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Comparative Life Cycle Assessment of virgin and retreaded truck tyres

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APPENDIX A

Chapter 1
Aim of the work

The primary objective of this study is to conduct a comparative analysis of the environmental impact between two product systems, i.e., a retreaded truck tyre and a virgin truck tyre, employing the Life Cycle Assessment (LCA) methodology to quantitatively evaluate their performances from the cradle to the grave and, therefore, to finally attain relative assertions related to these two systems. Central to this investigation is the critical examination of natural rubber (NR), a pivotal raw material for the tyre industry, commercially sourced from plantations of *Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg., a tropical tree species native to the Amazon basin. By delving into the details of its cultivation and processing, this research is intended to develop a Life Cycle Inventory dataset for modelling natural rubber, particularly focusing on the NR context in Thailand, one of the main producers and exporters worldwide, and seeking to establish a thorough understanding of the environmental implications embedded within the rubber supply network. Offering a rigorous and comprehensive analysis, this study aims to contribute to the ongoing discussion surrounding sustainable tyre manufacturing practices and to support decision-making within the automotive and rubber industries.

Chapter 2
Introduction

2.1 Brief history of natural rubber and tyres

Rubber knowledge and use date back to the ancient Mesoamerican and Andean civilisations and were limited to them before the European colonisation of Americas. The first European mention of rubber is reported in the *Decades de Orbe novo* of the Italian historian Peter Martyr d'Anghiera [1, 2]. Written starting from 1493 to 1525, the *Decades* were published as a complete edition in 1530 and are among the most relevant historical sources of the Age of Discovery [3]. In particular, describing the Mesoamerican ritual ballgames, in which solid black balls were used, in the *fifth decade* it is indeed possible to read [4, p.205]: "Their balls are made of the juice of a vine that climbs over the trees, […]. They cook the juice of these plants until it hardens in the fire, after which each one shapes the mass as he pleases, giving it the form he chooses. It is alleged that the roots of this herb when cooked give them their weight; at all events I do not understand how these heavy balls are so elastic that when they touch the ground, even though lightly thrown, they spring into the air with the most incredible leaps".

Those balls were manufactured from native species, primarily by mixing the latex contained in *Castilla elastica* tree (also referred to as Panama rubber tree) and the juice of *Ipomoea alba* (also called moonflower), that is a vine containing resins able to quickly coagulate the former latex [5-7].

Later, over the years, other accounts focused on the New World pointed out similar procedures among the different societies for obtaining balls and several other items: carving/puncturing trees to collect the latex, blending the two raw materials, heating and shaping before hardening was completed [5].

Up till now, the oldest rubber finds are solid balls dating to 1600 BC, discovered in Mexico [8, 9]. Thus, this means that ancient Mesoamerican cultures knew how to process latex into rubber products. It is also suggested that they were able to tailor the properties according to the applications, by changing the concentration of *Ipomoea alba* juice into the mixture [9]. This last statement is based on current empirical evidence that the mechanical properties of *Castilla elastica* rubber do vary by changing the juice to latex ratio. For instance, it is noted that a volume ratio equal to one maximises elasticity, thus would be the perfect choice for obtaining rubber balls [9].

The need for the procedure lies in the poor elastic behaviour of the purely dried latex, that resulted to be inappropriate for the desired applications. The ancient technique, instead, led to a rubbery material exhibiting suitable mechanical properties (elasticity, toughness, strength, wear resistance, etc.) to be used for their items.

It has been experimentally proven, by Nuclear Magnetic Resonance (NMR), Gas-Chromatography Mass-Spectrometry (GC-MS) and Fourier-Transform Infrared Spectroscopy (FTIR) analyses, that the extract of *Ipomoea alba* contains aliphatic methylene and methyl groups, carbonyl group, sulfonyl chloride group and sulfonic acid group [8]. On the other hand, the *Castilla elastica* latex (but this is generally/roughly valid for the natural latex secreted by other plants too) is an aqueous colloid composed of (1) rubber particles, made by polyisoprene chains and enclosed by a proteinaceous layer; (2) organic compounds, mainly proteins and resins; and (3) very small amount of inorganic matter. The adsorption of a film, constituted mainly by proteins, on rubber particles is also evident in the *Hevea brasiliensis* latex (see Section 3.3.5).

It is therefore asserted that the addition of the *Ipomoea alba* juice promotes the separation between the polymeric phase and the medium phase in the latex, solubilises/dissolves the adsorbed proteins that previously hindered polymer (inter-)chains interactions, and cross-links the polymer [8]. This explains how it was possible to obtain the coagulated rubber, far before the development of vulcanisation in the nineteenth century.

In the eighteenth century, it was thanks to the reporting works of Charles-Marie de La Condamine, Francois Fresneau and Jane-Baptiste Aublet, that the European scientific awareness of rubber (and its sources) increased.

Engaged in a scientific expedition in South America for the period 1735 – 1744, La Condamine commented the indigenous origins, procedures and uses of that material (of which some samples were sent to Paris) encountered in Ecuador, to which he referred to as ‘caoutchouc’ (French spelling), derived from the Amerindian name ‘cachuchu’ (i.e., weeping wood), while the plant was known as ‘heve’ by the native Ecuadorian Indians met; he is furthermore considered the first to have employed the term latex [1, 10-13]. It is important to mark that there is no absolute certainty on the precise plant described by La Condamine, however, it has been suggested that native ‘heve’ referred to a *Castilla* tree, and thus that the considered rubber tree belonged to the genus *Castilla* [12, 14].

Moreover, it was in that century (1770) that the name ‘India rubber’ was coined by Joseph Priestly [14, 15]. At the beginning of the nineteenth century, a first development of the rubber industry took place entailing new machines and techniques for rubber processing, and marked by the discovery of the vulcanisation in 1839 (by Goodyear/Hancock), which immediately foster western interests and consumption of rubber [14-16]. It is indeed reported that the first pneumatic tyre patent dates back to 1845, due to Robert William Thomson, and that the use of rubber in Great Britain accounted for 307 tons in the year 1840 [13, 15].

The rubber consumed, mainly originated from the native and wild tree species in the Americas, but as soon as this supply became insufficient, new lands and practices for the cultivation of rubber were sought [13, 14, 16]. Indeed, a collection of seeds (70,000 in quantity) indigenous to the Amazon rain forest were sent, in 1876, to the Kew Royal Botanic Gardens in London, for then being transported towards Ceylon, Singapore, Malaysia, and Indonesia, with the purpose of introducing the rubber seedlings [13, 15]. It was from those seedlings, that the Southeast Asian *Hevea b.* plantations derived during the twentieth century, also thanks to the development of the excision method for tapping the *Hevea b.* trees, regarded as the best plant species for obtaining rubber since 1888 [15].

In the 1900, the total exports of rubber reached approximately 45,000 metric tons, 834 of which from Southeastern Asia, where the *Hevea* plantations covered 2,000 – 2,800 hectares in that year [1, 13-15]. As the use of several rubber products lifted, included the consumption of rubber in the early versions of tyres, the Southeast Asian production, that was plantation-based, overcame wild rubber production from the Americas (1910s, 1920s) [1]. In the Far East, the area devoted to the crop and the rubber exported, reached 400,000 ha and 11,000 metric tons, respectively, in the year 1910, while, amounted to 1.6 million ha and 310,000 metric tons, respectively, in 1920 [14, 15]. Furthermore, it was in those years that *Hevea* breeding began, with the aim of improving the productivity, the climatic adaptation, and the resistance to attacks [1]. By the second half of the last century, the demand for rubber and the cultivation of its primary plant source encountered a significant increase worldwide, pushing and being influenced by technological developments, such as the internal Banbury mixer (by 1916) for compounding, the studies and use of accelerators and anti-degradants (e.g., 1,3-diphenylguanidine was marketed by 1921, mercaptobenzothiazole by 1925), and, above all, the pneumatic tyre success [1].

The aforementioned tyre concept (developed by Thomson in 1845 for carriages) did not spread further, until, nearly for decades later, John Dunlop, spurred by his son's demand for having smoother bicycle movements, re-developed the pneumatic tyre [1]. The time was propitious: the rising automotive industry triggered the success of that invention. In this way, the pneumatic tyre, originally thought for horse-drawn coaches (1845), and then for bicycles (1888), was rapidly used for motor cars, trucks (1917), airplanes (1910s), and later heavy vehicles (1950s) [1].

Apart from the development and use of synthetic rubbers, originally due to the war emergencies of Germany (in the Great War) and of the U.S.A (in the Second World War), natural rubber held and holds a pivotal importance for technically-demanding applications, and nowadays, over the 70 % of all the natural rubber produced globally, is employed as raw material for tyres [1, 15, 17].

2.2 General concepts about tyres

In the year 2010, the global tyre production amounted approximately to 1 billion units [18]. After one decade it experienced a twofold increase [19]. In 2022, the EU and the world tyre markets amounted to 423 million units and 2,32 million units, respectively [20, 21]. From a mass perspective, the 2018 world tyre production was estimated around 17 million tonnes [22].

Figure 2.1 shows the estimated tyre production in EU, according to the European Tyre and Rubber Manufacturers' Association (ETRMA) latest statistics report [17]. It amounted to 5.1 million tonnes in 2019 and decreased to 4.2 million tonnes in 2020. Similarly, the overall global production diminished in that year owing to COVID-19 pandemic, but strongly rebounded in 2021 [23]. In terms of units (actually) sold in the EU, there were 343 million tyres sold in 2019, with 5 % of them being truck tyres. In 2020, the total EU tyre sales amounted to 306 million units, with truck tires accounting for approximately the 5 % [17].

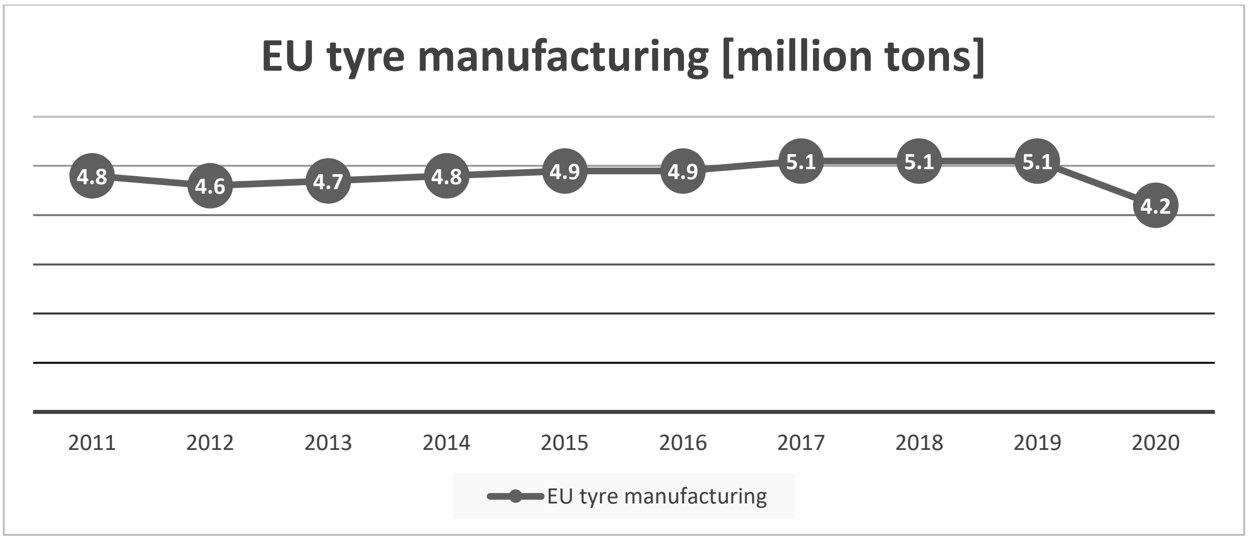

Figure 2.1: EU tyre manufacturing data for the period 2011 – 2020, adapted from [17].

As this short glimpse of statistics exhibits, it is indeed true that (1) tyres are crucial industrial products for our societies as they allow mobility/transport, that (2) the production of truck tyres represents only a part of the overall one (relatively small considering the number of units, but relevant in terms of mass[1]) and that (3) the EU tyre industry output has not changed substantially in the 2011 – 2020 decade. On the contrary, it is worth noting that in China the tyre industry has experienced a significant momentum, fuelled by its expanding automotive sector, growing from 250 million tyres in the year 2005 to 562 million units in the year 2014 [25, 26].

In the tyre market a distinction can be made between the original equipment tyres (OE) and the replacement tyres. While the OE refers to the components firstly installed on a vehicle by the manufacturer, and thus selected to match vehicle's specifications, the replacement tyres denote tyres that the owner of the vehicle buy to replace the original tyres, considering its individual preferences.

The need for vehicles, in particular motor vehicles, has experienced an increasing trend that will further continue in the future. This trend can be attributed to several factors, such as the ones associated with societal development, e.g., urbanization, income increase for specific markets and population growth [19, 22]. Thus, tyre production and sales will increase, at least in developing countries [22]. Along with tyre consumption, the replacement of tyres represents a fundamental need, resulting in the substitution of the serviceability limit states tyres (i.e., that no longer meet the functionality requirements for which they were designed) that are most referred to as end of life tyres (ELT).

It is of paramount importance to understand the complexity of tyre products, starting with the fact that not all tyres are equal. Indeed, they may differ in constituent materials, mass, size, design architecture, reaching desired performances in order to serve specific applications. In other words, several types of tyres exist that can be classified according to [27]:

(1) the vehicle category: bicycle, motorbike, passenger car, light truck, heavy truck, bus, off-the-road, agricultural, aeroplane tyres;
(2) the construction mode: bias, belted bias, radial, tubeless (etc.) tyres;
(3) the climatic conditions: dry, wet, all-season, winter, summer (etc.) tyres.

Radial type, that emerged as an incremental product innovation in 1946, witnessed an ever increasing diffusion over the bias configuration, becoming the standard construction for tyres [28]. This is due to the enhanced performance of the radial-ply type compared to that of the bias-ply type, mainly exhibiting a decreased (coefficient of) rolling resistance (i.e., decreased thermal energy loss, increased fuel-efficiency) and a longer service-life [27, 29]. Another important innovation in this

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[1] e.g., for the year 2014 the share in terms of units for truck tyres is near 5 %, while becomes 20 % if mass is considered [24].

field was the introduction and the progress of the tubeless configuration at the expense of the tubed one, further improving the tyre performance.

Tyre contributes to vehicle motion primarily acting as a support for the weight of the vehicle, allowing it to steer, accelerate and brake, ensuring grip and absorbing vibrations [22, 27]. Moreover, it must safely perform under several service conditions, or better under several sets of conditions. The application-specific requirements it must fulfil (e.g., service load, service velocities, service temperature range, etc.), the kind of surface on which it is used (e.g., asphalt roads, ground surfaces, agricultural or natural soils, racing tracks, etc.) and its actual conditions (e.g., dry, wet, covered with snow, with mud, etc.), all affect the design of the tyre (e.g., materials design, size, etc.). This is manifested, for instance, in the classification of tyres according to the vehicle category. Figure 2.2 displays the connection between two service requirements (velocity and load) and the tyre types (or equivalently, the applications).

