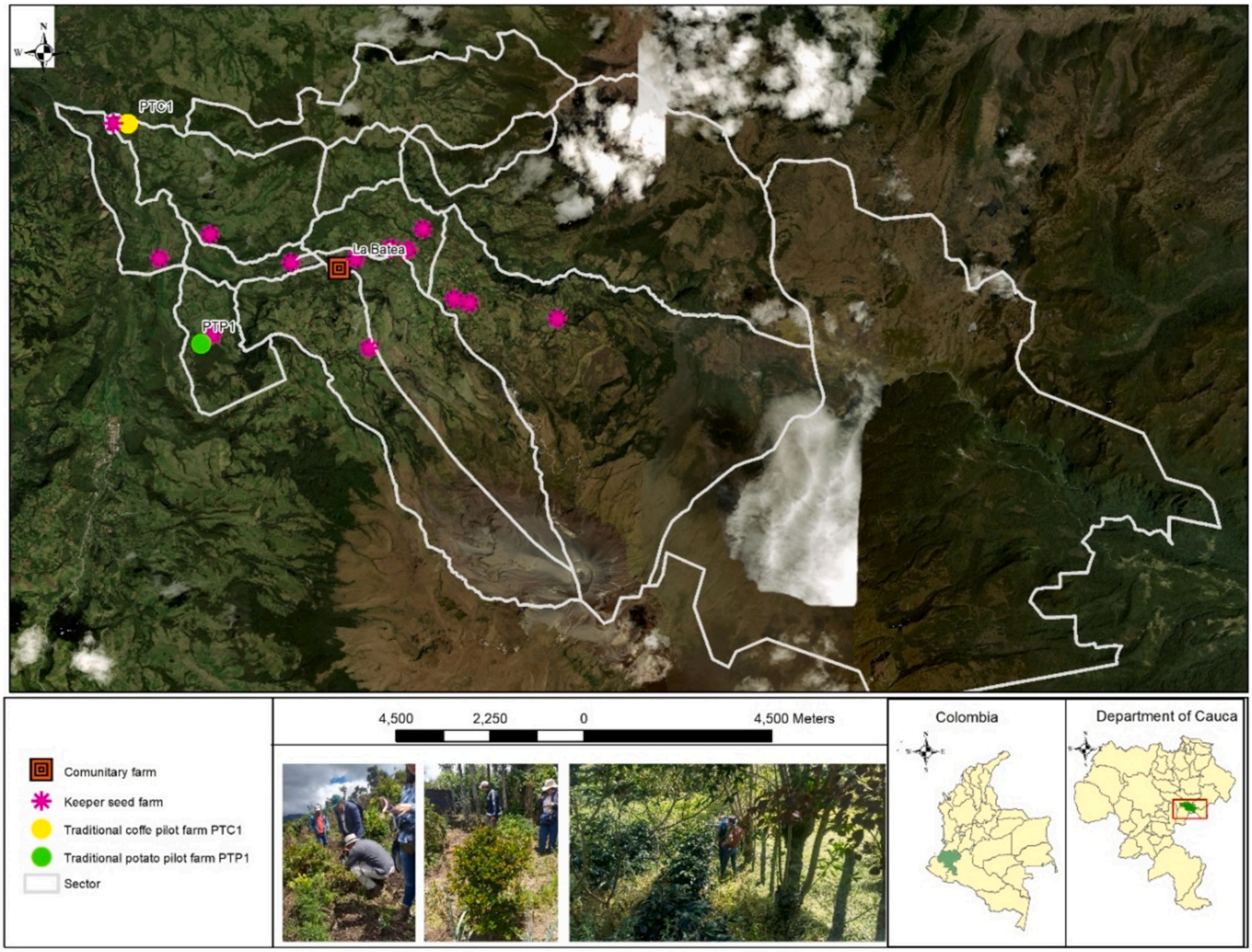

Fig. 3. Traditional agroecosystems location map of the indigenous territory of Puracé. Source: our own, from fieldwork and GIS.

study.

3. Results and discussion

3.1. Current scenario

The change in the productive model introduced by the Green Revolution led to the current landscape composed mainly of a matrix of pastures, the presence of commercial potato systems in the upper and middle part of the territory, between 2500 and 3200 masl, and monocultural coffee systems in the lower between 2000 and 2500 masl. This change led to the transformation of the traditional organic management systems, with more than 70 potato varieties, to the current commercial production. These systems, located in an area of 82.17 ha in extremely cold and very cold thermal Andean floors, are characterized by monoculture production with potato (*Solanum tuberosum*) of the Pastusa, Parda, and Suprema varieties, with an average yield of 16 tons/ha, 75 % of the final production directed to the regional market and 25 % for self-consumption in human food and animal feed. In the case of coffee (*Coffea arabica*), in the cold Andean thermal zone, the traditional varieties of Arabica, Colombia, and Caturra, due to national policy, were replaced by Castillo, to improve productivity and face the rust of coffee trees (*Hemileia vastatrix*), transforming traditional production systems with organic-based shade to high-yield unshaded systems, which requires agrochemical management, consuming 788.43 GJ/year for fertilization and 2,36 GJ/year of herbicides. Of the 25.81 ha in coffee, 42 % of the systems have shade, and 58 % correspond to monocultural Castillo variety, with 20.3 tons/year production.

At present, 68.8 % of the territory's surface in a *páramo* ecosystem made up of grasslands and dense stunted forest (Fig. 1), of high cultural value due to its spiritual importance from the community worldview; 16 % are kikuyo (*Pennisetum clandestinum*), ryegrass (*Lolium perenne*) and false poa (*Holcus lanatus*) pastures, technically not managed for dual purpose livestock use; 0.4 % of the area is in commercial potato monoculture under agrochemical management; 0.1 % in coffee systems of the Arabica variety; and only 0.1 % corresponds to a traditional crop, that is corn interspersed with native and creole seeds, which provide a fundamental legacy in the construction of an agroecological transition proposal by allowing the indigenous community to recover their agrodiversity and biocultural landscapes.

The cattle system is composed mainly of bovine cattle (*Bos taurus*), a double purpose of crosses between Norman, Gersy, and Holstein breeds with creole cattle. The inventory of 6469 head (3960 Livestock units of 500 kg or LSU500), made up of 4423 females and 2046 males. The productive system is extensive with a density of 1 ha per cow. The low density is related to the lack of technical management of the pastures. Despite the inclusion of concentrate and crop residues as complements, animal feed is insufficient generating soil erosion due to overgrazing and leading to the expansion of the grazing area towards the grasslands of the *páramo* ecosystem. Livestock is the second economic line of the territory, with an average milk of 3.3 lt/cow/day, for a total of 1,894,919 lt/year. Of these, only 3 % of milk and 2 % of meat is self-consumed, selling the rest of the livestock produce to the regional market. In smaller species, there are 95 sheep and 6082 poultry.

Agricultural production has been enormously transformed since the Green Revolution. It currently has an area of 130.92 ha, 82.47 % corresponds to market-oriented agrochemical management systems, which require 3547 GJ/year of fertilizers, 81 GJ/year of herbicides, 64 GJ/year of pesticides and 239 GJ/year of fungicides. However, it still has valuable traditional systems contributing to food sovereignty and traditional medicine (Montaño et al., 2021). The biophysical analysis (Fig. 4) of the territory in the Current Scenario shows that the NPP is 2,896,639 GJ, being the UhB 90.6 %, like the pattern presented for Colombia at the beginning of the 20th century (Urrego-Mesa, 2021b). The high percentage of UhB, which provides essential ecosystem services, is related to the conservation of the *páramo* ecosystem areas and dense high forest that, from the indigenous worldview, are understood as 'wild lands' that have a spiritual character and therefore a productive use limited.

The 9.4 % of NPP (271,255 GJ) is human appropriated in the territory, of which a part returns for agricultural uses in terms of BR, being 7.7 % of NPP (222,807 GJ). The cropland produce is 0.5 % of NPP (14,557GJ) of which 52.9 % is self-consumed and 4 % socialized outside the territory; the woodlands and scrub produce is 1.2 % of NPP (34.106GJ), reflecting that, despite energy coverage, firewood remains the largest fuel source for the families.

According to the central dedication of the territory to extensive dual-purpose livestock, 73.8 % of BR corresponds to pastures used to maintain the livestock, requiring the import of 16.8 % of feed (33,092 GJ). The energy produced by the cattle herd is 20,849 GJ, of which only 2.6 % is self-consumed and 97.4 % socialized outside the territory.

The external energy inputs (EI) required to run the agroecosystems are 46,296 GJ, of which human work is 8777 GJ (19 %), and agrochemicals account for 8.5 % which is equivalent to 3931 GJ, and machinery for 1.1 % which shows that the indigenous territory of Puracé has an agriculture dependent on human labor. However, dual-purpose livestock only covers 2 % of the milk and 3 % of the meat for self-consumption, which has led to the need to import food, currently 71.5 % of EI (Fig. 4).