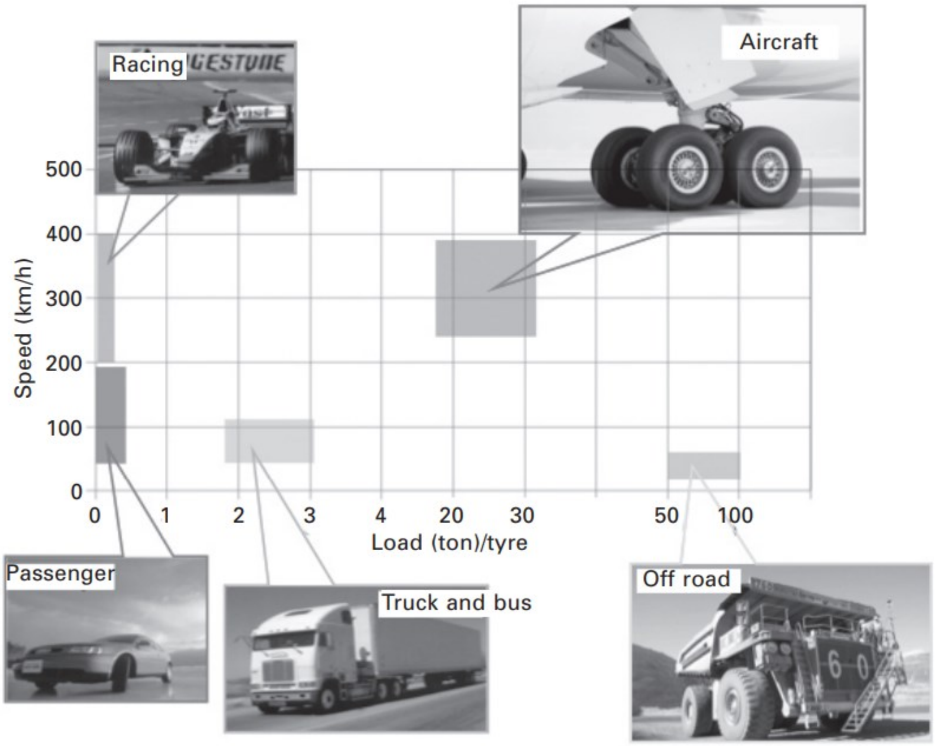


Figure 2.2: service conditions and tyre types, sourced from [27].

Considering the resulting bi-dimensional 'zone of use' for aeroplane tyres, the severity of the conditions emerges clearly. Focusing for instance on the well-known Boeing 747, it is indeed reported that all its tyres are designed to withstand 25 tonnes each, and to work at speeds as high as 380 km/h [27]. To safely operate during taxi, take-off and landing on the ground, the Boeing 747 is provided with five retractable wheeled landing gears, as shown in the Figure 2.3.

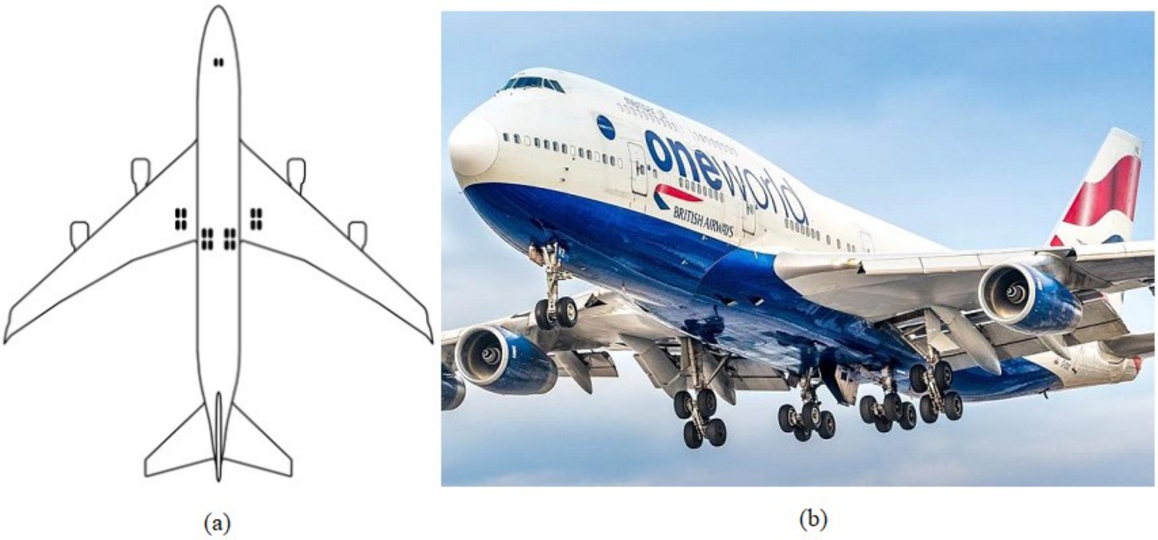


Figure 2.3: (a) Boeing 747 undercarriage arrangement, from [30]; (b) Boeing 747 undercarriage arrangement, from Pinterest.

One of these systems is located at the nose of the aircraft and it has two wheels in double configuration, among other constituents. The remaining four landing gears, two of which are positioned below the fuselage and the other two beneath the wings, carry four wheels each, arranged thus in bogie configuration. Thus, Boeing 747 distributes loads among its eighteen tyres, enhancing durability and safety (and guaranteeing not to exceed the structural limits of the airport runways). These tyres have outer diameter close to 1.3 m and width approximately equal to 0.5 m [27, 31]. Although an increase in the size of the tyre (and hence, of the overall landing gear system) enhances its bearing capacity, it will increase its mass, so will counteract the aircraft structural requirement for lightness. This contributes to explain the relatively small sizes required for aeroplane tyres. Moreover, during flying the presence of landing gear(s) outside the airframe will adversely impact the performance of the aircraft (e.g., aerodynamic drag (coefficient) will increase). Thus, retraction is needed to store the landing gears inside the structure/airframe (an operation called 'stowing up'). In the Boeing 747 case, separate hydraulic systems are present, fail-safe designed [30]. The resulting redundant systems permit safe landing even after the occurrence of failure events; the Boeing 747 is indeed designed to take-off and land operating with just two working landing gears [30, 32]. The required high load bearing capacity is achieved maintaining the tyres at specific pressure values, that depend on the aeroplane weight, number of tyres and structural characteristics of the runways [33]. The main inflation pressure of Boeing 747 tyres is approximately 1.4 MPa, which is two times that of truck tyres and more than five times that of passenger car tyres [27]. Furthermore, in the tyre design the service temperatures must be taken into account, that, in aircraft applications typically range significantly below and above zero degrees Celsius. In particular, aeroplane tyres extensively employ natural rubber in order to face with the challenging temperature, velocity and loading service conditions. They also incorporate nylon or aramid cord fabrics in the carcass to improve strength, enabling them to withstand high pressure and impacts, thereby augmenting the durability of the structure [27]. For all the tyre types, durability performance is definitely one of the most important aspects. In aircraft applications, tyres are generally retreaded up to six/seven times, after 200 – 300 flights, while the carcass life is about 10,000 km [27]. Tread patterns for aircraft tyres are generally ribbed for paved surfaces and crossed/block designed for unprepared runways. In practice, these patterns differ from those found in passenger cars and trucks. Briefly comparing truck tyres and aeroplane tyres, it is possible to state that due to the different requirements, in general, aeroplane tyres have higher pressure and smaller dimensions with respect to truck tyres. In addition, also the materials and the construction may change.

The design variables are indeed wisely selected in order to satisfy the application needs. In practice, these lasts may be less or more demanding, as previously shown in the Boeing case, and a specific type of tyre should safely perform in many different circumstances when possible. For example, we would prefer not to replace our passenger car tyres if it started raining (in cases of not extreme rain). In other words, the performances of tyres are tailored to the desired ones, and this may be pursued in a number of ways. The following example gathers some of these concepts: in addition to the dry situations, depending on the target region, a winter tyre should perform safely even dealing with ice conditions, in which a critically low coefficient of friction is generally encountered due to the film of water formed by the ice-tyre contact. The tread pattern is a fundamental design variable to face with these situations. While a smooth tread enhances dry performance (due to the greatest tyre-road contact/maximum grip, at the expense of wear behaviour; indeed, full smooth tyres are not used for ordinary mobility), a grooved tread promotes wet, snow and ice performances, depending on the specific pattern present. In particular, a tread composed of blocks with a multitude of deep grooves and the same tread with the addition of thin slits (called sipes) obtained into the blocks, are the usual patterns for snow and ice conditions, respectively [27]. Albeit sipes improve the ice behaviour, they may negatively affect the snow behaviour if their amount per block is high [27]. Thus, a proper tread pattern must be selected/designed reflecting the desired balance of the dry, wet, snow, ice performances of the winter tyre, trying to overcome the several trade-offs. A real instance is represented by the ICE ZERO™ winter tyre from Pirelli [34] shown in the Figure 2.4.


(a) (b)

Figure 2.4: (a) winter tyre and (b) particular of its tread, notice the pattern composed of grooves, blocks, sipes, and studs; from [34].

This kind of tyre is referred to as studded tyre, since its tread includes metallic studs, which can penetrate ice, to further improve grip. The Figure 2.5 qualitatively reports the attained balance of the performances.

Figure 2.5: performance of the tyre ICE ZERO™, as reported in [34].

Another route to balance winter tyre performances, that does not exclude the previous one but can be followed additionally, is to develop a special foamed immiscible blend for the tread, constituted by a functionalised high-*cis* polybutadiene rubber (HCBR), natural rubber (NR) and silica [27]. This shows that microstructural design contributes to the performance of tyres. It is not surprising then that tyres are highly engineered products.

Figures 2.6 and 2.7 show a general radial tubeless tyre and a wide base truck tyre, respectively. Their key constituents and regions are:

- the tread, the outermost part that comes in contact with the road surface, responsible for traction, water dispersion, wear resistance;
- the sidewall, the vertical section on the sides, that protects the casing laterally;

- the shoulder, that is the area between tread and sidewall, crucial for cornering stability;
- the belt package, that consists of several reinforcing layers of fabric and steel belts below the tread area, for strength and stability;
- the carcass (or body ply), generally made of structural plies (steel reinforced rubber, fabric cords), radially aligned;
- the inner liner, that is an airtight rubber layer which provides gas permeability for maintaining the right service pressure;
- the bead region, in which annular rubber-coated steel wires secure tyre to the rim of the wheel;
- the bead filler, an additional reinforcing rubber layer between bead and inner liner;
- the chafer, generally of steel or fabric cords, used to reinforce the outer bead area.

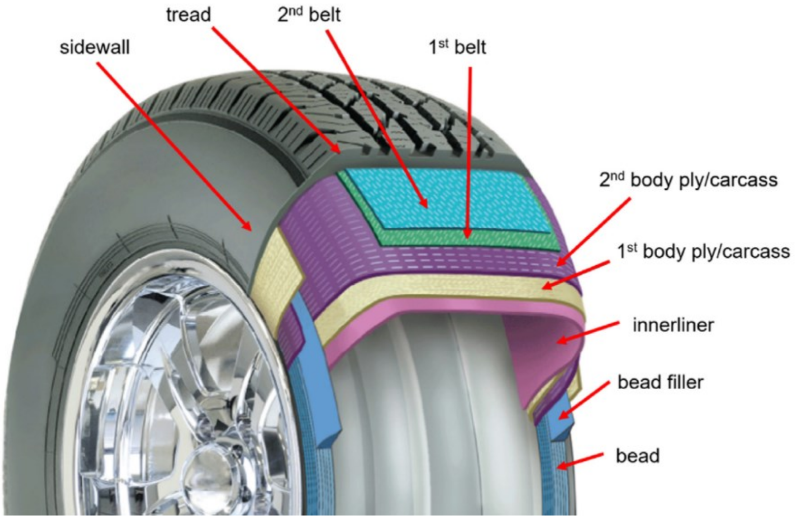


Figure 2.6: generic tyre, sourced from [24].

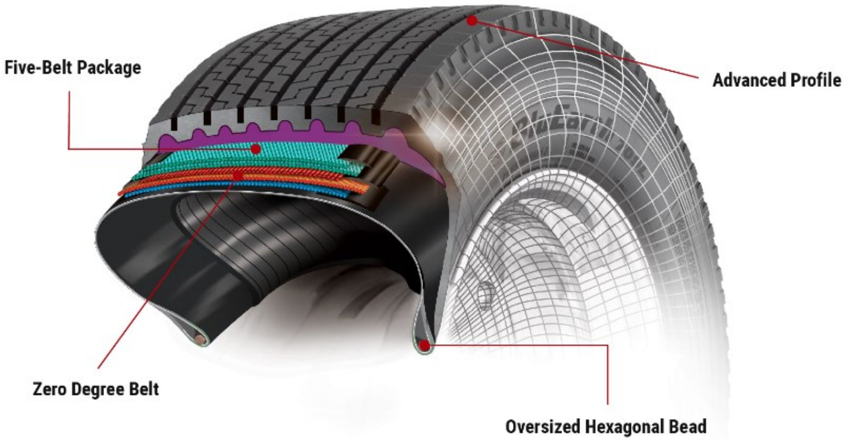


Figure 2.7: ultra-wide base tyre (Yokohama) for truck and bus applications, sourced from [35].

Both the tyres presented in those Figures exhibit the radial construction: the ply cords are aligned almost perpendicular to the tread midline, i.e., radially considering the central axis of the tyre. In a bias tyre, instead, the cords are arranged making a specific angle with the midline of the tread (or at different angles for different ply cords layers). In case of a tubed tyre, the inflation pressure is not guaranteed by the inner liner but by a system composed of a tube, a flap, and a valve.

Clearly, from a design perspective, several differences are expected between a passenger car tyre and a truck tyre since the different intended applications. With respect to a passenger car tyre, it is possible to assert that a truck tyre must exhibit higher fuel-efficiency, lower operating costs, simple maintenance [35], along with higher load-bearing capacity, higher stability, and greater durability. Besides the size of the tyres, compositional and constructional variations do exist (between all the tyre types, and in particular between passenger/light truck and truck tyres). For instance, making reference to Figure 2.7, the tread is designed specifically for increasing the mileage, the sidewalls are reinforced for dealing with the additional weight, other kinds of belts or present in different number are exploited for withstanding the higher stresses, specific beads are employed for reducing strain, and in praxis, the overall structure is designed for enhancing the retreadability. Furthermore, Figure 2.8 presents an overview of the compositions of generic passenger and generic truck tyres.