Sustainability cannot be inferred so directly from EROIs values taken one by one. It requires considering the whole energy pattern of the agroecosystem by looking at the entire set of EROIs from an interrelated flow-fund perspective. It is an assessment of what is taken from nature (the proportion of harvest/unharvest NPP biomass) and what is returned to them either as BR or UhB, or both respective to FP. The analysis of the bioeconomic EROIs (Fig. 5) shows that although the system is a slightly energy provider of net energy flows to the external society (EFEROI = 1.49), the high internal reuse of biomass (IFEROI = 0.31), which indicates a strong investment in the sustainable reproductions of the soil biota and livestock, combined with a still relatively low return to the external inputs, leads to a quite low joint final energy return (FEROI = 0.23). NPP-EROI = 1 indicates a quite relevant contribution of natural processes to the total photosynthetic produce thanks to the conservation of wild area and gallery forest that allow a low level of disturbance if we consider all the territory. This also reassesses the limited amount of socialized biomass exported to regional markets from the agroecosystem compared to FP extracted and locally consumed. The other side to the coin is the large amount of unharvested biomass free for the associated biodiversity (Figs. 4 and 5).

3.2. Custodian network

Traditional crops have great biocultural importance due to the diversity of seeds that they preserve, the associated knowledge, the function in the conservation of culture and biodiversity, and the sustenance of the food sovereignty of the community (Altieri and Toledo, 2011; López García and Guzmán, 2012; Sanabria Diago et al., 2022b). The *Cabildo* strengthened the seed recovery process and generated healing, revitalization, and conservation mandates. The network of seed

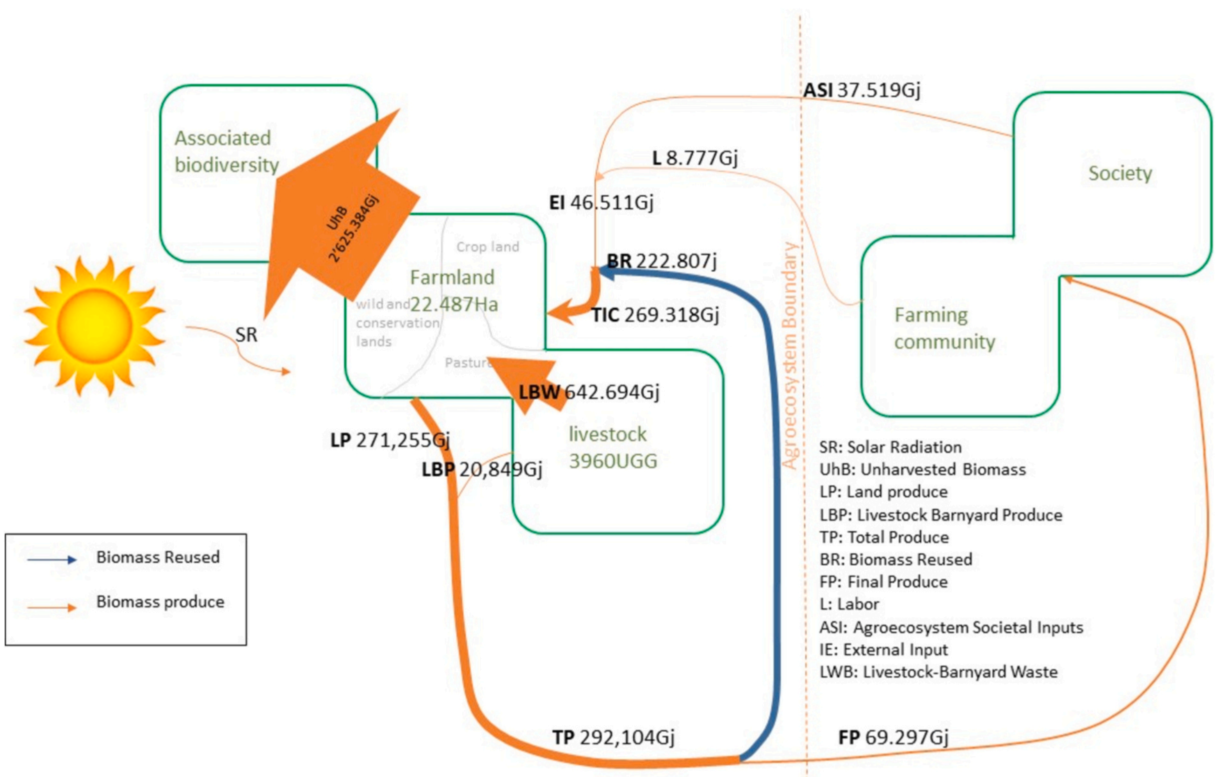

Fig. 4. Main energy flows of the indigenous territory of Puracé in the Current Scenario- Source: our own, from the data gathered in the field work.

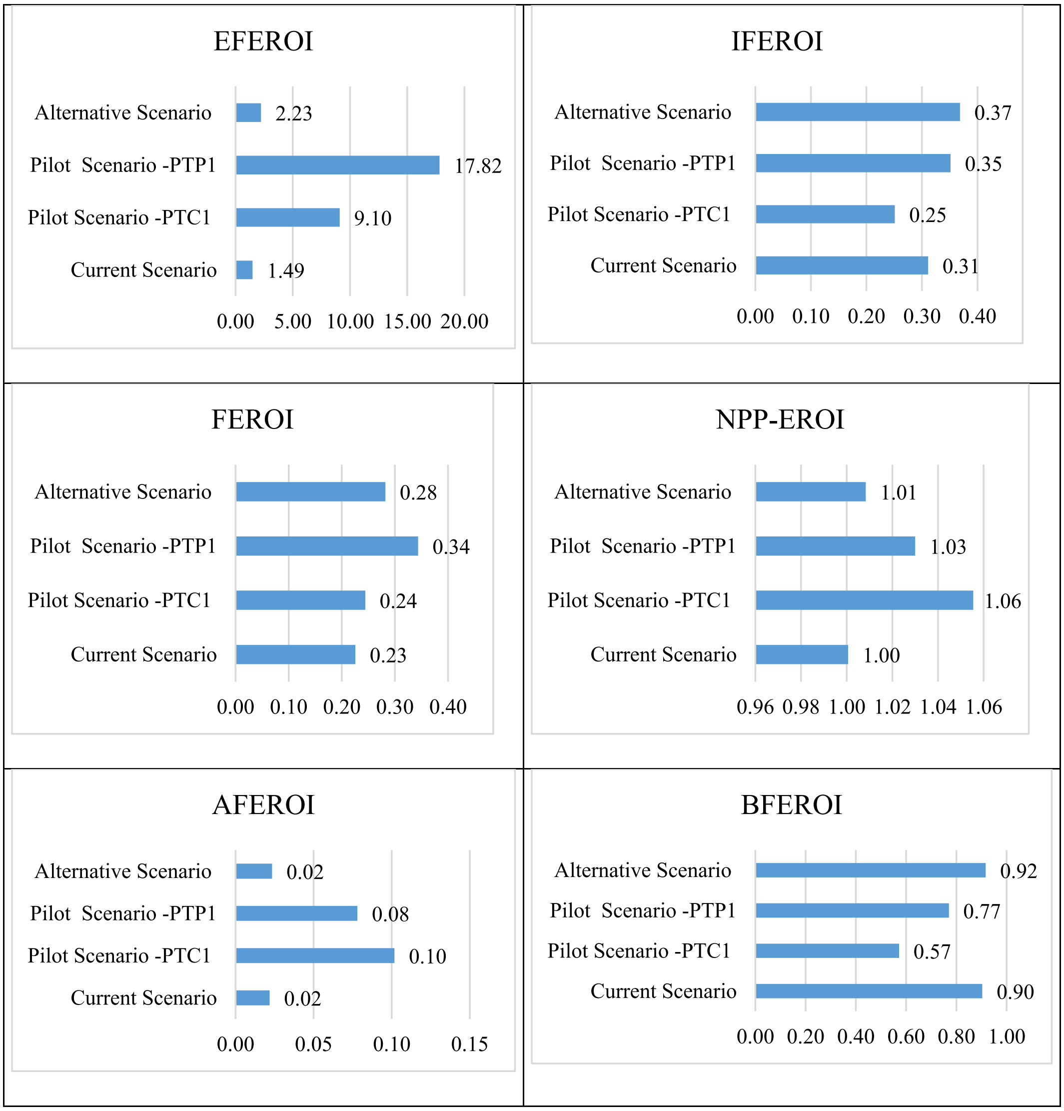

Fig. 5. Multiple EROIs (External Final EROI – EFEROI, Internal Final EROI -IFEROI, Final EROI, NPP EROI, Agroecological Final EROI, Biodiversity Final EROI) of the Current Scenario, the Pilot Scenario -with the two plots (PTC1 and PTP1), and the Alternative Scenario. Source: our own, from the data gathered in the field work.

custodians created in 2010 comprises 15 productive plots with areas from 283.7 m^2 to 16,134.1 m^2. The custodian system allows the conservation, experimentation, and diffusion of seeds within the community. The custodian's relationship with their productive system results from Kokonuko's worldview of biocultural heritage. The traditional production systems are multiple-use polycultures that house 62 (Fig. 6) botanical families of plants, including 143 genera and 183 species (Annex 1). 58.06 % of the varieties are for culinary use, 23.87 % are medicinal, 10.32 % are for food and medicine, and 8.9 % are for ornamental and craft services (Fig. 6). Of the varieties in the plots, the custodians use 155 species and sell only 39 of them through their channels. The remaining varieties are exchanged in the indigenous economy and kept for bad times, solidarity, sharing with family and close relatives, participation in barter organized by the *Cabildo*, and exchange between neighbors on the plot. These forms of interaction have greater weight and allow revitalization of traditional production systems. Through networks of trust and interchange, seeds are renewed, and indigenous knowledge is enriched.

Productive arrangements of 14 to 55 varieties of seeds harvested simultaneously formed the design of the plots. The linked productive cycles are the relationship with the three living spaces that govern the Kokonuko worldview, define the seeds and the sowing and harvest times through the path of the sun and the moon, of the agricultural calendars of the elders, which are marked dry, rainy, and frost times. For planting times, the custodians interpret bioindicators based on indigenous knowledge. There is a relationship between indigenous and Catholic spirituality, expressed in the plants planted in the orchards, their rituals, and the celebration of the festivities of San Miguel, patron saint of the indigenous territory of Puracé, which would allow the rains required for the sowing.

3.3. Pilot scenario

The coffee polyculture system (PTC1) has 1.1 ha, with shady Arabica coffee occupying 44 % of its surface, including lemon, orange, avocado, and banana cultivation. The management is 100 % organic, with a rotation of pastures and a food garden producing traditional arracacha, beans, corn, and vegetables. There is also a rest area, and a forest area dedicated to conservation. The preparation of the land is done exclusively with human labor, the removal of the shade from coffee plantations is minimal, and the products of the garden are for self-consumption, marketing only dry parchment coffee, meaning a complex agroecological management (Perfecto et al., 2014). NPP is 244.1 GJ (Fig. 7), of which 21.9 % is UhB, LP-Cropland is 4.2 % (8.3 GJ) and 70.9

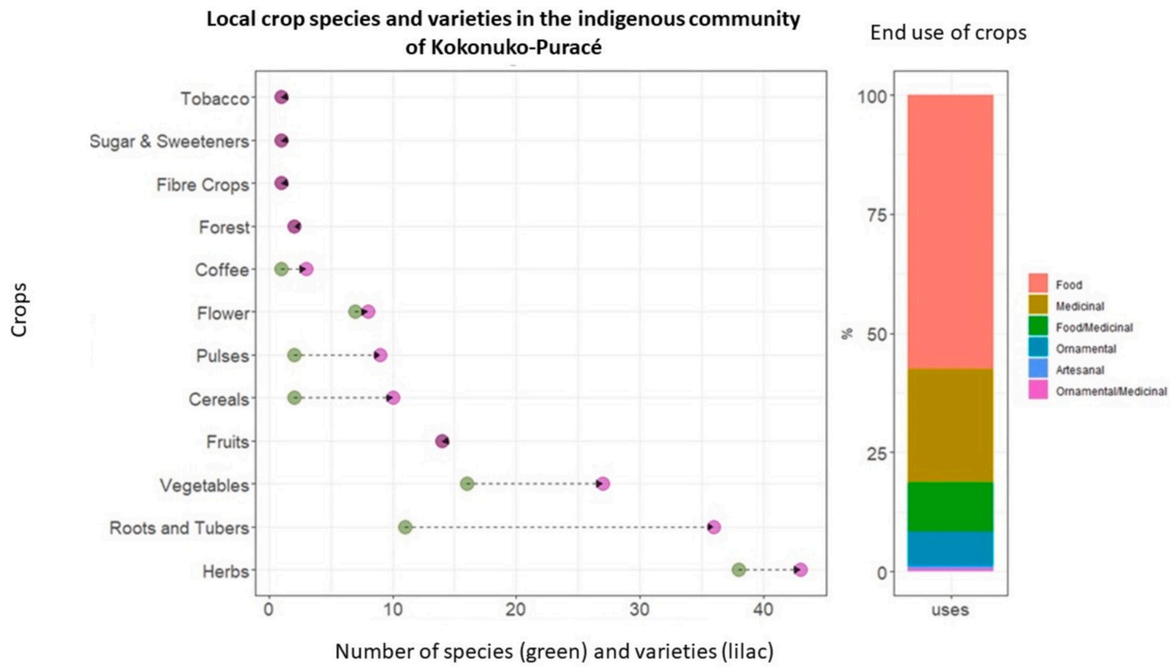

Fig. 6. Local crop species and end use in the indigenous community of Kokonuko-Puracé. Source: our own, from the data gathered in the field work.

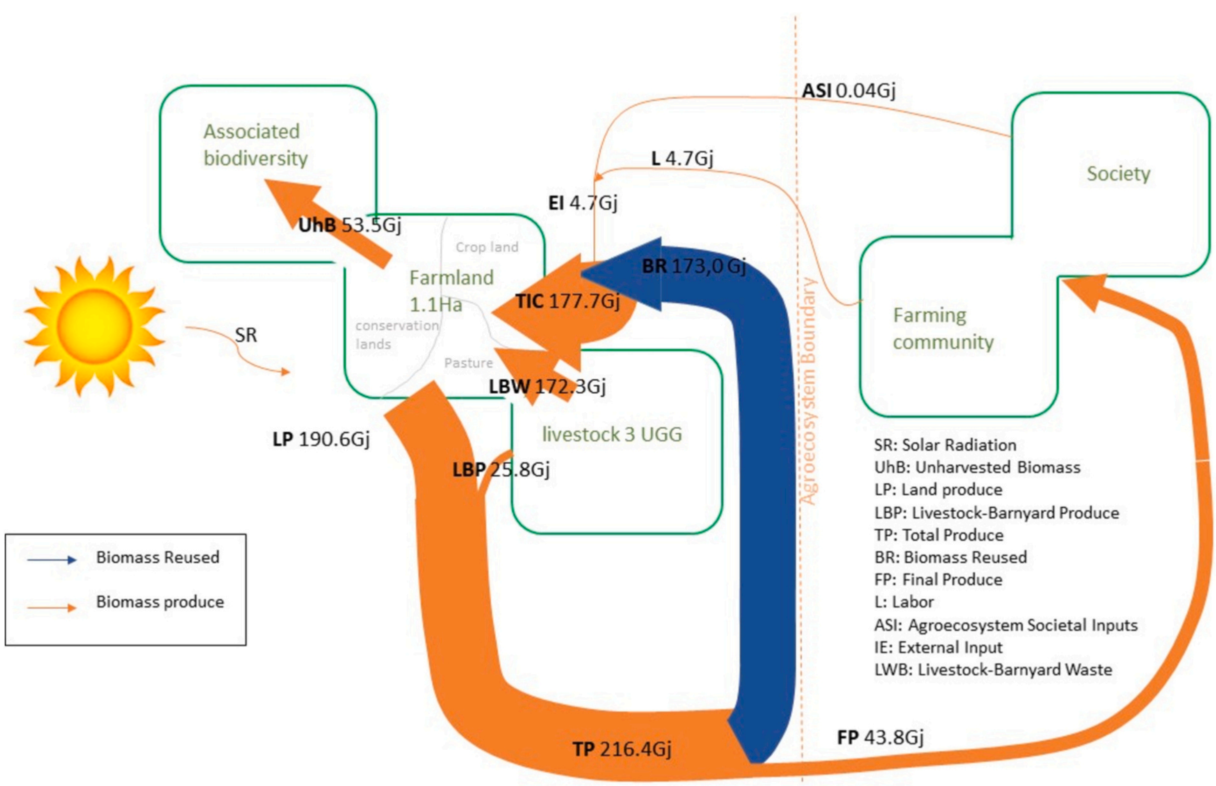

Fig. 7. Main energy flows from the organic coffee polyculture system of the indigenous territory of Puracé in the Pilot Scenario PTC1. Source: our own, from the data gathered in the field work.

% BR directly or indirectly returned to soil biota. The high amount of reused biomass is related to animal feed from grass and crop residues without use of external concentrated feed. LBP is 25.8 GJ, of which 5.2 % is self-consumed. The reason is the traditional production system being mainly oriented to vegetable production towards self-consumption, while animal production is mainly traded. In PTC1, both coffee and livestock have a commercial purpose, leading to greater socialized biomass taken from NPP.

The organic potato system (PTP1) has 1.94 ha, made up of a food garden, an area for minor species that correspond to laying hens, and an area designated for crop rotation, which produced beans, corn, and pumpkin with alternating native and creole potatoes, onion and arracacha, also used as cattle's pasture after harvested; the cycle of this area is two years and eight months. Management is 100 % organic; the system uses human force for soil preparation, sowing, hilling, cleaning, and harvesting; 23.8 % of EI is chemical fertilizers, and 6.3 % is machinery. NPP of PTP1 is 377.4 GJ (Fig. 8), of which 67.7 % is UhB, a value associated with the influence of the 'área brava' in the abstention from logging. BR is 28.8 %, and LP-Cropland 8.3 % of NPP (31.4GJ). The animal FP is 25.1GJ of NPP, of which 8 % is self-consumption, and 92 % for sale.

According to the biophysical analysis (Fig. 5), the two traditional productive systems evaluated have low dependence on EI, with EFEROI of 9.1 (PTC1) and 17.8 (PTP1). Therefore, organic production systems have a capacity to produce much greater food energy than the one it receives from society as EI. IFEROI accounts for the energy return of the effort made by farmers to reuse the biomass flows required to reproduce the living funds of the agroecosystem. The effort made by the custodians to reuse the biomass is evidenced in the low IFEROI accounted in both PTP1 and PTC1. FEROI values, that score the energy returns to satisfy the needs of society in terms of food, fuel, and raw materials out of the total inputs consumed (TIC) both external (EI) and internal (BR), are 0.23 for PTC1 and 0.33 for PTP1. Both productive systems have low biomass socialization that is only needed to help sustain the community economically to buy products and inputs from the regional markets, which is not a large amount in a communitarian economy mainly oriented to self-sufficiency.