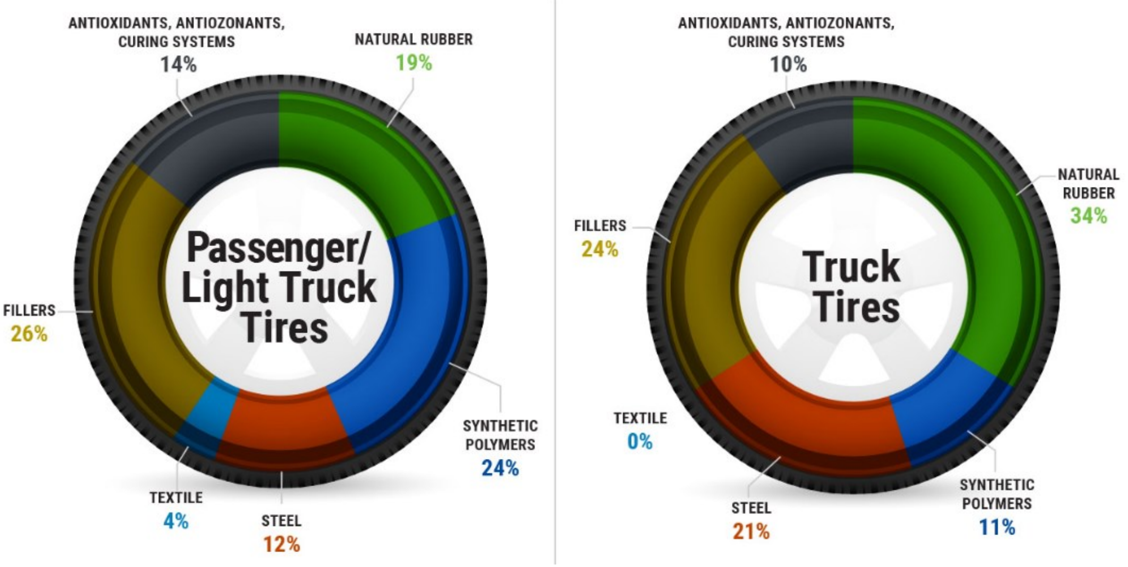
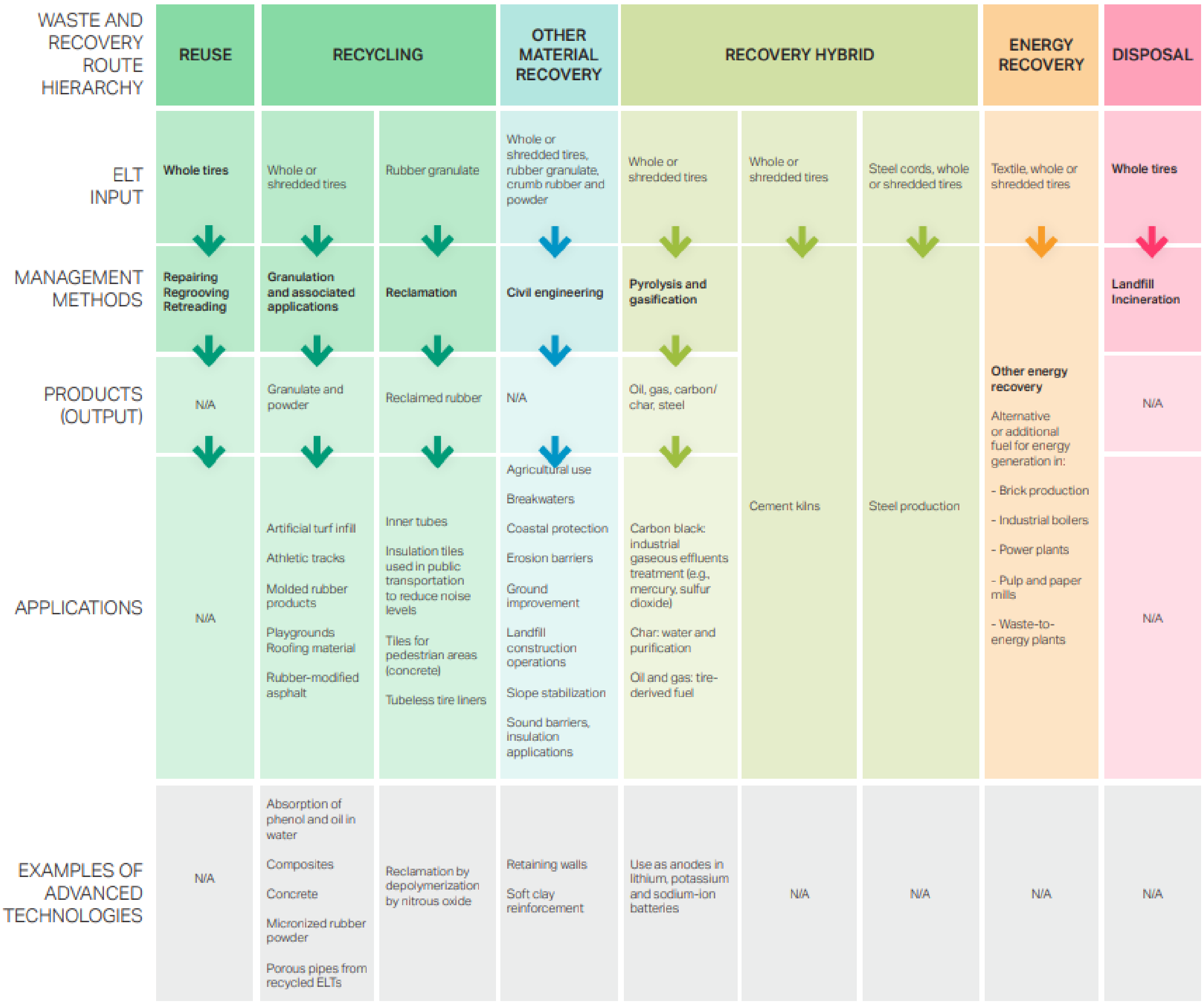


Figure 2.8: raw materials configuration mass ratio for lighter vehicles tyres and medium/heavy truck tyres, from [36].

It should be noted that (i) the proportion of steel is higher in truck tyres due to the aforementioned need for greater strength, (ii) these percentages do vary among the several tyre manufacturers and peculiar service conditions, (iii) the tyres are composed for roughly the 80 wt.% of rubbery compounds, and that (iv) the mass ratio of natural rubber is significantly high in truck tyres, representing over one third of the whole tyre.

As a matter of fact, for manufacturing the tyre components (briefly described previously) over one hundred of distinct raw materials are required [37], and in praxis, different rubber compounds are mixed for the different tyre parts because of their different conditions of stress-strain and heat. It is possible, hence, to grasp the complexity involved in designing tyres to meet specific performance requirements for the different applications.

As far as the end of life of tyres is concerned, it is reported that approximately 1 billion end-of-life tyres per year are reached worldwide [38]. Figure 2.9 shows an overview of the current alternative pathways.



WASTE AND RECOVERY ROUTE HIERARCHY	REUSE	RECYCLING		OTHER MATERIAL RECOVERY	RECOVERY HYBRID			ENERGY RECOVERY	DISPOSAL
ELT INPUT	**Whole tires**	Whole or shredded tires	Rubber granulate	Whole or shredded tires, rubber granulate, crumb rubber and powder	Whole or shredded tires	Whole or shredded tires	Steel cords, whole or shredded tires	Textile, whole or shredded tires	**Whole tires**
MANAGEMENT METHODS	**Repairing** **Regrooving** **Retreading**	**Granulation and associated applications**	**Reclamation**	**Civil engineering**	**Pyrolysis and gasification**	Cement kilns	Steel production	**Other energy recovery** Alternative or additional fuel for energy generation in: - Brick production - Industrial boilers - Power plants - Pulp and paper mills - Waste-to-energy plants	**Landfill** **Incineration**
PRODUCTS (OUTPUT)	N/A	Granulate and powder	Reclaimed rubber	N/A	Oil, gas, carbon/ char, steel				N/A
APPLICATIONS	N/A	Artificial turf infill Athletic tracks Molded rubber products Playgrounds Roofing material Rubber-modified asphalt	Inner tubes Insulation tiles used in public transportation to reduce noise levels Tiles for pedestrian areas (concrete) Tubeless tire liners	Agricultural use Breakwaters Coastal protection Erosion barriers Ground improvement Landfill construction operations Slope stabilization Sound barriers, insulation applications	Carbon black: industrial gaseous effluents treatment (e.g., mercury, sulfur dioxide) Char: water and purification Oil and gas: tire-derived fuel				N/A
EXAMPLES OF ADVANCED TECHNOLOGIES	N/A	Absorption of phenol and oil in water Composites Concrete Micronized rubber powder Porous pipes from recycled ELTs	Reclamation by depolymerization by nitrous oxide	Retaining walls Soft clay reinforcement	Use as anodes in lithium, potassium and sodium-ion batteries	N/A	N/A	N/A	N/A

Figure 2.9: end of life options for tyres, from [38].

From the environmental perspective, tyres impacts are related mainly to [37]: (i) the raw materials sourced, their potential processing in the downward network, their processing by the tyre manufacturers themselves; (ii) the use phase of tyres life cycle, with the release of tyre and road wear particles (TRWP) and the contribution of the rolling resistance to the energy consumption and emissions; and clearly, (iii) the ELT management.

One relevant alternative is to reuse the tyre at the end of its service by re-manufacture the tread and re-assemble it on the worn tyre, attaining a safely performing tyre. This process is denoted as retreading, and allows to reuse a tyre's structure, entailing several environmental advantages, besides being cheaper with respect to a new tyre purchase. However, this reuse route is possible only in some cases, depending on the old tyre conditions. According to Araujo-Morera et al. [22], retreading option contributes saving natural resources extraction, raw materials, water, energy, natural rubber industry land use, waste production, and air emissions. Generally, retreading is a common option for commercial fleets, in particular for truck tyres, which can be retreaded from four to nine times [39]. Regarding the European market, the number of truck tyres retreaded accounted for over five million units in 2011, and then showed a slightly decreasing trend, reaching four million units in 2020 [17].

In the last years, the tyre industry has addressed sustainability concerns reducing the environmental and social impacts. In addition to the environmentally friendly mindset, other driving forces have been the raw materials price fluctuations and the technological innovations. As tyre companies have to deal with numerous raw materials (note that natural rubber is itself a critical raw material for EU characterised by a high economic importance), they are particularly exposed to materials related risks, thus factors such as prices, legislation, geopolitics and conflicts may affect their supply. One of the most important risks to manage is indeed the volatility in commodity prices. Consider, for instance, the volatility of natural rubber price during the year 2020 or the increase in energy expenditure partly due to the Russo-Ukrainian war. As a result, tyre industry has started to focus more on the supply network, with a particular emphasis on natural rubber sourcing since its extensive use by tyre manufacturers and since the growing considerations about its environmental and social implications [23].

2.3 Life Cycle Assessment (LCA) methodology

Life Cycle Assessment is a method currently described by ISO 14040, 14044 to evaluate environmental aspects and potential impacts associated with a tangible or intangible product system throughout its entire life cycle. Therefore, this methodology represents a holistic approach, comprising all the stages or phases of the investigated system and their related environmental burdens/benefits. Indeed, it is only towards the quantification of these, that the LCA points to, neglecting the socio-economic factors [40]. Moreover, it should be marked that this methodology focuses on systems, rather than single products, thus, theoretically entailing the whole network of (unit) processes that provide and characterise the analysed function. In praxis, this is clearly not feasible from several perspectives, and boundaries to the investigated system(s) are necessary.

LCA encompasses four compulsory standardised steps, presented in Figure 2.10, and defined as:

1. Goal and Scope Definition, which entails the clear definition of the goal and scope of the study in terms of intended applications, driving reasons, target audience, functional unit, system boundaries, partitioning methods, assessed impact categories, data quality needs, assumptions, and limitations;
2. Life Cycle Inventory Analysis (LCI), the phase committed to the research, collection and validation of the data that quantifies the in-scope inputs and outputs for the unit processes in the analysed and modelled system;
3. Life Cycle Impact Assessment (LCIA), that is the step in which the LCI results are translated into environmental results representing the corresponding potential impacts (not the actual);
4. Interpretation, that is the final phase in which reasonings, judgements, and conclusions are attained, in relation to and restricted to the stated goal.

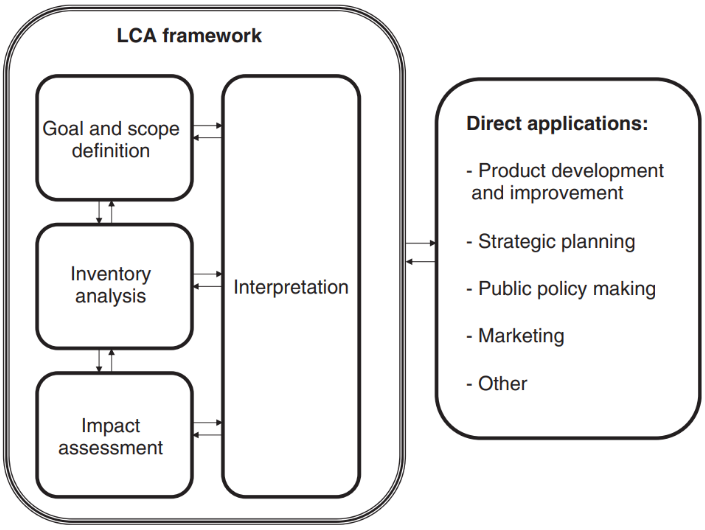


Figure 2.10: the four phases of LCA (i.e., the framework), and its applications; from [40].

As it can be seen from the Figure 2.10, performing this kind of study is generally an iterative procedure, at least in the checking and potential refinement of the inventory. Among the applications briefly summarises in Figure 2.10, the frequent ones are [41]: products comparison, benchmarking, eco-design, weak point analysis, development of Product Category Rules, development of Environmental Product Declarations, development of specific indicators (e.g., Carbon footprint), development of specific LCI results datasets, identification, monitoring or forecasting of the environmental impacts of products and industries. In other words, this tool can be used to obtain insights into the environmental aspects of specific systems, for identifying the status quo, proposing improvements, communicating performances, supporting decision making.

Chapter 3
Natural Rubber

Natural rubber can be obtained from over two thousands plant species [20], the most of which indigenous of tropical zones and belonging to seven families: Euphorbiaceae, Moraceae, Apocynaceae, Asclepiadaceae, Asteraceae, Sapotaceae, and Papaveraceae [15]. Some of these rubber yielding species are presented in Table 3.1. However, the most commercially relevant plant species is by far the tree *Hevea brasiliensis*.

Family	Scientific name	Common name	Type	Origin
Moraceae	*Castilla elastica* Sessé	Castilla/Panama rubber	Tree	Central America
	Ficus elastica Roxb.	Indian/Assam rubber	Tree	Asia (tropical)
	Ficus vogelii (Miq.) Miq.	West African rubber	Tree	Africa (tropical)
Euphorbiaceae	*Manihot glaziovi* Muell.Arg.	Ceara rubber	Tree	South America
Asteraceae	*Parthenium argentatum* Gray	Guayule rubber	Shrub	Central America
	Taraxacum kok-saghyz Rodin	Russian dandelion rubber	Shrub	Asia (temperate)
Apocynaceae	*Funtumia elastica* (Preuss) Stapf	Lagos silk rubber	Tree	Africa (tropical)
	Funtumia africana (Benth.) Stapf	Lagos silk rubber	Tree	Africa (tropical)

Table 3.1: minor rubber producing species, obtained extracting and combining information from [1, 13, 15].

3.1 World statistics

The world's annual production of natural rubber (in primary forms) in recent years (2017 to 2021) has been estimated to be steadily around 14 million tons, of which the 77 % produced in southeast Asia [42]. Table 3.2 ranks the main producing countries, according to the quantities produced[2] in the year 2020 [42].

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[2] Due to the specific classification employed by the source of origin of these data, i.e., FAOSTAT [42], it should be stated that these natural rubber production data represent the actual situation only partially (further details can be retrieved from the 'Definitions and Standards' portal of the FAOSTAT web platform [42]).

Country	Production [ton]
Thailand	4,703,171
Indonesia	3,037,348
Vietnam	1,226,096
Côte d'Ivoire	936,061
India	687,600
China	687,600
Malaysia	514,702

Table 3.2: ranking composed of data from FAOSTAT [42], regarding 2020 production of natural rubber.

The European Union is totally dependent on natural rubber imports, and, as far as the year 2020 is concerned, it imported mainly from Indonesia, Thailand, Côte d'Ivoire, and Malaysia [17].

Regarding the area devoted to rubber farming, the first six countries, in descending order, are shown in Table 3.3, according to the FAO Global Forest Resources Assessment 2020 (FAO FRA 2020, from now on) [43].

Country	Plantation area [ha]
Thailand	3,537,000
Malaysia	1,073,000
India	882,000
Cambodia	559,000
Côte d'Ivoire	542,000
Vietnam	500,000

Table 3.3: area of rubber plantations, extracted from [43].