NPP-EROI of the PTP1 system has a higher value (Fig. 5), which indicates its greater capacity to turn solar radiation into plant biomass to sustain both human needs and the biodiversity herbivory associated with the agricultural system. If we subtract FEROI from NPP-EROI, it is apparent that traditional systems can host more biodiversity, as demonstrated as well by the ethnobotanical characterization (Annex 1). AEFROI is small in traditional systems due to the low amount of biomass addressed to society, leaving a higher percentage on NPP to sustain the reproduction of the agroecosystem living funds (soil biota, trees and roots, livestock and biodiversity). The relationship between AFEROI and FEROI provides a measure of human colonization of the agroecosystem, labeled BFEROI (Guzmán Casado and González de Molina, 2017). While PTP1 and PTP2 have a lower value than the current scenario due to their higher land-use intensity and smaller scale, it reaches the highest level in the Alternative Scenario.

3.4. Mandate agreed with the community

Some of the indigenous communities of the world that build mandates or protocols that, from their worldview, establish the relationship with nature and guide the sustainability of their territories, have incorporated scientific knowledge to strengthen their actions (Whyte et al., 2016), as we can see in the Kokonuko people in Colombia.

The elaboration of an agreed mandate scheme for the reconstruction of the agroecological biocultural landscapes started from a SWOT analysis (Fig. 9), carried out with the elders and representatives of the indigenous authority, complying with the cultural steps of "opening the way", carried out by the traditional doctor, who consults through signs if the proposal is positive for the territory. SWOT indicates that the transition must incorporate the conservation of strategic ecosystems and those of spiritual importance so that the revitalization of traditional systems in the reconstruction of biocultural landscapes respects sacred sites and those of community importance.

From SWOT (Fig. 9) it is possible to infer that for the protection and conservation of seeds, it is necessary to identify the traditional productive plots, which make up the central nucleus of a network of custodians. This network must grow to integrate all families into the network of custodians to gradually replace the use of commercial varieties with native and creole seeds and advancing in parallel in the substitution of agrochemical inputs for organic ones. Recovering the gallery forests of the streams and rivers is also important. On the other hand, since livestock is a principal product area in the territory, which has generated harmful effects on the soil and the moor, it is necessary to

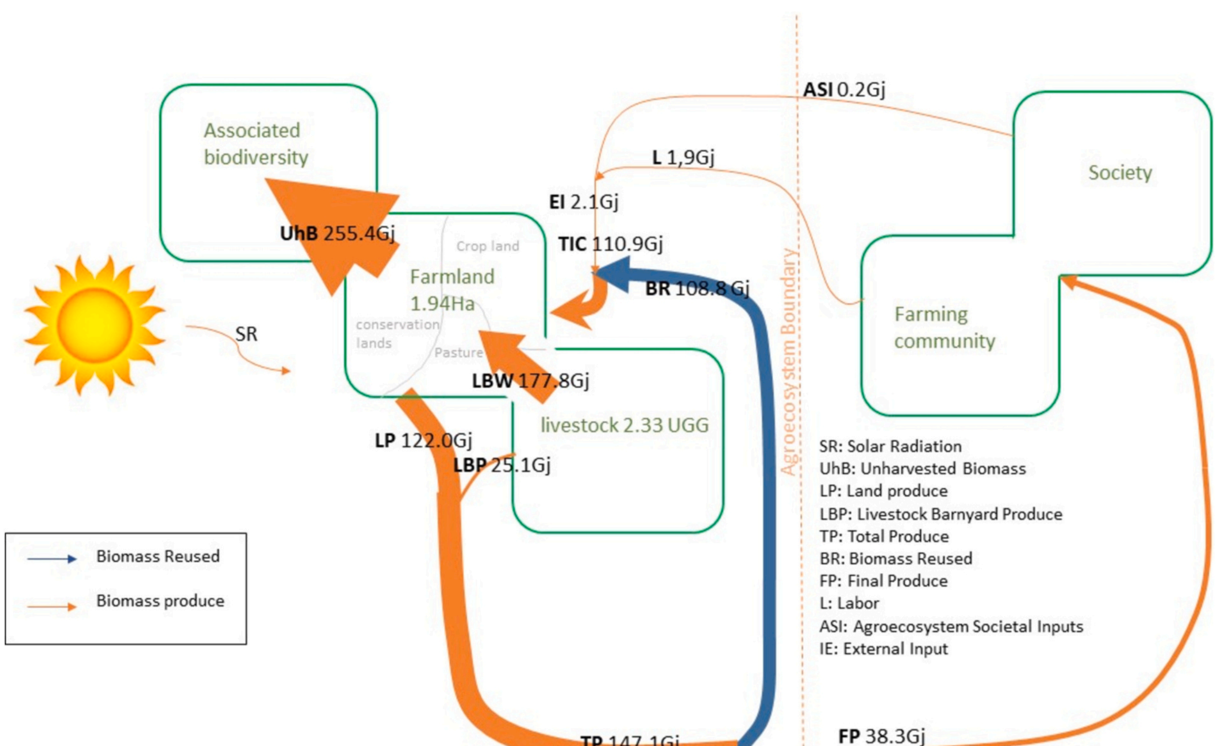

Fig. 8. Main energy flows from the organic potato system of the indigenous territory of Puracé in the Pilot Scenario PTP1. Source: our own, from the data gathered in the field work.

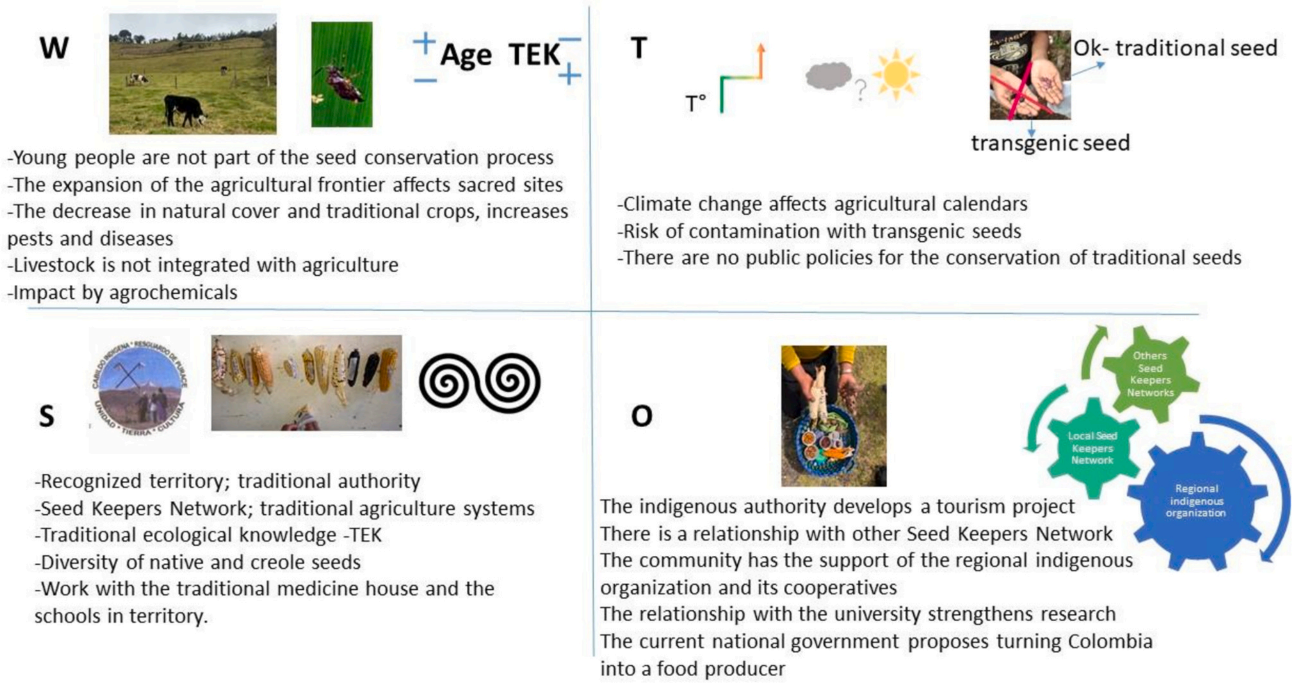

Fig. 9. SWOT Analysis of the indigenous territory of Puracé. Source: our own, from the participatory action research explained in the text.

determine the adequate quantity that should exist and investigate minor species that have been lost and can be recovered to make a transition from larger livestock to smaller species.

One of the main problems of maintaining traditional systems is economic sustainability. Therefore, the farm units of the community must do work in three simultaneous directions: strengthen the systems of their economy, indigenous health, and food sovereignty; guarantee a good internal use value of the surplus production sold outside the community, which means to investigate ways of using it that integrate conservation of seeds into the tourist activities in the territory; and search for new commercialization chains of the regional indigenous organization and agroecological markets.