It must be noted that the ranking proposed in table 3.3 (taken from FAO FRA 2020) is only partial, as some relevant producing country (such as Indonesia and China) did not inform about the related planted areas [43]. Nonetheless, data from FAO FRA on this issue (i.e., rubber plantation area) are deemed as the most reliable, as also indicated in [44, supporting material]. For the sake of completeness and comparison, information on the rubber area in Indonesia and China can be retrieved from the FAOSTAT database [42]. This alternative source however contains information about the harvested areas and not the plantation ones. Hence, the rubber harvested area for the year 2020 was 3,726,173 hectares in Indonesia (official figure), and 745,000 hectares in China (unofficial figure) [42]. Thus, the corresponding plantation areas for those two countries are likely to be higher.

The Figure 3.1 exhibits the extent of rubber worldwide [44]. Note that it combines data regarding the years 2010 and 2012 (see the supporting material for the quoted source).

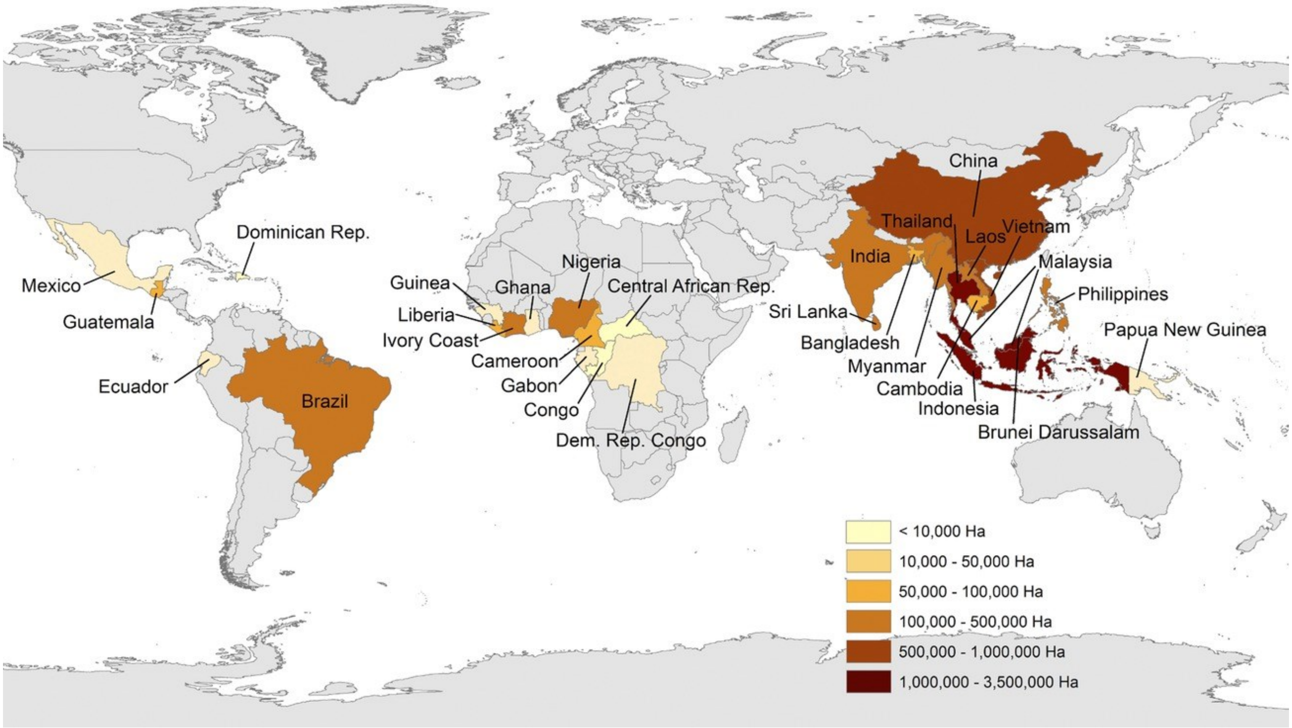

Figure 3.1: rubber plantations in the world, directly sourced from [44].

According to the FAO FRA 2020 [43], rubber plantations globally accounts for less than 8 million hectares, mainly covering the regions of South and Southeastern Asia. This, however, represents a large underestimation due to the lack of some countries' data. Indeed, it is estimated that the total global harvested area (i.e., productive area), in the year 2020, amounted to approximately 13 million hectares [42].

It is therefore clear that rubber agriculture represents a significant socio-economic activity, which involves (partially or fully) up to 30 million people worldwide [45].

3.2 Thailand as natural rubber producer

Thailand is the first natural rubber producer all over the world since 2003 [46] and the main European supplier [47]. In 2020, its production accounted for the 34 % of the total world production [42]. The export of rubber mainly regards China, EU, Malaysia, USA, Japan, and South Korea, with quantities that in the year 2022 amounted to 2,400,146 tons, 386,763 tons, 335,426 tons, 273,303 tons, 228,108 tons, 213,488 tons, respectively [48]. It should be emphasised that natural rubber holds socio-economic importance, as it represents the primary source of income for nearly 6 million people of the country on a population of 70 million citizens [49, 50]. According to FAOSTAT data [42], the national production of natural rubber (in primary forms) boomed from 186,100 tons in

1961, to 4,703,171 tons in 2020, showing a gradually increasing trend[3]. This achievement was made possible because the area committed to the cultivation of *Hevea b.* experienced a fourfold increase from 1960 to 2005 [51], while in the period 1990 – 2020, it showed an increment of the 106 %, corresponding to 1.8 million hectares of land (see Section 3.5, Table 3.8). It should be noted that, in general, Thailand has lost over 9 million hectares of forests from 1973 to 1998, representing a decrease of 41.5 % of the country forest area (see Section 3.5, Table 3.7).

The national annual production and export are presented in Table 3.4, according to the Rubber Division of the Department of Agriculture (Ministry of Agriculture and Cooperatives, Thailand) [48].

Year	2013	2015	2017	2019	2020	2021	2022
Production	4,170,428	4,473,370	5,131,710	4,736,498	4,418,767	5,168,837	5,142,492
Export	3,664,941	3,749,456	4,443,283	4,035,830	3,801,314	4,176,529	4,400,013

Table 3.4: annual production and export of natural rubber, regarding Thailand [48].

Figure 3.2 represents Thailand, emphasizing the main four regions in which is typically classified [52, supplementary material].

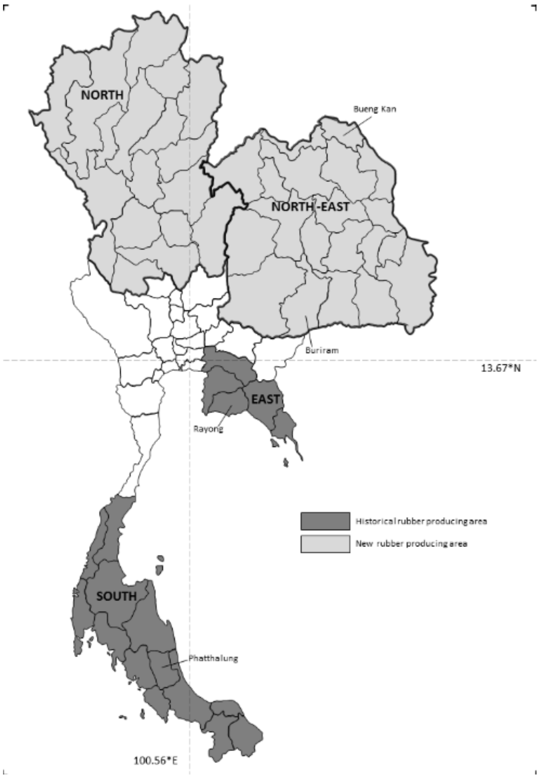

Figure 3.2: Thai country map, subdivided into main regions, directly sourced from [52].

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[3] Same comment on data quality as in note 2 (at Section 3.1).

Apart from some considerations of general validity, this study specifically focuses on the production of natural rubber in Thailand. The results of which are preparatory and used for the corresponding LCI. A brief note on Thai production data should be made. The previous comment about certain FAOSTAT data (Footnotes 2 and 3 at Sections 3.1 and 3.2, respectively), specifically regarding only the production quantity data, holds validity also in the country-specific statistics and thus in the case of Thailand. Hence, in this paragraph and elsewhere in this work (e.g., Section 3.4, Appendix A.1) other sources, deemed as clearer, more consistent and more representative of the Thai NR production, have been used, namely the Thailand Rubber Statistics (2023) [48]. These are official statistics from the Thai institutions, which consistently report the overall production and the production by types (Ribbed Smoke Sheet, Block rubber, Concentrated latex, Compound rubber, and Others). In other words, the total production is given by the sum of the production quantities for all the five types reported, as can be easily proved by comparing, for instance, the disaggregated quantities for the year 2022 of the Table 3.6 (in Section 3.4.1) with the total quantity shown in Table 3.4.

3.3 Hevea brasiliensis

The tree *Hevea b.* (family of Euphorbiaceae), also denoted as Para rubber or Rubber tree (common names), holds thus paramount importance in the world, being responsible for almost all (> 99 %) the natural rubber global production [13]. Indeed, since the last century, this tree species has been the practically sole source of latex.

3.3.1 Historical classification

Referring to the Section 2.1, in the following a concise yet detailed insight into the taxonomic delineation of *Hevea b.* is provided.

Fresneau, sent in 1732 to Cayenne in French Guiana, was able to find and describe a tree species that would later become known as *Hevea Brasiliensis* and to critically ponder on the possible applications of the rubbery material [1, 13]. He was also in contact with La Condamine, from whom he had drawn inspiration and enthusiasm for the quest.

Stemming from his years of exploration in French Guiana (1762-1764), Aublet published in 1775 the '*Histoire des plantes de la Guyane française*' in which almost four hundreds tropical plant species were described for the first time, including one rubber tree species of the genus *Hevea*, that he termed *guianensis* [1, 53, 54]. It is worth noting that Aublet likely presumed that his Guiana rubber tree was the same previously documented by La Condamine and Fresneau; this could elucidate Aublet's choice to designate the genus as *Hevea* [12].

It is pivotal to remind that several latex-bearing species exist and existed at that time. This initially led to misleading classifications, taxonomic debates, and confusion.

In 1824, Adrien de Jussieu published the *'De Euphorbiacearum generibus'*. In it, a drawing by Carl Willdenow presented the binomial *Siphonia brasiliensis* for the first time, with reference to a specimen native to the Amazon estuary (near Belém) that he had previously and probably received from Franz Sieber; thus, considering it belonging to a species different from the *Hevea guianensis* Aublet [55-57]. It is thus possible that Willdenow chose the specific epithet (i.e., the name of the species, in plant taxonomy) and attributed it to the type material before the publication of 1824 [12].

The same scientific name was then attributed to a species previously identified in 1800 in the actual Venezuelan Amazon by Alexander von Humboldt and Aime Bonpland [12]. Indeed, in the seventh volume of the '*Nova genera et species plantarum'*, published in 1825 by Humboldt, Bonpland and Kunth, a detailed depiction of *Siphonia brasiliensis* tree appeared [12, 56, 58]. It is worth mentioning that in the same description, is present, as footnote, a mention of the Willdenow tree, denoting differences between the two plants [12, 56]. That footnote, furthermore, may support the suggestion that it was from a comparison with the Willdenow specimen that Kunth then opted for the same name [12].

However, with the current knowledge, it is possible to state that the Humboldt tree does occur near the upper Orinoco, but not in the lower Amazon area; from the other hand, the Willdenow tree is not found in the Orinoco basin [12, 56]. This, according to botanical nomenclature, is a case of homonym: same epithets based on different taxa (*Siphonia brasiliensis* H. B. K. versus *Siphonia brasiliensis* Willd. ex A.Juss.).

In the '*Genera plantarum*' published by Schreber in 1791, the genus name *Siphonia* appeared for the first time, citing as author Louis Richard, who had returned to Europe two years earlier bringing a conspicuous assortment of illustrations and specimens from his voyage in South America) [12, 59, 60]. The generic name *Siphonia* was later found as a heterotypic synonym of the genus Hevea.

In the fourth edition, released in 1805, of Linnaeus' *Species Plantarum* supervised by Willdenow, the species name *Siphonia cahuchu* appeared [12, 61, 62]. It was later documented as a heterotypic synonym of *Hevea guianensis* var. *guianensis*, which is an accepted variety of *Hevea guianensis* [63].

J. F. Gmelin revised and then published in 1792 the thirteenth edition of the *Systema Naturae* by Linnaeus, in which he designated a species under the generic name *Caoutchoua* and the specific name *elastica* [12, 64]. Nowadays, this binomial is recognised as a heterotypic synonym of *Hevea* *guianensis* var. *guianensis*, while the genus *Caoutchoua* as heterotypic synonym of *Hevea* (which, as formerly stated, was named by Aublet).

It was in 1865 that Johann Mueller Argoviensis (i.e., from Aargau) transferred the species *Siphonia brasiliensis* Willd. ex A.Juss. to the genus *Hevea*, obtaining the ‘combinatio nova’ *Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg. In other words, *Siphonia brasiliensis* is the basionym of *Hevea brasiliensis* [56, 65]. This last being the currently accepted species.

Other genus and species names, later considered as synonyms, were developed in the past (also due to interpretations of nomenclature rules that led to confusion), and also infraspecific variants for a particular species can exist, as in the case of the tree species under consideration. In conclusion, *Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg. is the accepted nomenclature for the rubber tree exploited all over the globe for extracting the raw material for natural rubber [65].

3.3.2 Agroclimatic requirements

The native environment of *Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg. is characterised by a wet tropical climate, in particular by latitudes within 5 ° (i.e., amidst 5 °N and 5 °S latitude of the equator), altitudes below 200 m, average temperature in the range 25 – 28 °C, > 2000 mm per year of rainfall and no distinct dry period [1, 13, 15]. Optimal cultivation of *Hevea b.* entails the following climatic requirements [1, 13, 15]: exposure to sunlight of 2000 hours per year, with a rate of 6 hours per day; humidity near 80 % and mild wind; temperatures in the range 20 – 34 °C, with a mean of 28 °C; evenly distributed rainfall in the range 2000 – 4000 mm per year. Furthermore, suitable loamy soil exhibiting proper drainage is necessary for growing *Hevea b.* trees [13, 66]. Traditionally, *Hevea b.* has been cultivated in regions within 10 ° latitude (i.e., amidst 10 °N and 10 °S latitude of the equator) denoted as traditional rubber growing areas or humid tropics: in Southeast Asia these zones correspond to Malaysia, Indonesia, southern Thailand, south Vietnam [1, 67]. With the expanding demand of natural rubber worldwide, this tree species has spread out onto less suitable environments, indicated as non-traditional areas, reaching the Tropic of Cancer [1, 15, 16]. Indeed, nowadays, *Hevea b.* cultivation extends also over suboptimal zones such as Côte d’Ivoire (7 °N latitude), Cambodia (12 °N latitude), central (12 °N latitude) and north central (16 °N latitude) Vietnam, Northeastern Thailand (19 °N latitude), Laos (20 °N latitude), southwest China (22 °N latitude), southern plateau of Brazil (23°S latitude, Southern Tropic), Myanmar (23 °N latitude), northern India (29 °N latitude) [15, 16, 67, 68]. Some of these areas are less appropriate, being prone to several kind of stress: dry conditions, diseases, intense wind, low temperature, elevated altitude, but are still exploited [15].

As it is possible to deduce from the previous discussion, water (as rain) plays a paramount role in the growth and development of the crop. In other words, for clarity, it can be stated that *Hevea b.* plantations are managed exploiting rainwater (with rare exceptions: e.g., nurseries, some dry areas) [69]. In Thailand, the rainy season is from May to December [70].