Finally, research should continue the adaptation capacity that these traditional production systems have to climate change, and on the species that can be incorporated into the UhB flows that are important to contribute to the conservation of wildlife, especially in the *páramo* area, of vital importance for the water cycle and biodiversity. It is from this mandate that Alternative Scenario is proposed.

3.5. Alternative scenario

The scenario for the reconstruction of biocultural landscapes proposed, based on the mandate agreed upon with the community, has established that the *páramo* and forest areas remain in a good state of conservation (Fig. 10), requiring an increase in carrying capacity to 1.12 LU500 in the area that is currently in open pastures. For this, it has proposed to convert the pastures to a silvopastoral system with a design that starts from the recognition of the traditional multifunctional cropping-livestock mixed system, with associated crops, rotations, staggered production, and soil nutrient cycling relying on traditional practices. The proposed agroforestry system integrates live fences on boundaries and division of gatekeepers, division of strips, and primary cultivation of lechero (*Euphorbia laurifolia*; 541 plants/ha), aliso (*Alnus acuminata*; 120 plants/ha), tilo (*Thitonia diversifolia*; 432 plants/ha) and acacia blanca (*Acacia decurrens,* 60 plants/ha).

The Alternative Scenario also proposes replacing the chemical inputs used in the territory and strengthening the recovery of agro-diversity. Accordingly, the results obtained with the traditional farm systems (Pilot Scenario) are based on the reconversion of the conventional potato model to the traditional potato system (PTP1), and from conventional coffee model to traditional shade coffee system (PTC1). Consequently, the traditional agroecosystems would have been expanded to the area of commercial potatoes and coffee, which means that the 130.92 ha would become traditional systems (Fig. 10). Of the total production, 53.7 % would be for self-consumption (food sovereignty and traditional medicine), and 42.3 % would go to the regional market.

NPP would increase by 12.4 % to 3′256,383 GJ (Fig. 11), TP would increase by 13.1 % to 330.210 GJ, EI would decrease by 13.8 % to 39,906 GJ, BR would increase by 8.3 % to 241,316 GJ, and UhB by 12.3 % to 2,948,097 GJ. The increase in UhB is associated with the decision to conserve the *páramos* and forests, and increase their area in spaces of community importance for conservation, which would guarantee the maintenance of ecosystem services despite the increase in FP.

Maintaining the primary vocation of the territory of extensive dual-purpose livestock, transitioning to an agrosilvopastoral system will allow animal feed to be 74.9 % of BR (180,733 GJ). The energy produced by the cattle herd would increase 5.2 % to 21,924 GJ in the Alternative Scenario, 2.5 % for self-consumption and 97.5 % to be sold outside. The decrease in the percentage of self-consumption occurs because the same amount of milk currently consumed would be maintained, and the rate of external sales increases. The external inputs required by the agroecosystems would decrease 9.8 % to 33,849 GJ, and human work would amount to 6057 GJ (15.2 % of the total inputs), turning external fertilizers a minimal quantity out of the total inputs (321 GJ).

The biophysical energy analysis (Fig. 5) shows that the capacity of the system to provide energy would increase by 50 % up to an EFEROI of 2.23. A high biomass reuse would be maintained, leading to an IFEROI of 0.37. However, due to the high shares of UhB and BR, the agroecosystem capacity to sustain human needs in the territory would involve a FEROI of 0.28. Whether this would be problematic or not for the population in the Puracé community needs to be accounted for looking at its own healthy reproduction as a living fund in forthcoming research. The NPP-EROI of 1 states that the indigenous territory of Puracé would be a good sustainability level, while BFEROI reaffirms that the conservation of the ‘área brava’ and gallery forest would allow a low

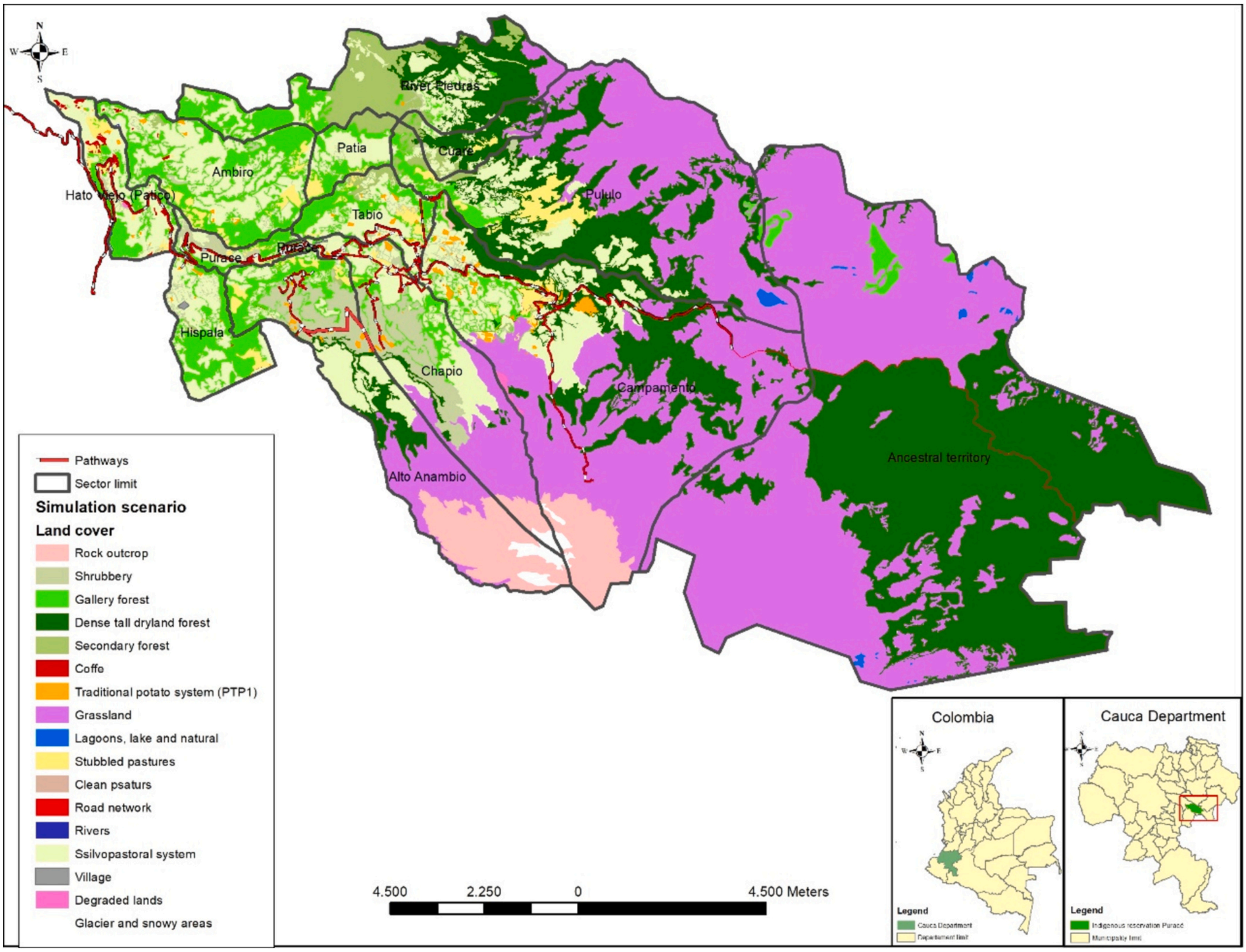

Fig. 10. Land cover map in biocultural landscape reconstruction simulation scenario. Source: our own, elaborated through GIS from the participatory action research conducted by combining indigenous and scientific knowledges.

level of farming disturbance.

3.6. Comparative analysis

Before the Green Revolution traditional systems were energy-efficient, supplying most of community needs, with low reliance on inorganic inputs. With the change in the production model, and the introduction of high-yield seeds and agrochemicals, production increased considerably. However, as demonstrated in the case study, this was done at the cost of affecting food sovereignty, culture, and sustainability, since it generated dependency on agrochemical inputs and the capacity of the systems to maintain biodiversity. The importance of the community worldview of the landscape structure, and of the relationship established by biophysical flows in the territory, stands out. The indigenous conception culturally restricts the extraction of resources because the spiritual character of some spaces keeps traditional knowledge of high ecological importance, historically allowing its conservation and sustainable use. This reflects the presence of the indigenous worldview in the biocultural landscape, giving it a spiritual character and maintaining the traditional agroecosystems, thanks to which 90.6 % of the NPP that currently photosynthesis brings about remains in the territory, following a pattern found in other Indigenous territories (Frascaroli, 2016; Toledo et al., 2019; Verschuuren et al., 2021). This pattern shows that communities define management rules that imply the restriction of agricultural use, which favors the conservation of biodiversity. The results show that traditional agroecosystems have higher NPP, FP, BR and UhB (Table 1). Therefore, scaling these systems up to the whole Kokonuko agroecosystem in the Alternative Scenario more sustainable landscapes would be generated, as shown by the increases in the same indicators and the reduction in the requirement of EI coming from fossil fuels.

When comparing the results of the biophysical analysis of the indigenous territory of Puracé with those obtained for Colombia (Urrego-Mesa, 2021a), it is found that the values of the custodians' plots for these indicators (EROIs) are similar to those obtained for the country before 1960, when the production model was still quite organic and had greater diversity, which is consistent with the community-oriented management and design of these agricultural systems.