Thailand, as a whole, presents tropical climatic conditions, which are favourable to cultivate the species. Its historical rubber-growing regions of the south and the east are humid and hot for all the year, while its northern and northeastern regions are non-traditional areas for growing rubber, exhibiting excessively low minimum temperature, humidity deficit, and a significant dry season for four – six months [1, 15, 52].

3.3.2.1 Phenology

Being grown under several agroclimatic conditions, some of which are not optimal, *Hevea b.* demonstrates, as reaction, noteworthy phenological changes. Conditions of seasonal dryness and cold (encountered moving towards the Northern Tropic) induce wintering, i.e., defoliation. This behaviour contrasts with its native, mostly evergreen phenology [71-74]. In other words, *Hevea b.* trees, cultivated within the tropics, have adapted to resist periods of environmental pressure by becoming deciduous [73, 75]; thus, shedding their leaves in conditions of intensive drought and cold stress levels. In particular, it has been proposed that this reaction to drought represents an interspecific evolutionary adaptation strategy by avoidance and not tolerance [76].

Under drought stress (due to atmospheric or soil conditions), the xylem vessels in young *Hevea b.* trees are more prone to cavitation, especially in the leaf petiole, and it is has been demonstrated that cavitation, potentially caused by the water stress, is limited thanks to the closure of the stomata (present on the surface of leaves), hence leaf petioles play an important role protecting from dysfunctions [16, 77, 78].

Moreover, *Hevea b.* shows evidence of a complex process of nutrient retranslocation (i.e., internal conservation mechanism), involving nitrogen, phosphorous, and potassium in leaves turnover: during the deciduous foliar period (leaf senescence phase), a relocation of approximately 50 % of leaf nutrients and 21 % of soil nutrients to the tree body occurred, followed by subsequent nutrient uptake up until the leaf budding period [73]. It is worth noting that the understanding the soil role in this process would be significant, as the nutrient retranslocation is linked to fertilisation practices and latex production [73].

3.3.3 Plantation

Concerning Thailand, this tree species was introduced in 1899/1900 in the southern region (and few years later in the eastern part of the country) and its planting has been intensively encouraged by the Thai state since the 1960s [51, 52, 66, 79]. Thai rubber plantations are mainly (> 80 %) covered by the clone RRIM 600, which thus represents the most common [78, 80, 81]. This high-yielding clone contributes, together with the cultivation methods, to the peculiar high yields of Thailand plantations, which are among the greatest in the world [52].

3.3.3.1 Cultivation systems

Several cultivation systems can be implemented for managing a plantation, which preliminarily can be distinguished between monospecific and diversified (i.e., multi-cropping) agricultural systems.

In the monoculture system, also referred to as monospecific, only a species is grown. On the contrary, agroforestry methods allow several species to grow alongside tree species, thus promoting the establishment of multi-species plantations. In their mature and complex state, these agroforests resemble configuration and biodiversity observed in secondary forests. Though the concept of agroforestry is old, it has been improved scientifically from the last century. It entails the integration of woody perennials (trees) with herbaceous plants (crops) and/or animals on the same unit of land, focusing on the use of native species, in order to generate multiple outputs [82]. According to their composition, it is thus possible to categorise agroforestry systems in: (i) agrisilvicultural systems, which integrate trees and crops; (ii) silvopastoral systems, that combine trees and grazing/animals; and (iii) agrosilvopastoral systems, where trees, crops and animals are together. It is important to mark however that several classifications are possible, depending on the criterion used (e.g., function, arrangement, etc.). Moreover, due to their inherent complexity, these systems exhibit significant variation: Nair [82] identified 18 main agroforestry practices commonly encountered in tropical regions. At this point, it may be appropriate to provide a comment concerning the concept of intercropping. The term intercropping defines a vast group of practices in which at least two crop species are cultivated on the same area at the same time. Of course, also this concept is implemented in practice with various spatial arrangements and with diverse compositions. It is important to note that the species planted, may show overlapping life cycles. For instance, in a two-cropping system, a crop is planted among an established crop before the harvesting of this last, thus being cultivated simultaneously only for a period of time lower than the entire life cycle: this method is called relay intercropping. Hence, the considerations here presented on agroforestry and intercropping, highlight differences between the two, one of which is that while the former entails always the tree component, the latter does not.

In Thailand, the overall rubber plantation area exhibits primarily three (rubber) productive practices: monocultural system, intensive agroforestry system, and low-intensity agroforestry system. In the following, these systems are clarified with specific regard to rubber cultivation in Thailand.

The monoculture method, which is significantly predominant, represented over 85 % – 90 % of the entire rubber area in 2010 (note that this share likely regards the year 2010 or 2011, since it is sourced from [83]; the share of 95 % is reported in Somboonsuke and Wettayaprasit (2013) quoted in [84], but this figure was not taken as reference due to unavailability of the related source) is characterised by the management of *Hevea b.* clones established with standard planting densities, in order to maximise latex production and satisfy the main constraint of light capturing during the day (so to avoid competition). The other necessary resources are not generally limiting factors: water is fairly available (except for dry areas), carbon dioxide is abundant, and nutrients are provided by fertilising. It is worth noting that increasing the planting density leads to: an increase in latex production per hectare, and a decrease in production per tree; moreover, since the rate of production increase per hectare ultimately decreases, an optimum density (range) can be found [15]. This optimal quantity is also influenced by the planting spatial arrangement, in particular the distances between the trees and between the rows play an important role on competition, which affects growth. The ideal situation for growth is achieved when inter-tree distance (or equivalently intra-row) equals the inter-row spacing. Furthermore, planting scheme selection depends on the land characteristics and its land use (i.e., one of the aforementioned rubber productive systems, in this case). For example, while one arrangement type may be more suitable for plane regions, another configuration may be more effective in hilly terrains. Generally, (in Thailand) the common scheme for planting is 3 m x 7 m, i.e., an inter-tree spacing of three metres and an inter-row distance of seven metres, resulting in a theoretically tree density of 476 stems per hectare [51, 85]. Of course, in practice, density is in a range of values, not far however from the aforesaid amount. In the relatively new planted area of northeast Thailand, an inter-row spacing of 7 – 8 m is used [86].

A standard or mean planting density actually adopted in Thai rubber plantation is not available, however, this usually ranges from 400 to 550 trees per hectare, depending on the country and spatial scheme [13, 15].

The intensive agroforestry system integrates rubber production with the production of other crops (or livestock), and in 2010 represented approximately 5 % of the whole rubber area (figure from [83]) but it has possibly a greater diffusion at present (as later clarified in the second part of this paragraph). These agroforests are generally simple, being characterised by a low degree of complexity, since the modest number of supplementary species or livestock added. In a study conducted in Phatthalung and Songkhla provinces[4], Simien and Penot [83] found that intensive rubber agroforestry farms are mainly based on: (i) rubber intercropped system (primarily with pineapple or corn as additional crop); (ii) rubber-fruit tree system (with several possible associations); (iii) rubber-rice system; (iv) rubber-livestock system (very sporadic). Thus, intercropping is encountered and indeed it constitutes a popular choice permitting to grow agricultural crops (i.e., intercrops) during the rubber trees establishment phase and therefore to generate income when Hevea b. trees cannot be tapped and/or to ensure food supply.

The rubber areas of this kind usually share the same spatial arrangement of monocultures (3 m x 7 m) [51, 70, 85]. This is mainly explained by the changes in land use that are still occurring, as clarified in the last part of this paragraph. In a recent study, focused on twelve rubber agroforestry farms from five southern provinces, Jongrungrot [87] has observed also other spatial patterns (intra-row x inter-rows): 3 m x 5 m, 3 m x 5.5 m, 3 m x 6 m, 2 m x 7 m, besides the common one of 3 m x 7 m; also noting the use of these arrangement in all the country and their use in monocultural systems too. It is important to mark that these patterns were found in systems constituted with at maximum two species each, apart from rubber tree. For this reason, these systems can be considered as simple (intensive) agroforests, since the low variety of the composition and the low (or completely null) density of non-rubber woody species. It is reported that agroforestry system of this type, established in Songkhla province, may achieve yield comparable to those of monoculture systems [85]. Warren-Thomas et al. [70] analysed 47 agroforestry and 34 monoculture plots in the Phatthalung province, all characterised by high-yielding rubber trees in productive phase, obtaining similar yields for agroforest system type (mean 1.34 tons of dry mass per ha per year) and monoculture system type (mean 1.51 tons of dry mass per ha per year) and noting, though, that (i) a small difference can exist and that (ii) these yields could have been reduced by the heavy El Niño event.

Low-intensity rubber agroforests, which in 2010 accounted for less than 10 % (statistic from [83]) of the rubber cultivation area, represent more complex systems including a wider range of species, in particular tree species, both indigenous and not, along with *Hevea b.* trees. This approach, traditionally called jungle rubber, has a well-established history, as it was the original method of rubber cultivation in southern Thailand. Stroesser et al. [84] focused on 53 agroforestry patches located in the Phatthalung province (South Thailand) obtaining, for the related complex systems, average stem densities in the range 180 – 310 trees per hectare, in which the density of the

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[4] Two southern provinces representing the 13 % of the country plantation area [72].

additional (i.e., non-rubber) tree species varies in the range 100 – 250 trees/ha. Hence, the *Hevea b.* planting density is low in these cases, leading to low yields. Warren-Thomas et al. [70] evaluated a mean planting density of 162 tree per hectare, among 39 agroforestry plots (belonging to all levels of complexity, from intensive to jungle-like systems) located in Phatthalung and Songkhla provinces. It is reported that, in jungle rubber systems located in southern Thailand, *Hevea b.* is cultivated with: (i) fruit trees (e.g., mangosteen, durian, sator bean, alak, longkong, longan, ramboutan, etc.) and herbaceous crop species (e.g., gnetum, etc.); (ii) only timber species (e.g., ironwood, neem tree, tung, mangium, champaka); (iii) fruit trees, herbaceous plants and timber species; (iv) trees and animals [83, 84]. It is recognised that the rubber yield attained with these low intensity practices, which of course varies from case to case, is remarkably lower compared to other production systems, producing less than half rubber than that achieved with monocultures [70, 85].

Note that, considering the definitions of intercropping and agroforestry, in this context of natural rubber it may be possible to use them interchangeably only as far as agrisilvicultural systems are concerned (*Hevea b.* is a tree species).

In Thailand, the cultivation of rubber trees and the subsequent latex production falls under the jurisdiction of the Ministry of Agriculture and Cooperatives [66]. The Rubber Research Institute of Thailand (RRIT), operating under the Department of Agricultural Extension, is tasked with enhancing the productivity. Additionally, the promotion, financing, and oversight of the replanting activities are the responsibilities of the Office of the Rubber Replanting Aid Fund (ORRAF), which reports to the Department of Agriculture (DOA) [66]. In 2015, both the RRIT and the ORRAF were incorporated into a new governmental agency denoted as Rubber Authority of Thailand (RAOT) [49, 85].

The majority (> 70 %) of the *Hevea b.* plantation area worldwide is managed as smallholdings, the remainder being large estates [16]. Rubber smallholders are thus small-scale farmers who manage relatively small areas of land dedicated to rubber cultivation as part of their livelihood activities. This occurs particularly in Thailand, where *Hevea b.* plantations are mainly owned by smallholders, with a share in the range 90 – 95 % of the overall country planted area [66, 83, 88]. The mean holding spans for approximately 1 – 3 hectares of land [66, 83, 88], while medium sized plantations average to 9.6 hectares, but representing less than the 7 % of the total planted area [66]. Indeed, the average area per household, in Thailand for the year 2021, accounts to circa 2.32 hectare [89]. It is reported that, in 2001, rubber farms in Thailand were roughly one million [90], and that in the year 2021 the number of households reached approximately 1.7 million [89]. Thus, the structure that characterises Thai rubber production allows rubber to be a pivotal income source (circa 3 billion

Euro per year) for a great amount of people (not only the farmers but also their families), thus gaining significant social importance [66]. It should be asserted, nonetheless, that the monoculture plantation system, which, as previously mentioned, essentially dominates the current situation in Thailand [49, 70, 83, 87], is profitable when rubber prices are high [88]. Moreover, it offers employment opportunities and foster economic expansion, during periods of high prices [87]. However, when prices diminish, the farmers' revenues, based primarily on (monocultural) rubber, are negatively affected. From the economical viewpoint, diversification, i.e., cultivate additional crops/livestock, may thus represent a viable opportunity to deal with situations of reduced rubber prices. In other words, decreasing the margin dependence on rubber and increasing the share of the production of non-rubber species of the overall margin, will increase economical resiliency, minimising the influence of fluctuating or decreasing rubber prices [83, 84, 88]. This means that, even from the economic point of view, systems other than the monocultural one (e.g., agroforestry systems) may be of great interest for Thai smallholders. For instance, the low prices encountered at the end of the last century and in the decade 2010 – 2020, had pushed towards these diversified systems. In the rubber areas progressively transformed from mono to inter cropping systems (diversification), it is however important: to control the planting distances, so as to avoid narrow ones and thus decreasing the competition for light and nutrients, and to prune the intercrops, which should be chosen on the basis of the ecosystem of the plot [87]. The reason to shift towards agroforestry were and are economical (resilience/stability, income increase in specific situations), but not only, since social functions (social role of foods) played and play a role [84]. Furthermore, there are also benefits from other perspectives, e.g., the environmental point of view. The environmental services that rubber agroforestry systems may deliver are becoming known also in the scientific literature: increased soil properties, soil nutrients content, and soil protection against erosion [82, 85, 91]; enriched biodiversity (e.g., bird and butterflies) [70]; useful byproducts, if animals are present [87]; increased wind and drought resistances [85]; microclimate regulation and exploitation of native species [82]. In summary, a multi output system (in the wide variety of agroforestry practices) enhances economic resilience (against perturbations of price volatility), may improve income, and represents an ecologically sustainable alternative. As a matter of fact, in the last decades the ORRAF (then RAOT) has started to actively promote the agroforestry practices to the Thai smallholders [85].

Following the intensive country export policies of the second half of the twentieth century, agroforestry practices were progressively abandoned in favour of the monocultural system (also, a ORRAF ban came into force and was rescinded only in 1992), even if nowadays they are gaining momentum (e.g., RAOT promotes these systems from 2015), they remain rare, that means that these practices are not developed on large areas, and are found mainly in southern Thailand (indeed all the studies cited on these topics refer to south provinces, as do also other studies in literature) [49, 91]. It should be noted that between mono- and multi- culture rubber systems, the entire management changes (e.g., fertilisers rates, pest management, etc). In all cases, *Hevea b.* clones are used and during the establishment phase (early unproductive years) it is good practice to grow annual cash crops (e.g., coffee, chili, tea, pineapple) to earn additional income for few years (i.e., short-term intercropping), when the rubber trees are not harvestable [16, 49, 66]. A planting density of 440 trees per hectare is quite an average of the whole Thai situation, thus it is assumed here as representative of the standard tree density. This is supported by the specific literature analysed (see Section 3.5.3.4 and Table 3.16), in particular by [92].

Supporting programs have always been important for Thai rubber farmers, who received assistance in several ways. Clonal varieties have been developed to improve desired characteristics (e.g., wood, to give new potentially attractive possibilities for the smallholders). The Office of Rubber Replanting Aid Fund (ORRAF) was established in 1960 for promoting high quality production of rubber, for delivering plantation technology, for facilitating trade, for offering monetary aid for the creation of new plantations, and most importantly, for subsidising smallholders with the expenditures of tree replanting (1311 EUR per ha), turning to be pivotal in order to avoid shifting to other crops [66].

3.3.3.2 Cultivation sites

In Thailand, plantations extend throughout the entire country land, and are located as shown in Table 3.5 (which refers to 2021 situation). As it is possible to note, nearly the 58 % of plantations sites are in southern Thailand. It is reported that these represented the 85 % of the total in the year 1999 (and covered the 63 % of all the agricultural area) [83]. This is confirmed also by [93]: in praxis up to the last century the vast majority of plantations were grown in the south. In the last decades, the plantation area has expanded (see Section 3.5, Table 3.8), particularly in northeast Thailand, where land previously under other uses has been converted for the first time, in the 1990s, into rubber planting areas [52, 67, 79, 94]. Indeed, the plantation area in that region of the country has undergone a twofold increase from 2001 (76,238 ha) and 2005 (152,890 ha) [86]. The literature takes into account the evolution stating that, for example, the rubber plantation area: before 2009, was mainly (84 %) found in the southern region (while the 11 % in the central region) [66]; before 2011 it was mainly situated (for the 80 %) in southern Thailand [51]; before 2010 it was mostly located (70 %) in southern Thailand [93]; in 2014 it was mostly located (for the 70 %) in southern Thailand [95]; in 2018, it mainly occurred (60 %) in southern Thailand [87].

Regarding the rubber manufacturing facilities, it is possible to affirm that these are mostly located in southern regions [96].

Table 3.5 presents, for the Thailand case and with reference to the year 2021, the rubber plantation area, the area that can be tapped, and the production of rubber [89].

	Area of standing trees [ha]	**Area that can be tapped [ha]**	**Production [tons]**
Whole country	3,914,689	3,516,091	782,792
North	247,179	211,560	39,522
Northeast	996,759	936,527	209,845
Central region	401,036	361,399	67,820
Southern region	2,269,715	2,006,605	465,605
Surat Thani*	377,616	334,803	80,610
Songkhla*	353,314	306,356	68,417
Nakhon Si Thammarat*	306,453	283,246	66,972

Table 3.5: plantation and harvested areas and production of Thailand, its main regions, and the three main southern provinces referring to year 2021; * stands for province, the main (from the production perspective) three southern provinces are shown in descending order of extent of production.

3.3.3.3 Plantation lifecycle

Regarding *Hevea b.* planting in Thailand, the predominant technique involves stump budding with improved varieties or clones (bud grafting): while the Rubber Research Institute of Thailand (RRIT) previously offered free seedlings, they now provide high quality seedlings, for improving the yield [66]. The establishment of a plantation entails preparing the land for the subsequent cultivation of the seedlings: chopping of the understorey and tilling of the land (with tractors) are required. Note that this particularly holds for monocultural rubber systems.

Generally, *Hevea b.* trees become productive, i.e., ready to be tapped, from the fifth – seventh year [13, 46, 52, 93, 97]. Their life can be distinguished, thus, in a first, immature, unproductive phase, denoted also as establishment stage, and in a second, productive, mature phase, indicated also as tapping stage. The productive phase of this species can continue up to an age of 25 – 35 years [15, 16, 52]. However, since after 25 years the trees become characterised by decreased yields, the economic lifetime of Hevea b. trees is commonly set at 25 years. Independently on the duration of the mature phase, after this stage, the trees are harvested through chainsaws (for felling and bucking operations) for allowing new tree to be planted and for obtaining rubber wood [66, 79, 98]. In praxis, stumps, roots, branches, and leaves are burnt on site (generally, but not always), while the stem is used as raw material for the local wood industry. Indeed, rubberwood (also denoted as *Hevea* wood) is a medium density tropical hardwood that is used, as industrial timber, for several applications, such as flooring, furniture, accessories [16, 66]. Once the lumber is obtained from the

Hevea b. tree stems, it is loaded (generally manually) onto small-sized trucks directly at the plantation and then sent towards the sawmills for domestic use or for export [66]. The remaining biomass of the trees (i.e., stumps, roots, branches and foliage) are often incinerated to prepare the land for the subsequent replanting [79]. It is moreover reported that the removal of stumps and roots is believed to decrease the risk of white root disease [79, 99].

It is worth noting that rubber and *Eucalyptus* ssp. plantations represent the most important sources of industrial wood, as felling in natural forests is prohibited [66]. Some density values for *Hevea brasiliensis* wood reported in literature are:

- for clone RRIM600, grown in Sao Paulo state, Brazil, 30 years old an average basic density of 553 kg/m^3, while density at 12 % moisture content (mass and volume at 12 %) equals 678 kg/m^3 [100];
- in general, so for the genus, air-dry density in the range 560÷640 kg/m^3 [101];
- for 25-30 years old trees (cut down for replanting) in Krabi province, Thailand, the average density at 12 % moisture content is 614 kg/m^3 [102];
- average density, calculated as oven-dry mass divided by green volume (i.e., basic density), of 550 kg/m^3, for clones in the Nong Khai province, Thailand [76];
- for clone RRIM600, grown in Mato Grosso do Sul state, Brazil, 33 years old, average basic density of 590 kg/m^3 and apparent density between 560÷650 kg/m^3 [103];
- for the species in the Asian continent, a basic density of 530 kg/m^3 is reported in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (simply 2006 IPCC Guidelines, from now on) [104].

Replanting occurs then every 25 years for establishing new trees. Regarding the Thailand specific literature (i.e., focused on Thailand practices), there is strong evidence and consensus on the implemented plantation lifecycle: following Jawjit et al. [46] the Thailand plantation lifetime is 20-25 years; following Petsri et al. [79], the (economic) lifetime of rubber trees is 25 years; following Jawjit et al. [92], the plantation cycle of trees is 25-30 years; according to Musikavong and Gheewala [95] the lifetime of plantations is 25 years. In other generic literature, that means not focused on Thai sites, the situation is similar: according to Warren-Thomas et al. [44, supplementary material], the lifetime of monocultural rubber trees is 25 years (consider that the great majority of rubber plantations in Thailand are monocultural, as stated in paragraph 3.3.3.1); while in the work of Birnbach et al. [97] (focused on Malaysia), a value of 25 is used, that they explicitly sourced from Petsri et al. [79], which was specific for Thailand case. Hence, considering these references, it is here supposed a plantation cycle for *Hevea b.* trees of 25 years.

Concerning, instead, the area annually subjected to replanting, this is reported to be: 48,000 ha (300,000 rai) according to [66, 98]; 34,372 ha during the period 1990 – 2004, according to [79]. Both data are sourced from the ORRAF, they are deemed consistent with each other, and are also in line with the values reported by the Royal Forest Department [105]. Furthermore, for the period 1990 – 2004, the annual average area on which combustion occurred is 11,455 ha [79], where the gap between replanted and burnt area is clearly due to the part of growers that did not practice the combustion operation. These data can be validated also considering the FAO Global Forest Resources Assessment 2015 (FRA 2015) [106], in which the total land area burned in Thailand in the period 2003 – 2012 averages to 694,000 ha; thus, acting as an upper bound for the previous values.

During the cycle, it is good practice to control weeds through the application of herbicides (mainly glyphosate), in order to reduce competition with *Hevea b.* tree, especially those in the establishment stage of growth, and to facilitate the tapping operations [1]. The inventory includes the application of glyphosate as an herbicide (see Section 5.1.1).

3.3.4 Fertilisers

Among the elements required for growing and developing plant organisms, three are denoted as primary (or also macronutrients): N, P and K, since they are needed in large amounts [15]. Fertilisation supports plant growth and productivity by supplying these primary nutrients. It is important to underline that a correct fertilisation, and more generally soil management, is pivotal in both the establishment and mature *Hevea b.* tree phases [99, 107]. This becomes utterly significant in conditions of low soil fertility (i.e., low amount of plant nutrients), as in most humid tropical soils [107]. Moreover, the rubber cultivation and re-cultivation over several planting cycles may lead to decreased soil fertility [99, 107]. The same effect is caused by harvesting and burning biomass [99]. High amounts of fertilisers may degrade the soil and water bodies [108]. It is good practice, thus, to balance the *Hevea b.* nutrient demand with the actual soil nutrient status. This means that the fertilisation dosage, should depend on the results of soil testing, in order to preserve the soil from degradation and to improve the latex yield [15, 107]. Apart from inorganic substances, sometimes organic fertilisers are also used, but quantitative information is currently absent. In praxis, the application rates of N, P, and K fertilisers in rubber plantations depend on the soil type/texture, age of trees, tree density but also on social and economic factors (e.g., traditional practices, etc.). It may be relevant to note that further studies are needed to evaluate how the whole nutrient demand is affected by the complex retranslocation process characteristic of *Hevea b.* trees under environmental constraints, so as to properly manage fertilisation.

Further discussion, with nutrient rates applied in *Hevea b.* plantations in Thailand, is explicated in the following.

The N, P fertilisation values assumed in this study (see Section 5.1.1) are taken from Jawjit et al. [93], who obtained the information from interviews and from the RRIT (the RRIT report of 2009 that the authors quoted, was not accessible); however, in the literature, the actual type(s) of fertilisers and the corresponding amount(s) used in Thai rubber plantations are not clearly specified. The reason is that fertiliser use, together with its practices, varies significantly in praxis, depending on several factors (e.g., age of plant, soil type/texture, climatic conditions, tradition and knowledge of the farmers, rubber prices). According to IFASTAT [109], the total fertilising quantity applied in Thai rubber plantations is lower than the one here assumed. On the contrary, in other studies [79, 92, 99, 110-112], the nitrogen, phosphorus and potassium fertilisers consumptions for Thai Hevea plantations are in line with those here assumed, or higher. In particular, Jawjit et al. [92], based on ten Thai farmers surveyed, report: (a) an average fertilisation of 203 kg/(ha*y) during the establishment phase (until the seventh year of the tree) while an average of 312 kg/(ha*y) in the productive stage; (b) that the related consumption is lower than the one suggested by the Thailand Rubber Institute (TRI); (c) annual values of N, P_2O_5, K_2O fertilisers equal to 34.2, 13.7 and 34.2 kg per ton of fresh latex, respectively. It should be noted, however, that: no indication about the representativeness of the ten rubber sites is given; with regard to (b), no other reference to the recommended TRI values is given, nor the search for them was profitable. From (c) and from other assumptions (e.g., allocation factors, yield) made in that work, instead, it is possible to deduce consumptions equal to 102.6 kg N fertiliser per ha per year, 41.1 kg P_2O_5 fertiliser per ha per year and 102.6 kg K2O fertiliser per ha per year; for a total of 246.3 kg/(ha*y).

Petsri et al. [79] state that: (d) the Department of Agriculture (DOA) recommends four different sets of composite fertilisers ($N-P_2O_5-K_2O$) depending on tree age and site conditions; (e) the nitrogen fertiliser annual consumption varies from 1 kg/(ha*y), in the first months of growth, to 46.88 kg/(ha*y) for trees in productive phase, derived from a LCA of the Thailand Research Fund (TRF) related to 2007 and from directives, proper of 2004, of the Department of Agriculture of the Ministry of Agriculture and Cooperatives; (f) the total composite fertiliser use ranges from 1.25 kg/(ha*y), in the first months of growth, to 312.5 kg/(ha*y) for trees in productive phase (8-25 years). In this case, it is important to mark that: none of the two sources (TRF, DOA) were available; the average total consumption for trees in productive stage is practically the same of that obtained via interviews by Jawjit et al. [92]. From the original detailed information, here briefly summarised in (f), it is possible to deduce an annual average (over the 25 years life cycle) consumption of 256 kg fertilisers per ha per year, which is similar to the total consumption previously calculated from Jawjit et al. [92] of 246.3 kg fertilisers per ha per year.

Kullawong et al. [112], based on 29 farmers interviewed, holding mature rubber sites in Northeast Thailand, report that: (g) fertilisers practices can be distinguished in high (used by approx. 14 % of the sample), medium (approx. 72 %) and low (approx. 14 %) intensity, depending, among other factors, on the amounts applied; (h) nitrogen contents supplied [kg/(ha*y)] were 137.6, 82 and 34.8 for the high, medium and low groups, respectively; (j) phosphate contents [kg/(ha*y)] were 97.7 and 33.3 for high and medium categories, respectively; (k) potash contents [kg/(ha*y)] were 69.3 and 30.1 for high and medium categories, respectively; (l) the RAOT suggested quantities [kg/(ha*y)], in case of productive sites, are 75-150 of nitrogen, 25-50 of phosphate and 90-120 of potash [112]; (m) the amount of chemical fertilisers used by the farmers surveyed was relatively high, despite the low rubber price situation, and maybe due to the lower fertility and rubber experience proper of the studied region with respect to the southern regions.

Chambon et al. [52] analysed a sample constituted by 414 rubber growers (474 mature plots), identified and selected according to precise criteria in order to ensure representativity, from four different Thai provinces, and they attain that: (n) commonly NPK fertilisers, in several grades, were intensively used (i.e., in large amounts); (o) the average use [kg/(ha*y)] corresponded to 105, 53, 92 of N, P and K, respectively; (p) fertilisers consumption varies significantly, and fertilisation is more intensive in new rubber-cultivating areas than in older regions.

Dumrongrak [111] assert that the recommended fertiliser use entails: (q) 75 kg N/(ha*y) or 150 kg N/(ha*y), depending on the soil organic matter content; (r) 25 kg P/(ha*y) or 50 kg P/(ha*y), depending on the soil available phosphorus; (s) 87.5 kg K/(ha*y) or 118.75 kg k/(ha*y) depending on the soil available potassium.

Chotiphan et al. [110] report that: (t) Thai suggested application rates are 180 g N/(tree*y), 80 g P/(tree*y) and 170 g K/(tree*y); thus, giving a more accurate depiction of the consumption, since the rates referred to the single plant.

It is possible to point out that: (l) and (q) converge (coincide for two thirds of the nutrients applications) on the fertilisers use recommended by the Thai institutions and it is thus here assumed as reliable information; fertilisers average consumptions as registered on the field in (o), and in those obtained from (c), are all consistent with each other and with the recommended ones, with regard to all the three primary nutrients. Moreover, the N and P application rates described in (h) and (j) for the medium intensity level are also in line with the recommendations.

The N, P (in the form of phosphate) and K (in the form of potash) fertilisers consumptions, as amount of nutrients supplied, assumed in this study (70, 35, 70 kg per ha per y, respectively) are in line with the ones reported in the literature analysed, and represent a mixed fertilisation system (N-P-K) characterised by an overall application of 175 kg of inorganic fertilisers per ha per y. Additionally, according to (t), the tree density assumed in this study (i.e., 440 trees per hectare, see Section 3.3.3.1) would lead to recommended fertilisers consumptions of 79.2 kg N/(ha*y), 35.2 kg P/(ha*y) and 74.8 kg K/(ha*y), which are well comparable/coherent with the rates assumed for performing this study.

The choice here made is motivated since, given the high variability of fertilisers amount used and the lack of access to the original institutional sources of the recommended consumption, the nutrient rates selected represent a conservative alternative, among the rates applied in praxis (reported in the studies previously considered), to guarantee consistency.

Finally, as it is evident from the discussion, this study may possibly underestimate the use of fertilisers and their related emissions. It is worth mentioning that the quantities reported as 'per ha' do depend on the number of trees per ha (i.e., tree density), since each tree requires the nutrients. Furthermore, it is fundamental to understand whether the expression 'fertiliser consumption/use/rate' (found in literature) refers to the actual amount of nutrient supplied to the plant(ation), or to the synthetic fertiliser as a whole, since it contains the nutrient as a part of it only; in other words, the supplied nutrient content generally differ from the fertiliser consumption, representing only a part of the whole chemical. This was considered in the analysis of the literature, and as previously mentioned, in this study the 'fertiliser use/consumption/rate' expressions refer to the nutrient content.