EFEROI of traditional productive systems (Pilot Scenario) shows a lower dependence on EI than the Current Scenario (Fig. 5). In the Alternative Scenario, this dependence decreases thus increasing EFEROI. In the case of IFEROI, the organic potato system (PTP1) presents greater reuse of biomass as they are transitory crops integrated with livestock, generating more significant recirculation of biomass than traditional coffee polyculture (PTC1) and the Current Scenario of the territory. Alternative Scenario causes an increase in IFEROI that resembles the behavior of the territory with the Pilot Scenario, mainly with PTP1 (due to the greater area dedicated to this productive system).

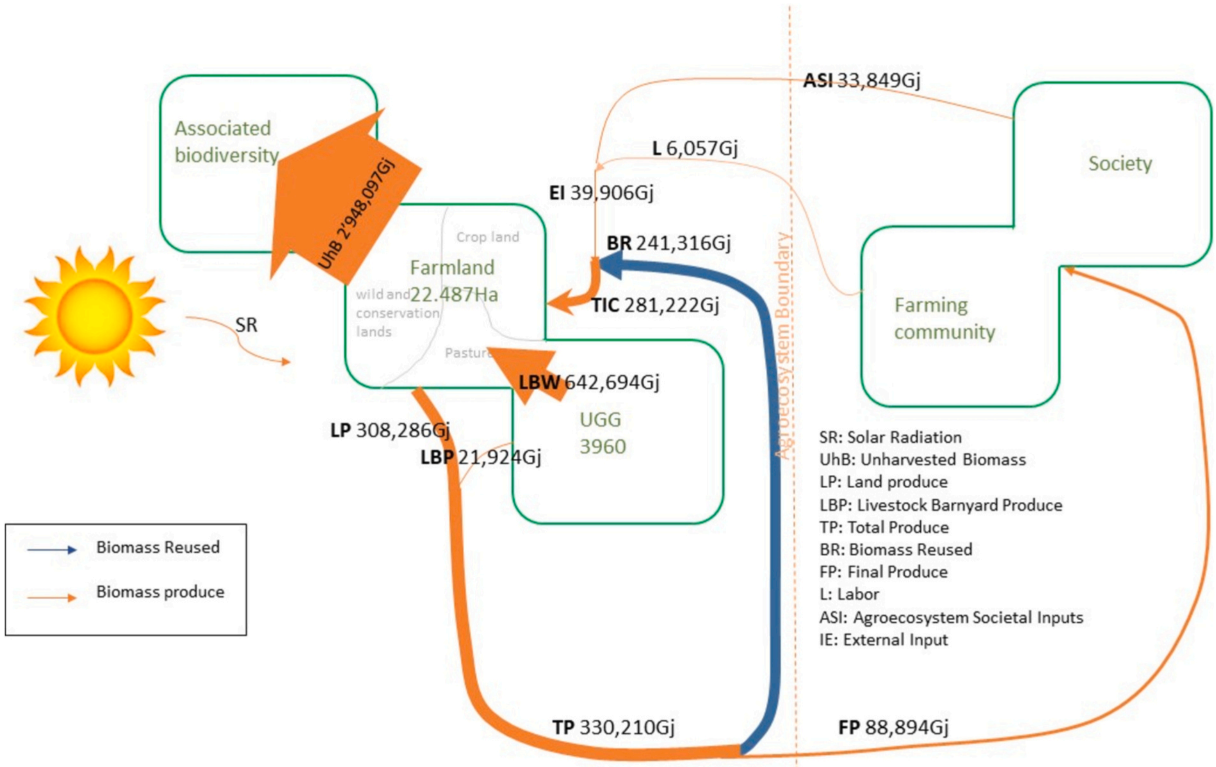

Fig. 11. Main flows of the indigenous territory of Puracé in the Alternative Scenario simulation. Source: our own, from the participatory action research conducted by combining indigenous and scientific knowledges.

Table 1
Energy content of the main biomass flows of the agroecosystem according to function.

	Area	NPP GJ/ha	TP GJ/ha	EI GJ/ha	BR GJ/ha	UhB GJ/ha
Current Scenario	22,487.6	128.8	13.0	2.1	9.9	116.7
Pilot Scenario -PTC1	1.12	217.9	193.2	4.2	154.5	47.7
Pilot Scenario -PTP1	1.94	194.5	75.8	1.1	56.1	131.6
Alternative Scenario	22,487.6	144.8	14.7	1.8	10.7	131.1

NPP: Net Primary Production; FP: Final Production; EI: External Inputs; BR: Biomass Reused; UhB: Unharvested Biomass; PTP1: traditional potato farm; PTC1: traditional shade coffee polyculture system. Source: our own, from the field work and simulation carried out through participatory action research.

FEROI in PTP1 presents greater joint energy efficiency than PTC1 and an improvement in the Alternative Scenario, which increases FP by increasing FEROI from 0.23 to 0.28.

Regarding NPP-EROI (Fig. 5), PTP1 performs better than PTC1 as expected due to the higher energy yield per unit of land of potatoes. The flip side is that coffee beans contain a smaller fraction of total NPP, making their exports more sustainable if the remaining unharvested biomass remain or return to the soil. In both the Current Scenario and the Alternative Scenarios, this indicator is related to the existence of the 'área brava' preserved, thanks to the indigenous community's biocultural relation with its territory that recognizes this area as a site of great spiritual value and allowing management rules that imply the restriction of agricultural use and limitation of income only within the framework of rituality. AFEROI considers that FP depends not only on energy inputs but also on unharvested biomass. In the case of traditional productive systems, this indicator has a greater capacity to provide energy flows available for human use, with the PTC1 being the better scored. In the case of the Alternative Scenario, there is no change in this indicator compared to the Current Scenario. Finally, BFEROI indicates that, in traditional production systems, PTC1 has less human colonization and ecological disturbance than PTP1. Concerning the scenarios for the entire territory, the Alternative Scenario would have a greater capacity to maintain the associated biodiversity within the agricultural system than the Current Scenario.

The results shows that the greater complexity of traditional farm systems provides a greater possibility of having sustainable farm systems over time, reflected in greater EFEROI in the indigenous territory of Puracé, while the rest of EROIs point out that they have a greater capacity to guarantee the healthy reproduction of the agroecosystem living funds, maintain biodiversity and, at the same time, enable enough and varied food production for human communities. Therefore, the traditional farm systems studied would facilitate the reconstruction of the biocultural landscapes of the territory, promoting the productive reconversion from the network of seed custodians and the management of polycultures, which would improve the treatment of the territory as a socio-ecological system. Finally, the possible reconstruction of agroecological biocultural landscapes evaluated in this work shows the possibility that the territory improves energy efficiency and sustainability, while guaranteeing higher levels of food production for the community and of unharvested biomass for maintaining the trophic chains that sustain biodiversity. However, it is essential to continue working on processes to strengthen food sovereignty and to analyze other products from biocultural heritage, which can further improve a future scenario of territorial sustainability.

4. Conclusions

Having an indigenous organization with the capacity to govern its own territory, and with a community governance process aimed at claiming identity, has allowed the constitution of an innovative participatory action research methodology that combines indigenous and scientific knowledges to advance in an agroecological transition that restores biocultural landscapes. The proposed transition is based on the establishment of a network of traditional seed custodians, who preserve native seeds in their plots and enrich the productive systems with native seeds resulting from exchanges with other networks, and their testing in family farm systems as 'best practices', combined with a biophysical analysis that allows evaluating the sustainability options and paths between the Current Scenario and the Alternative Scenario proposed by the indigenous organization based on a deliberative process.

In the Current Scenario, extensive cattle ranching predominates in the lower and middle part of the indigenous territory of Puracé, with gallery forests that have been the product of the reconstruction of the indigenous community based on the environmental policy that the territory has defined once the land has been recovered by the community. Conventional agriculture of commercial potatoes and coffee are grown with agrochemical management. At the same time, the upper part of the land corresponds to spaces of restricted use due to the spiritual importance for the indigenous community, although it is also affected by the expansion of extensive livestock.

Seeking to reconstruct ancestral biocultural landscapes in a context of agroecological transition, the Alternative Scenario points out to the reconversion of extensive livestock areas devoted to silvopastoral systems, the transition of commercial potato and coffee systems from agrochemical management to organically-based and nature-positive production systems, the maintenance of traditional varieties, and the restriction of use in areas of spiritual importance, in accordance with the mandate of the indigenous authorities. This will allow progress in the direction that recovers the indigenous biocultural heritage, guaranteeing food production while conserving biodiversity, within the framework of a deliberative process that facilitates the assessment of feasible scenarios.

This research reaffirms that agroecological productive systems have greater efficiency, improving territorial conditions for biodiversity, as shown in traditional coffee systems in Costa Rica and in the various indigenous systems of South and Central America (Montero et al., 2021; Ferri and Arnes Garcia, 2023; Picado and Infante, 2020; Toledo and Barrera-Bassols, 2008).

CRediT authorship contribution statement

Marta Montaño: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Olga Sanabria:** Writing – review & editing, Supervision, Funding acquisition. **Oswaldo Quilindo:** Data curation. **Alexander Urrego-Mesa:** Writing – review & editing. **Enric Tello:** Writing – review & editing. **Joan Marull:** Writing – original draft, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

We would be grateful if you considered the publishing of the enclosed manuscript Community reconstruction of biocultural landscapes. Application in the Kokonuko Indigenous Territory in Ecological Economics.