3.3.5 Latex and tapping

The latex harvested from the *Hevea b.* trees is a colloidal suspension constituted by several elements dispersed in an aqueous medium (up to 11 separate fractions were characterised after ultra-centrifugation) [13, 15]. The dry matter content in fresh latex is in the range of 25 – 50 %, mostly rubber particles, which generally represent 30 – 40 % of the latex and whose sizes range from 0.02 to 3 μm [13, 15]. In other words, the dry rubber content (DRC) of fresh latex goes from 30 to 40 % and in praxis it depends on several aspects, e.g., the climate conditions, period, clone type, fertilisation [113]. At the surface of a rubber particle a complex layer, composed of proteins and lipids, is absorbed, which contributes to its stability in the mixture, since ensures a negative charge [13, 15]. Beside rubber particles, other two types of particles are present [13, 15]: lutoids particles, with sizes in the range 2 – 5 μm, which contain an acid serum, generally denoted as B serum, divalent cations, and proteins; lipoids or Frey-Wyssling particles, with diameters in the range 4 – 6 nm, with elevated carotenoids and surrounded by a double membrane. It is possible to state that, apart from rubber, fresh latex is constituted by [13, 15, 113]: 1 % of proteins (27 % of which surround rubber particles); < 1 % of carbohydrates, mainly cyclitols, glucose and sucrose; 1.5 – 3 % of lipids, primarily triglycerides, sterols, free fatty acids and phospholipids; nucleic acids; < 1% of mineral matter, mainly potassium, phosphorus, magnesium; and 55 – 60 % of water.

Natural rubber, considering *Hevea b.* rubber, is a (high molecular weight) polymer (denoted as *cis*-1,4 polyisoprene) constituted by 150 – 2,000,000 isoprene units and biosynthesised in the laticifers starting from sucrose [13, 15]. According to the proposed mevalonate pathway, the main steps can be identified as (i) production of acetate and acetyl co-enzyme A from sucrose, (ii) attainment of isopentenyl pyrophosphate (IPP) (indicated also as isopentenyl diphosphate – IDP) via mevalonate, and (iii) polymerisation of IPP units into natural rubber (sequential condensation) with the totality of isoprenic bonds (near 99.8 %) in *cis* configuration [13, 15]. Another pathway for the IPP, denoted as MEP (methylerythritol phosphate) route, may be involved in the biogenesis of rubber [15, 113]. Apart from the detailed mechanism, it is clear that this synthesis encompasses (i) an initiation stage, in which allylic diphosphates are synthesised, catalysed by *trans*-prenyltransferase, (ii) an elongation stage, in which the *cis*-1,4-polymerisation of isoprene units from IPP occurs, with the catalytic activity of a *cis*-prenyltransferase (i.e., addition of IPP to polyisoprenyl diphosphate), and (iii) termination [113].

The latex is thus produced, up to a certain amount, and stored in specific vessels, called laticifers, with turgor pressure in the range 7.9 – 15 atm, which exhibits its maximum value at dawn and decreases with the daytime due to transpirational stress (i.e., higher H_2O loss through transpiration leads to a decrease in pressure potential within laticifers) [1, 15]. The laticiferous system exploited for the tapping is part of the bark of the trunk of the tree, and it is composed of cells or tubes which are laterally connected (i.e., articulated anastomosing laticifers) forming a reticular structure [1]. These secondary laticifers, present in the bark, extend in anticlockwise manner from bottom left to top right with an inclination of 30° with respect to the tree axis and are structured as concentric rings (in cross-sectional view) alternating with the phloem and parallel to the cambium [1, 15].

The metabolic activities are fundamental in the latex production after harvesting (denoted as latex regeneration), harvesting process that is known specifically as tapping: in order to obtain the latex from the *Hevea b.* tree, its bark is manually cut for circa 1 mm depth, generally in the early morning, so that the elevated turgor pressure ejects latex from the vessels, which flows, generally for few hours ([Birnbach et al. [97] report 2 – 3 hours]), through the channel created, being then collected in a cup, and the flow halts when the pressure diminishes and vessels become plugged [1, 13, 15]. This process, which does not damage the cambium, may entail different techniques, but generally it involves half of a spiral cut about the circumference, from top left to bottom right in order to comprise the great part of the laticifer system, and with an interval of one day for the next tapping (this particular harvesting frequency is called alternate day), thus it is regularly repeated [1, 13, 15]. The tapping of the *Hevea b.* trees generally begins when a minimum girth is reached (50 cm at a height of 1.25 m), that means at 5 - 7 year old, and is ended when trees attain 25 year old, after which they are cut down [13, 66]. Since the cuts wound part of the bark, the process of bark regeneration is pivotal for the differentiation of the latex vessels from the vascular cambium [1]. Indeed, a regular and not highly intensive tapping of the *Hevea b.* tree results into rubber regeneration that leads to increased yield [15]. It can be added that, sometimes, ethephon is used for increasing yield (a process known as stimulation). At each tapping, collection of the fresh latex occurs thus for a specific amount of time, after which, however, it is possible to have some late residues of latex: first, a quantity of latex could still be flowing, and since this amount is collected in the cup before the next tapping, it will be in coagulated form and it is denoted as cup lump; secondly, a quantity of coagulated latex is collected from the tapping channel, and called tree lace; thirdly, some residues on the stem and on the ground, indicated as scrap, may have been formed during the process and thus collected [13]. As a whole, these residues constitute the so called field coagulum or coagula, which represents a relatively small part of the total yield. Finally, it must be marked that harvesting *Hevea b.* trees is labour-intensive and expert workers (called tappers) are needed [114]. As far as Thailand is concerned, the stimulation of the yield via ethephon is not considered in the inventory (Section 5.1.1) due to the lack of evidence of its use in the country plantations.

3.3.5.1 Transportation to facilities

Both fresh latex and field coagulum deteriorate within few hours after collection. Due to their non-rubber constituents, coagulation and putrefaction reactions spontaneously occur, unless proper preservation is performed after the collection [13]. This is the rationale for the use of chemicals, generally ammonia, and most importantly for the prompt transport into specific facilities (generally smallholdings, in Thailand) where a first processing (primary processing) is done, in order to permit storage and further treatment. In praxis, it is good practice to employ ammonia for the preservation of fresh latex upon its arrival at the factory, preventing auto-coagulation before subsequent processing [114]. The average transportation distance of fresh latex from plantation sites to primary processing factory, as far as Thailand is concerned, is 30 km (one way trip), generally travelled with vehicles of 2.5 tons capacity each [46]. This distance is the one assumed in Section 5.1.2 of the inventory.

3.4 Primary processing

Primary processing is relevant as it yields raw rubber products, also denoted as primary (also raw or intermediate) rubber products. The fresh latex collected from the plantation can be used to obtain a liquid material or a dry rubber. Field coagulum also represents a resource for further treatment. In Thailand, farmers generally sell field latex, coagulum, and unsmoked rubber sheets to primary rubber manufacturers, which can be distinguished into: concentrated latex producers, block rubber manufacturers, and sheet rubber manufacturers [115]. The raw rubber products are briefly discussed in the following.

3.4.1 Primary rubber products

For some applications, the latex is directly concentrated to increase its dry rubber content (DRC). This concentrated latex is then used in the production of gloves, condoms, mattresses, balloons, etc., which represent, generally, the 10 % of all the global production of natural rubber [13, 114]. The remainder 90 % of the global rubber produced, is in dried form. Various types of solid rubber exist, for different applications, obtained starting from the latex and the main ones are: sheet rubber, technically specified or block rubber, crepe rubber. All the types (i.e., all the primary rubber products) can be available in different grades, according to several factors (e.g., colour, transparency, elements contents, presence of dirt or bubbles, viscosity, etc.).

Sheet rubber manufacturing follows a relatively simple process, which is widely performed in smallholdings in Thailand. After collection, the fresh latex is first diluted to enhance the processing, the colour and the transparency and the sedimentation of impurities, then it undergoes coagulation through the use of formic acid (other organic acids can be employed as alternatives), obtaining a spongy slab, which is washed and later, generally after few hours or the following day, squeezed through flat rollers for removing the entrapped water and thus attaining a thin (3 mm) sheet [13, 114]. After, the wet sheets obtained are dried so as to obtain ribbed smoked sheets (RSS), if drying occurred partially or entirely in smoke houses, or air dried sheets (ADS), if drying took place in hot air compartments. When, instead, nor of these two drying types are performed, unsmoked sheets (USS) are obtained, which are dried under shadow, and sometimes only partially [116]. These unsmoked sheets are often made by the rubber cultivators themselves. When smoke drying is performed, the sheets are hung on trolleys and exposed to temperatures in the range 40 – 60 °C for 3 – 6 days [13, 114, 116]. The rubber products obtained (sheets) are finally (visually) controlled, graded, baled, and marketed to intermediaries. It may be remarked that these RSS, ADS, USS, are generally produced in small estates. This process leads also to scrap rubber (0.007 tons per ton of RSS produced), bubble latex (0.08 tons per ton of RSS produced), and rubber cutting (0.035 tons per ton of RSS produced) as co-products, while the water used is treated by a specific wastewater system [96].

Block rubber manufacturers produce natural rubber in compact bales (blocks), palletised and packed with PE film, employing both field latex and field coagulum with minimal process changes. This product is denoted as technically specified rubber (TSR) and depending on the producing country it takes a related name, e.g., Standard Thai Rubber (STR), Standard Malaysian Rubber (SMR). The shared phases, generally performed in large factories, among the several TSR producing methods are: latex coagulation, water soaking for field coagulum, size reduction, drying, baling, testing, grading and packing [13]. Three macro stages constitute TSR manufacturing: cleaning of the raw materials, mixing and shredding the rubber inputs, and drying. To guarantee the appropriate quality of the inputs (latex, coagulum, USS), control and removal of contaminants (e.g., dirt) are two necessary operations that must be performed, in general manually [115]. After this step, denoted as preliminary cleaning process, the input materials (all coagulated) are cleaned again and cut in the pre-breaker machine [115]. Later, the resulting rubber is water soaked in circulating tanks, pressed, cleaned, cut again in the pre-breaker and then separated from the water [115]. Next, the dry rubber is sent to crepe rollers (from 2 to 8 passes) so as to obtain sheets [13]. Then, depending on the final grade desired, mixing process can be performed, after which the mixed rubber is made more homogeneous through another pass in the crepe rollers, and into the circulating tank; later, the rubber is cut into small fragments (denoted as crumb rubber) through a shredder, which are then ready for drying by hot air blowing [115]. Once dried, the TSR obtained is compacted, after being tested, to form blocks (of dimension: 675 x 330 x 190 mm^3) to permit optimal packing, then covered with PE film and palletised in one ton units [114, 115]. TSR can be produced in different grades: CV grade, L grade, 5 grade, 10 grade, 20 grade, and 50 grade, depending on ISO specifications (concerning the dirt content, initial plasticity, nitrogen content, volatile matter content, ash, viscosity, etc.) [13]. Considering the whole process, it can be stated that water plays a significant role, and its consumption is relatively high. This implies that efficient treatment of wastewater must be achieved. Electricity is also required for running machines, especially those needed for the cleaning phases; while fuel is used to generate heat needed for the drying system, indeed, dryers are generally fuelled by diesel and LPG [115]. Processing of STR 20 generates 0.024 tons of scrap rubber per ton of STR 20, as co-product [96].

Crepe rubbers, produced for applications in which light colouring is preferred, can be obtained using both field latex and/or coagulum [13]. Production of the so called pale crepe rubber entails dilution of fresh latex, bleaching, coagulation (in the same manner of sheet rubber production), washing, crepe formation, air drying for two weeks [13, 114]. In some cases, sheets of pale crepe are laminated to obtain products with desired thickness, called sole crepes [13]. If field coagulum is employed, this must be softened and purified from contaminants by water soaking, before being washed and formed into crepe [13].

Moreover, it can be noted that TSR manufacturing allows several advantages over the production of the other rubber types. Indeed, block rubber production is characterised by a lead time as low as a half day, more homogeneous quality, ease of handling, storage, and transport, higher mechanisation [13, 114]. It is important to mark that TSR (in particular STR grade 20) rubber production entails the use of field coagulum as input material, and in praxis the use of USS as input material is confirmed by [47, 115] (for the detailed specification and testing methods see [13]).

In Thailand, according to the latest official rubber statistics of the Rubber Division of the Department of Agriculture (Ministry of Agriculture and Cooperatives) [48], the national natural rubber production, disaggregated by type, is exhibited in Table 3.6.

Year	**RSS [tons]**	**Block rubber [tons]**	**Concentrated latex (DRC) [tons]**	**Compound rubber (DRC) [tons]**	**Others [tons]**
2013	912,676	1,579,788	775,662	804,784	97,518
2022	693,002	1,986,375	1,097,664	1,177,139	188,312

Table 3.6: Thai NR production in 2013 and 2022, disaggregated by type; from [48].

Furthermore, from [48] it is possible to derive that circa the 83% of the block rubber produced in Thailand in the year 2022 is exported, 86 % of which is graded STR 20. This indirectly suggests, with high confidence, that this grade of block rubber is used in the tyre industry (see Section 3.4.3). Moreover, it should be noted that the production of the STR 20 represented a high share of the total block rubber production for each year of the last decades; for instance, it is reported that it amounted to 80 % before the year 2010 [93].

3.4.2 Upstream production of natural rubber

The term upstream production of natural rubber comprises both field latex and field coagulum.

Birnbach et al. [97], whose study is focused on Malaysia, calculated that 2.17 kg of fresh latex (35 % DRC) are needed to produce 1 kg of concentrated latex (60 % DRC). Following Jawjit et al. [93] the ratio is 2:1 but without specifications on the DRC; according to Jawjit et al. [46] 1 ton (DRC) of concentrated latex is attained starting from 2.5 tons of fresh latex; Jawjit et al. [92] remark a ratio 2.5:1 between input and output. For Musikavong and Gheewala [96] 2.46 tons of fresh latex are used as input to generate 1 ton of concentrated latex (60 % DRC).

Following Jawjit et al. [93]: the amount of fresh latex needed to produce 1 ton of RSS primary rubber product is 3.3 tons; to produce instead one ton of STR 20, 2 tons of fresh latex are required (this last authors' estimation is more difficult because STR 20 is made also from cup lump, tree scrap, earth scrap). According to Musikavong and Gheewala [96] 1 ton of RSS is obtained starting from 3.31 tons of fresh latex, while 3.10 tons of fresh latex are used to produce 1 ton of STR 5, and 1.18 tons of cup lump plus 0.367 tons of USS are required to obtain 1 ton of STR 20 (the authors have considered specific few factories in southern regions).

Apart from [97], these cited studies are Thai-specific, thus representativeness is deemed high.

The mass ratios between the harvested material (i.e., field latex, field coagulum) necessary to manufacture the intermediate (or also called primary) rubber products and the intermediate products themselves, are depicted by the ratios here specified: regarding concentrated latex a ratio of 2 is chosen for conservative reasons; for RSS a ratio equal to 3.3 is assumed; concerning block rubber (TSR) a ratio of 2 is selected, thus fairly using the ratio reported for STR 20 as proxy for the whole type of block rubber (since this grade represents the main part of that category); in the case of compound rubber, this type of rubber is assumed as TSR and thus with the corresponding ratio. Moreover, since the compound rubber produced in Thailand is generally from 80 to 95 % natural rubber [117], it is here supposed that compound rubber is made by 80 % of natural rubber, and then that this NR is in the form of TSR. In other words, block rubber type is used (in Appendix A.1) also as a proxy for compound rubber type, due to lack of data on the inputs necessary for its production.

This information is used for estimating the latex yield (field latex and field coagulum yields; reported in the Appendix A.1 to this work) used for the LCI of natural rubber plantation (Section 5.1.1 in the inventory).