On behalf of all authors, I state that:

- The work is all original research carried out by the authors.
- All authors agree with the contents of the manuscript and its submission to the journal.
- No part of the research has been published in any form elsewhere, unless it is fully acknowledged in the manuscript.
- The manuscript is not being considered for publication elsewhere while it is being considered for publication in this journal.
- Any research in the paper not carried out by the authors is fully acknowledged in the manuscript.

Data availability

Data will be made available on request.

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Appendix A. Appendix

Annex 1
Agro-diversity in the indigenous territory of Puracé.

Botanical family	Species	Common name	Native species	Local use
Myrtaceae	*Acca sellowiana* (O. Berg) Burret	Feijoa		Food
Asteraceae	*Achyrocline lehmannii* Hieron.	Botón de oro		Medicinal
Amaryllidaceae	*Allium sativum L.*	Ajo blanco		Food/Medicinal
		Ajo morado		Food/Medicinal
Amaryllidaceae	*Allium cepa* L.	Cebolla "pati roja"		Food/ Medicinal
		Cebolleta		Food/ Medicinal
		Cebolleta blanca		Food/ Medicinal
		Cebolleta colorada		Food/ Medicinal
Amaryllidaceae	*Allium fistulosum* L.	Cebolla blanca		Food/ Medicinal
		Cebolla larga		Food
Amaryllidaceae	*Allium sativum* L.	Ajo		Food/Medicinal
Amaryllidaceae	*Allium schoenoprasum* L.	Cebollin		Food
Asphodelaceae	*Aloe vera* (L.) Burm. f.	Sábila		Medicinal
		Sábila macho		Medicinal
Verbenaceae	*Aloysia citrodora* Paláu	Cidrón		Medicinal
Asteraceae	*Ambrosia cumanensis* Kunth	Artemisa		Medicinal

(*continued on next page*)

Annex 1 (*continued*)

Botanical family	Species	Common name	Native species	Local use
Apiaceae	*Apium graveolens* L.	Apio		Food
Apiaceae	*Apium petroselinum* L.	Perejil		Food
Apiaceae	*Arracacia xanthorrhiza* Bancr.	Arracacha		Food
		Arracacha amarilla		Food
		Arracacha del Ecuador		Food
		Arracacha morada		Food
Asteraceae	*Artemisia absinthium* L.	Ajenjo		Medicinal
Asteraceae	*Baccharis latifolia* (Ruiz & Pav.) Pers.	Chilco		Medicinal
Asteraceae	*Bellis perennis* L.	Margarita		Ornamental
Amaranthaceae	*Beta vulgaris* L.	Acelga		Food
Amaranthaceae	*Beta vulgaris* L.	Remolacha		Food
Boraginaceae	*Borago officinalis*	Borraja blanca		Medicinal
		Borraja		Medicinal
Brassicaceae	*Brassica oleraceavar. Botrytis*	Coliflor		Food
Brassicaceae	*Brassica oleracea* L.	Col		Food
		Repollo		Food
		Repollo de monte	X	Food
		Repollo de peña	X	Food
Brassicaceae	*Brassica rapa* L.	Nabo		Food
Asteraceae	*Calendula officinalis* L.	Caléndula		Medicinal
Cannaceae	*Canna indica* L.	Achira		Medicinal
Solanaceae	*Capsicum annuum* L.	Ají		Food
Rutaceae	Citrus × limonia (L.) Osbeck	Limón		Food/Medicinal
Rubiaceae	*Coffea arabica* L.	Café arábigo		Food
		Café castilla		Food
		Café caturra		Food
Apiaceae	*Coriandrum sativum* L.	Cilantro		Food
Cucurbitaceae	*Cucurbita maxima* Duchesne	Zapallo		Food
Asteraceae	*Cynara scolymus* L.	Alcachofa		Medicinal
Poaceae	*Cynodon plectostachyus* (K. Schum.) Pilg.	Pasto		Food
Asteraceae	*Dahlia spp.*	Dalia		Ornamental
		Dalia amarilla		Ornamental
Apiaceae	*Daucus carota* L.	Zanahoria		Food
		Zanahoria blanca		Food
Caryophyllaceae	*Dianthus caryophyllus* L.	Clavel		Ornamental
Poaceae	*Digitaria sanguinalis* (L.) Scop.	Pasto blanco		Food
Amaranthaceae	*Dysphania ambrosioides* (L.) Mosyakin & Clemants	Paico		Medicinal
Asteraceae	*Eupatorium acuminatum* Kunth	Frailejón cenizo		Medicinal
Moraceae	*Ficus carica* L.	Higo		Medicinal
Apiaceae	*Foeniculum vulgare* Mill.	Hinojo		Medicinal
Asparagaceae	*Furcraea andina* Trel.	Fique		Artesanal
Geraniaceae	*Geranium spp*	Geranio		Ornamental
Iridaceae	*Gladiolus*	Gladiolos		Ornamental
Convolvulaceae	*Ipomoea batatas* (L.) Lam.	Batata		Medicinal
Acanthaceae	*Justicia phytolaccoides* Leonard	Descansé		Medicinal
Asteraceae	*Lactuca sativa* L.	Lechuga		Food
Lamiaceae	*Lepechinia bullata* (Kunth) Epling	Salvia negra		Medicinal
Malvaceae	*Malva parviflora* L.	Malva		Ornamental/Medicinal
Euphorbiaceae	*Manihot esculenta* Crantz	Yuca blanca		Food
Asteraceae	*Matricaria chamomilla* L.	Manzanilla		Medicinal
Lamiaceae	*Melissa officinalis L.*	Toronjil		Medicinal
Lamiaceae	*Mentha rotundifolia* L.	Menta		Medicinal
Lamiaceae	*Mentha sativa* L.	Herbabuena		Medicinal
Musaceae	Musa × sapientum L..	Plátano		Food
Solanaceae	*Nicotiana tabacum* L.	Tabaco		Medicinal
Lamiaceae	*Origanum majorana* L.	Mejorana		Medicinal
Lamiaceae	*Origanum vulgare* L.	Orégano		Food
Oxalidaceae	*Oxalis tuberosa* Molina	Oca	X	Food
Passifloraceae	*Passiflora edulis* Sims	Maracuya		Food
Passifloraceae	*Passiflora ligularis* Juss.	Granadilla		Food
Passifloraceae	*Passiflora tarminiana* Coppens & V.E. Barney	Curuba		Food
Poaceae	*Pennisetum clandestinum* Hochst. ex Chiov.	Kikuyo		Food
Piperaceae	*Peperomia garcia-barrigana* Trel. & Yunck.	Siempreviva		Medicinal
Lauraceae	*Persea americana* Mill.	Aguacate		Food
Fabaceae	*Phaseolus vulgaris* L.	Frijol amarillo		Food
		Frijol cacha	X	Food
		Frijol morado		Food
		Frijol ombligo rojo		Food
		Frijol plano	X	Food
		Frijol rayado		Food
		Frijol rojo		Food
		Frijol torta		Food
Solanaceae	*Physalis peruviana* L.	Uchuva		Medicinal
Fabaceae	*Pisum sativum* L.	Arveja		Food
Plantaginaceae	*Plantago major* L.	Llantén		Medicinal
Poaceae	*Poa pratensis* proles *alpestris* Asch. & Graebn.	Pasto poa		Food

(*continued on next page*)

Annex 1 (*continued*)

Botanical family	Species	Common name	Native species	Local use
Polygonaceae	*Polygonum nepalense* Meisn.	Corazón herido – lengua de sapo		Medicinal
Rosaceae	*Prunus persica* (L.) Batsch	Durazno		Food
Myrtaceae	*Psidium guajava* L.	Guayaba		Food/Medicinal
Brassicaceae	*Raphanus sativus* L.	Rábano		Food
Rosaceae	Rosa × gallica L.	Rosa		Ornamental
Lamiaceae	*Rosmarinus officinalis* L.	Romero		Medicinal
Rosaceae	*Rubus glaucus* Benth.	Mora de castilla		Food
Rosaceae	*Rubus ulmifolius* Schott	Mora común		Food
Polygonaceae	*Rumex crispus* L.	Barrabas		Medicinal
Rutaceae	*Ruta graveolens* L.	Ruda		Medicinal
Lamiaceae	*Salvia officinalis* L.	Salvia		Medicinal
Viburnaceae	*Sambucus nigra* L.	Sauco		Ornamental
Asteraceae	*Smallanthus sonchifolius* (Poepp.) H. Rob.	Yacón		Medicinal
Solanaceae	*Solanum betaceum* Cav.	Tomate de árbol		Medicinal
Solanaceae	*Solanum lycopersicum* L.	Tomate		Food
Solanaceae	*Solanum nigrum* L.	Yerba mora		Medicinal
Solanaceae	*Solanum quitoense* Lam.	Lulo		Food/ Medicinal
Solanaceae	*Solanum tuberosum* L.	Papa amarilla		Food
		Papa colorada careta	X	Food
		Papa común		Food
		Papa conga rosada	X	Food
		Papa guata		Food
		Papa huevo de indio	X	Food
		Papa huevo de toro	X	Food
		Papa manzana	X	Food
		Papa careta	X	Food
		Papa montañera	X	Food
		Papa parda		Food
		Papa parda blanca		Food
		Papa parda roja		Food
		Papa peruana		Food
		Papa sabanera blanca		Food
		Papa sabanera		Food
		Papa tornilla amarilla	X	Food
		Papa tornillera morada	X	Food
		Papa única		Food
		Papa yema de huevo		Food
Amaranthaceae	*Spinacia oleracea* L.	Espinaca		Food
		Espinaca de bejuco		Food
Asteraceae	*Taraxacum officinale* F.H. Wigg.	Diente de león		Food
Lamiaceae	*Thymus vulgaris* L.	Tomillo		Food/ Medicinal
		Tomillo crespo		Food/ Medicinal
		Tomillo gris		Food/ Medicinal
		Tomillo verde		Food/ Medicinal
Melastomataceae	*Tibouchina lepidota* (Bonpl.) Baill.	Siete cueros		Ornamental
Tropaeolaceae	*Tropaeolum tuberosum* Ruiz & Pav.	Majua	X	Food/Medicinal
Liliaceae	*Tulipa*	Tulipán		Ornamental
Basellaceae	*Ullucus tuberosus* Caldas	Ulluco	X	Food
		Ulluco blanco		Food
		Ulluco rosado		Food
		Ulluco morado		Food
Fabaceae	*Vicia faba* L.	Haba		Food
		Haba de la rosada		Food
Violaceae	*Viola × wittrockiana* Gams	Pensamiento		Ornamental
Poaceae	*Zea mays* L.	Maíz		Food
		Maíz amarillo		Food
		Maíz amarillo criollo		Food
		Maíz capio blanco	X	Food
		Maíz criollo		Food
		Maíz espín		Food
		Maíz maní		Food
Poaceae	*Zea mays* L.	Maíz negro		Food
		Maíz del Patía		Food
Zingiberaceae	*Zingiber officinale* Roscoe	Jengibre		Medicinal

Annex 2
Energy flows in the different scenarios.

Current scenario				
Energy flows	Current Scenario	GJ/year	%	
NPP	Net Primary Production estimated	2′896.639		
UhB	Unharvested Biomass	2′625.384	90.6 %	NPP

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Annex 2 (*continued*)

Current scenario				
Energy flows	Current Scenario	GJ/year	%	
TP	Total Produce (TP)	292.319		
LP	Land Produce (LP)	271.255	9.4 %	NPP
LP	LP-Pasturaeland	164.364	5.7 %	NPP
LP	LP-Cropland	14.557	0.5 %	NPP
LP	LP-Green manure	58,228	2.0 %	NPP
LP	LP-woodlands & scrub	34,106	1.2 %	NPP
LBP	Livestock-Barnyard Produce (LBP)	20,849		
BR	Biomass Reused (BR)	222,807	7.7 %	NPP
BR	Farmland Biomass Reused	58,444	26.2 %	BR
BR	BR-Seed	215		
BR	BR-Green manure	58,228		
BR	Livestock-Barnyard Biomass Reused	164,364	73.8 %	BR
BR	BR-Grass	164,364		
EI	External Inputs (EI)	46,296		
L	Labor (L)	8777	19.0 %	EI
ASI	Agroecosystem Societal Inputs (ASI)	37,519		
LBSI	Imported livestock food	33,092	71.5 %	EI
FSI	Agrochemicals	3931	8.5 %	EI
FSI	*Chemical fertilization*	3547	7.7 %	EI
FSI	*herbicides*	81	0.2 %	EI
FSI	*pesticides*	64	0.1 %	EI
FSI	*fungicides*	239	0.5 %	EI
FSI	Machinery	497	1.1 %	EI
LBW	Livestock-Barnyard Waste (LBW)	642,694		

Pilot Scenario PTC1				
Energy flows	PTC1 Coffee polyculture system	GJ/year	%	
NPP	Net Primary Production estimated	244.1		
UhB	Unharvested Bioomass	53.5	21.9 %	NPP
TP	Total Produce	216.4		
LP	Land Produce	190.6	78.1 %	NPP
LP	LP-Pasturaeland	152.2	62.3 %	NPP
LP	LP-Cropland	10.3	4.2 %	NPP
LP	LP-Cropland self-consumed	8.3	80.6 %	LP-Cropland
LP	LP-Cropland exported	9.3	90.3 %	LP-Cropland
LP	LP-Green manure	20.5	8.4 %	NPP
LP	LP-woodlands & scrub	7.6	3.1 %	NPP
LBP	Livestock-Barnyard Produce (LBP)	25.8		
LBP	Livestock Final Produce self-consumed	1.3	5.2 %	LBP
LBP	Livestock Final Produce exported	24.5	94.8 %	LBP
BR	Biomass Reused (BR)	173.0	70.9 %	NPP
BR	Farmland Biomass Reused	20.6	11.9 %	BR
BR	BR-Seed	0.1		
BR	BR-Green manure	20.5		
BR	Livestock-Barnyard Biomass Reused	152.4	88.1 %	BR
BR	BR-Grass	152.2		
BR	BR-Crop residue	0.2		
EI	External Inputs	4.74		
L	Labor	4.7	99.1 %	IE
ASI	Agroecosystem Societal Inputs	0.04	0.9 %	IE
LBSI	Imported livestock food	0.04		
FSI	Agrochemicals	0.0		
FSI	*Chemical fertilization*	0.0		
FSI	*herbicides*	0.0		
FSI	*pesticides*	0.0		
FSI	*fungicides*	0.0		
FSI	Machinery	0.0	0.0 %	IE
LBW	Livestock-Barnyard Waste	172.3		

Pilot Scenario PTP1				
Energy flows	PTP1 Organic potato system	Gj/year	%	
NPP	Net Primary Production estimated	377.3		
UhB	Unharvested Phytomass	255.4	67.7 %	PPN
TP	Total Produce	147.1	39.0 %	PPN
LP	Land Produce	122.0	32.3 %	PPN
LP	LP-Pasturaeland	72.1		
LP	LP-Cropland	31.4	8.3 %	PPN
LP	LP-Cropland self-consumed	0.2	0.5 %	LP-Cropland
LP	LP-Cropland exported	4.4	14.0 %	LP-Cropland

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Annex 2 (*continued*)

Pilot Scenario PTP1				
Energy flows	PTP1 Organic potato system	Gj/year	%	
LP	LP-Green manure	9.9	2.6 %	PPN
LP	LP-woodlands & scrub	8.6	2.3 %	PPN
LBP	Livestock-Barnyard Produce (LBP)	25.1		
LBP	Livestock Final Produce self-consumed	2.0	8.0 %	LBP
LBP	Livestock Final Produce exported	23.1	92.0 %	LBP
BR	Biomass Reused (BR)	108.8	28.8 %	PPN
BR	Farmland Biomass Reused	9.9	9.1 %	BR
BR	BR-Seed	0.0		
BR	BR-Green manure	9.9		
BR	Livestock-Barnyard Biomass Reused	98.9	90.9 %	BR
BR	BR-Grass	72.1		
BR	BR-Crop residue	26.8		
EI	External Inputs	2.1		
L	Labor	1.9	89.1 %	EI
ASI	Agroecosystem Societal Inputs	0.2	10.9 %	EI
LBSI	Imported livestock food	0.2		
FSI	Agrochemicals	0.0		
FSI	*Chemical fertilization*	0.0		
FSI	*herbicides*	0.0		
FSI	*pesticides*	0.0		
FSI	*fungicides*	0.0		
FSI	Machinery	0.0	0.0 %	EI
LBW	Livestock-Barnyard Waste	177.8		

Alternative Scenario				
Energy flows	Alternative Scenario	GJ/year	%	
NPP	Net Primary Production estimated	3,256,383		
UhB	Unharvested Biomass	2,948,097	90.5 %	PPN
TP	Total Produce	330,210	10.1 %	PPN
LP	Land Produce	308,286	9.5 %	PPN
LP	LP-Pasturaeland	180,733	5.6 %	PPN
LP	LP-Cropland	15,692	0.5 %	PPN
LP	LP-Cropland self-consumed	7993	50.9 %	LP-Cropland
LP	LP-Cropland exported	7473	0.2 %	LP-Cropland
LP	LP-Green manure	60,357	1.9 %	PPN
LP	LP-woodlands & scrub	51,505	1.6 %	PPN
LBP	Livestock-Barnyard Produce (LBP)	21,924		
LBP	Livestock Final Produce self-consumed (2.6 % LP)	545	2.5 %	LBP
LBP	Livestock Final Produce exported (2.6 % LP)	21,379	97.5 %	LBP
BR	Biomass Reused (BR)	241,316	7.4 %	PPN
BR	Farmland Biomass Reused	60,583	25.1 %	BR
BR	BR-Seed	226		
BR	BR-Green manure	60,357		
BR	Livestock-Barnyard Biomass Reused	180,733	74.9 %	BR
BR	BR-Grass	180,733		
EI	External Inputs	39,906		
L	Labor	6057	15.2 %	EI
ASI	Agroecosystem Societal Inputs	33,849	84.8 %	EI
LBSI	Imported livestock food	33,092		
FSI	Agrochemicals	321		
FSI	*Chemical fertilization*	287		
FSI	*herbicides*	0		
FSI	*pesticides*	3		
FSI	*fungicides*	31		
FSI	Machinery	436	1.1 %	EI
LBW	Livestock-Barnyard Waste	642,694		

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