3.4.3 Types of natural rubber for tyre industry

There is no consensus in the literature on the inputs from which tire-grade rubber is obtained. In other words, there is no unique answer to the query regarding which specific type (or types) of natural rubber, among the primary rubber products, is sourced for tyre applications.

According to Hirata et al. [27] both RSS and TSR types are used as raw materials in tyres applications. Following Jawjit et al. [93] the RSS and RSSB (in bale form) are used as raw materials for producing tires (this is also accepted and "used" by Musikavong and Gheewala [96]). Following Jawjit et al. [93] block rubber is used for belts etc. (this is also accepted and "used" by Musikavong and Gheewala [96]). In the work of Pyay et al. [47, figure 1] it is possible to read that both STR 20 and RSS types are used for vehicle tires. According to Sakdapipanich and Rojruthai [113]: the main type of raw rubber product used for automobile tyre manufacturing is RSS; and tyre rubber is obtained with 30% USS, 30% field coagulum (both converted into wet crumb), 30 % latex rubber and 10 % plasticiser (coagulated latex is blended with the wet crumb). Considering the data collected from European tyre companies, the NR type employed is the TSR.

Therefore, in this LCA study, with high confidence the focus is put on the TSR only, in particular on the STR 20 grade, as the primary raw rubber type used for tyres (see Sections 5.1, 5.2 and 5.3).

3.4.3.1 Transportation to tyre manufacturers

For the LCA analysis, the assumed transport regarding rubber products, from Thailand to Europe, is here briefly discussed. The distance from primary processing facility, where the block rubber (as STR 20 grade) production occurs, towards a port for the next shipping is not assessed, since lack of specific manufacturing site and any literature average. The resulting transportation is neglected. However, all the remaining distances and transportations (regarding TSR) are considered as follows, focusing on Ofir (Europe) as final destination where tire-grade rubber (TSR) is used for manufacturing.

For port-to-port shipping (ocean freight transportation) are considered:

- port of origin: Laem Chabang, since it is the main port of Thailand (in terms of exported NR quantity), as confirmed by the latest Thailand Rubber Statistics [48, table 8];
- port of destination: Trieste or Genova (two of the main north Italian ports).

Using the web search tool available at [118], real information about the distances and the carriers was collected.

Considering Trieste as discharge port, the transport stages (in order of precedence) are as follows:

1. 13853 km by ocean container ship (from Laem Chabang to Trieste);
2. Alfabeta km with rail (from Trieste to XXX);
3. Gammadelta km by truck (from XXX to Ofir).

Note that: Trieste means Trieste Marine Terminal (TMT); Padova means Padova Interporto (ITPDA).

In this LCA, Trieste port was assumed as the European destination. If instead Genova port had been considered, the transport stages (in order of precedence) would have been those expressed below:

1. 13830 km by ocean container ship (from Laem Chabang to Genova);
2. Epsilon km with rail (from Genova to XXX);
3. Zeta km by truck (from XXX to Ofir).

3.5 Land use change (LUC)

A land use represents the way in which land is utilised by humans for various purposes (e.g., agricultural, residential, industrial), and therefore, it encompasses the different functions assigned to a particular area of land. Land use changes describe alterations in how land is used over time. These conversions, that can result from e.g., agricultural expansion, deforestation, urbanisation, may affect ecosystems, biodiversity, and climate. The net emissions arising from both land use activities and changes are commonly termed land use emissions [119]. Regarding land use classes, several classifications exist, organized hierarchically in levels that increase in detail. For instance, a classification system used in Thailand, based on three levels, distinguishes between five main land use classes (or types) at the first level (agricultural land, forest land, water bodies, miscellaneous land, built-up land), thirty-four land use types at the second level (paddy field, perennial, orchard, pasture and farmhouse, etc.), achieving the finest classification in the third level (e.g., teak, rubber tree, etc. for the perennial type of the second level) [120].

3.5.1 Overview of data, sources, and methodology

According to Warren-Thomas et al. [70, p.18], in Thailand "much lowland forest has been converted to rubber", mainly characterised by a monocultural production, as previously specified. From Warren-Thomas et al. [44], it is possible to understand that the original land use of the current rubber plantations in continental southeast Asia were mainly agriculture and tropical forest, in other words: conversion of cropland and forest into *Hevea b.* has occurred. Indeed, in the work of Warren-Thomas et al. [44, supplementary material] it is reported that, for montane mainland Southeast Asia (MMSEA), the land uses, before the rubber plantations were established, were natural vegetation/cropland mosaics (for the 56 %), cropland (for the 30 %) and forest (for the 14%) [note that all these percentages are related to a part, over 60%, of the total rubber planted area, that was possible to identify].

Data and literature were analysed in order to understand the former land use types of the current rubber plantation area in Thailand. Only direct Land Use Change (dLUC) is considered.

From the Thai Office of Forest Land Management, the most recent data available representing the forest area are shown in Table 3.7, which is obtained from the original statistics [121].

Forest area in Thailand [ha]	**%**	**Year**
22,170,700	43	1973
19,841,700	39	1976
17,522,400	34	1978
15,660,000	31	1982
15,086,600	29	1985
14,380,300	28	1988
14,341,700	28	1989
13,669,800	27	1991
13,355,400	26	1993
13,148,500	26	1995
12,972,200	25	1998
17,011,078	33	2000
16,759,098	33	2004
16,100,130	31	2005
15,865,259	31	2006
17,158,565	33	2008
16,339,126	32	2013
16,365,664	32	2014
16,358,557	32	2015
16,347,969	32	2016
16,345,016	32	2017

Table 3.7: forest area in Thailand, from [121].

It is important to state that since the year 2000, the presented data had been obtained via satellite. Moreover, the total area of the country results to be equal to 51,764,592 ha [121]. These data are also used from the Global Forest Resources Assessments of the FAO (FAO FRAs) for the specific case of Thailand. However, one difference that is pivotal to mark is that while the original data of the Office of Forest Land Management [121] (i.e., information shown in Table 3.7) do not include *Hevea b.* areas, in the FAO FRA 2020 [43] the rubber plantation area is instead included, so counted as forest area. In the last FAO FRA report (i.e., 2020) a particular reclassification and correction concerning the land cultivated with rubber trees (i.e., changes in the definitions applied) occurred. Indeed, nonetheless the previous report (i.e., FAO FRA 2015) considered rubber areas as forests, the total forest area in Thailand in the year 2015 was reported as 16,399,000 ha, which is more than consistent with the corresponding figure reported in Table 3.7, which however does not include rubber areas. This same pattern occurs for the statistics related to the other years, leading to the conclusion that errors, at least in the reporting, were done. The FAO FRA 2020 report solved the issue adding the area committed to rubber cultivation to the forest area obtained from Thai official sources (e.g., Royal Forest Department), thus, it represents not only an updated version but also a correct and reliable source. Moreover, the data quality is enhanced with respect to FAO FRA 2015 for some specific variables (indicators) analysed in that report, and in particular this is true for two indicators relevant for our purpose, that are the status and the trend of forest area. Tier classification system implemented in FAO FRA 2020 is different from that used in the previous assessment (i.e., of 2015), one remarkable change is that in the former (2020), tiers were no more assessed by countries themselves, but by the FAO. For these reasons, the FAO FRA 2020 report it is here considered as a fundamental basis for the subsequent discussion and calculations. Data from the report is also accessible via the FAO FRA web platform [122], specifically for Thailand.

Prior to delving into the particulars, it is important to refer to the definitions and classifications set forth by the FAO FRA 2020 "Terms and Definitions" [123, pp. 4-6,8,11]:

- the category **forest** corresponds to "*Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use*";
- the category **other wooded land** corresponds to "*Land not classified as "Forest", spanning more than 0.5 hectares; with trees higher than 5 meters and a canopy cover of 5-10 percent, or trees able to reach these thresholds in situ; or with a combined cover of shrubs, bushes and trees above 10 percent. It does not include land that is predominantly under agricultural or urban land use*";
- the category **other land** corresponds to "*All land that is not classified as "Forest" or "Other wooded land"*";
- the subcategory **naturally regenerating forest** relates to "*Forest predominantly composed of trees established through natural regeneration*";
- the subcategory **planted forest** relates to "*Forest predominantly composed of trees established through planting and/or deliberate seeding*";
- the subcategory **plantation forest** relates to "*Planted Forest that is intensively managed and meet ALL the following criteria at planting and stand maturity: one or two species, even age class, and regular spacing*";
- the subcategory **other planted forest** relates to "*Planted forest which is not classified as plantation forest*";

- rubber trees plantations are regarded as forests;
- **primary forest** indicates "*Naturally regenerated forest of native tree species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed*";
- the term **above-ground biomass (AGB)** refers to "*All biomass of living vegetation, both woody and herbaceous, above the soil including stems, stumps, branches, bark, seeds, and foliage*";
- the term **below-ground biomass (BGB)** refers to "*All biomass of live roots. Fine roots of less than 2 mm diameter are excluded because these often cannot be distinguished empirically from soil organic matter or litter*";
- the term **dead wood** refers to "*All non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter or any other diameter used by the country*".

The explanatory notes present in the cited document, are here omitted, even if they are relevant in some cases; it is therefore suggested to read them directly from the quoted source.

However, there is no consensus about rubber areas general assignment to the forest category, since monocultures are very distant to be forests from several point of views, either exist ongoing disputes on categories, species assignments to categories and rationale and in particular on the effects on the results that those definitions have (consider for instance deforestation; or also the fact that in FAO FRA 2015 it was possible to distinguish clearly between primary, other naturally regenerated, planted forests, while in FAO FRA 2020 only the natural regenerating and planted are available).

Table 3.8 reports the extents of the Thai forests according to FAO FRA 2020 [122] (country-specific data). estimated values are underlined.

FRA 2020 categories	**Area [1000 ha]**								
	1990	**2000**	**2010**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Forest	19,361	18,998	20,073	20,061	20,017	19,981	19,945	19,909	19,873
Naturally regenerating forest	17,641	17,011	16,831	16,359	16,348	16,345	16,342	16,339	16,336
Planted forest (**rubber**)	1,720	1,987	3,242	3,702	3,669	3,636	3,603	3,570	3,537
Other wooded land	0	0	0	0	0	0	0	0	0
Other land	31,728	32,091	31,016	31,028	31,072	31,108	31,144	31,180	31,216
Total land area	51,089	51,089	51,089	51,089	51,089	51,089	51,089	51,089	51,089

Table 3.8: extent of Thai forests, from [122]; estimated values are underlined; note that total land area differs from the country area (which is land area plus inland water area, equal to 51,312 thousand ha).

It is fundamental to state that, since in the FAO FRA 2020 web platform [122] rubber plantation is reclassified, for 100 %, as “plantation forest” category (introduced species) and the 100 % of the “planted forest” category is constituted by the “plantation forest” subcategory, all the “planted forest” area is composed of rubber plantations, as there are no other vegetation/crops flowing in that forest area category and therefore rubber plantations, which are considered as plantation forests, totally comprise the planted forest area of Thailand. Considering this, not all the categories and subcategories (planted, plantation, plantation of introduced species, rubber) are shown in the Table 3.8, in order to avoid repetition.

Due to this classification, it is evident that (i) the total forest area results from the sum of naturally regenerating forests and planted forests, (ii) forest area has not substantially changed over the last three decades, (iii) naturally regenerating forests have decreased while rubber plantation area has conspicuously increased during the same time period, (iv) the rubber plantation area increase has occurred at the expense of both “naturally regenerating forest” area and “other land” area.

With regard to (iv) it can be observed that “naturally regenerating forest” area decreased from 17,641 thousand ha in 1990 to 16,336 thousand ha in 2020, so reduced by 1305 thousand ha. “Other land” area, calculated as the difference between total land area (its value is considered equal to the

FAOSTAT 2015 value, constant for all the reference years) and the “forest” area (and “other wooded land” that is considered null), decreased by 512 thousand ha in the time period 1990-2020. Hence, considering 1990 and 2020 figures only, so the extreme values (i.e., extremities) of time range, it is possible (only) to affirm that the expansion of rubber plantation area (of 1817 thousand ha) has occurred to ≈ 72 % at the expense of “naturally regenerating forest” area and to ≈ 28 % at the expense of “other land” area.

Albeit “primary forest” category is defined, as previously commented, it is not shown in the FAO FRA 2020 main report, nor on the web platform, for the case of Thailand; the access to this level of disaggregation would instead be beneficial for all the land use change discussions and calculations for that region.

Table 3.9 shows the temporal evolution of the rubber harvested area in Thailand, according to country-specific FAOSTAT data [42].

Year	Harvested area [ha]	Year	Harvested area [ha]	Year	Harvested area [ha]
1990	1,400,000	2001	1,503,944	2012	2,519,760
1991	1,097,835	2002	1,553,764	2013	2,634,034
1992	1,152,873	2003	1,600,658	2014	2,915,813
1993	1,211,380	2004	1,655,991	2015	3,015,361
1994	1,249,468	2005	1,691,099	2016	3,047,586
1995	1,276,359	2006	1,742,896	2017	3,057,079
1996	1,310,404	2007	1,766,849	2018	3,203,696
1997	1,344,506	2008	1,819,502	2019	3,272,927
1998	1,386,411	2009	1,856,072	2020	3,292,671
1999	1,432,084	2010	1,929,257	2021	-
2000	1,462,076	2011	2,042,502	2022	-

Table 3.9: rubber harvested area in Thailand, period 1990 – 2020, from [42].

In practice, no general consensus on the methodologies for estimating land use change has been achieved yet, also due to the fact that debates on the topic are relatively recent [124]. Ecoinvent v2.2 (2007) lacked a consistent method while Ecoinvent v3.0 included for the first time a consistent methodology for evaluating LUC impacts from crops production, proposed by Nemecek et al. [125] and based on the 2006 IPCC Guidelines methodology [124, 126]. LUC modelling in the Ecoinvent v3.3 (2016) included the World Food LCA Database (WFLDB) model proposed by Nemecek et al. [126], providing estimates for all the crops present in the FAO database, which were supported by an Excel tool developed by Blonk Sustainability (Gouda, Netherlands) and later adjusted by Quantis Sàrl (Lausanne, Switzerland) [124, 126]. Novaes et al. [127], in the context of Brazilian agriculture, proposed the so-called BRLUC method to estimate direct LUC, which was later adapted and implemented in Ecoinvent database v3.3 [124, 127].

In this study, a direct land use change (dLUC) screening procedure is conducted in alignment with the procedure applied in the Ecoinvent database; direct LUC impacts are evaluated in accordance with the methodology proposed by Nemecek et al. [125], which is focused on impacts stemming from natural ecosystem changes. This focal point can also be seen as a limitation, thus some authors recommend to widen the analysis. This aspect has been taken into consideration in this investigation.

In this LUC assessment, a period of time of 21 years is considered for allocating emissions from land use change, i.e., from 2000 to 2020. This choice is based on three elements: (i) in the literature, a 20-year period is recommended [125, 128, 129]; (ii) the allocation period selection is, in any case, arbitrary [129]; (iii) data availability. Considering these supporting factors, the time period 2000 – 2020 is used in the following, which covers twenty-one years, and it is therefore consistent with the suggested period.

3.5.2 Estimate LUC potential relevance

First of all, it is possible to estimate direct LUC significance following the approach developed by Milà i Canals et al. [128], which constitutes of two conditions, with the addition of a third condition, as indicated by Nemecek et al. [125].

Figure 3.3 shows the related decision tree, for the specific case here analysed, i.e., natural rubber production in Thailand and for the specific time period 2000 – 2020. Note that in the diagram the resulting path is highlighted in bold.

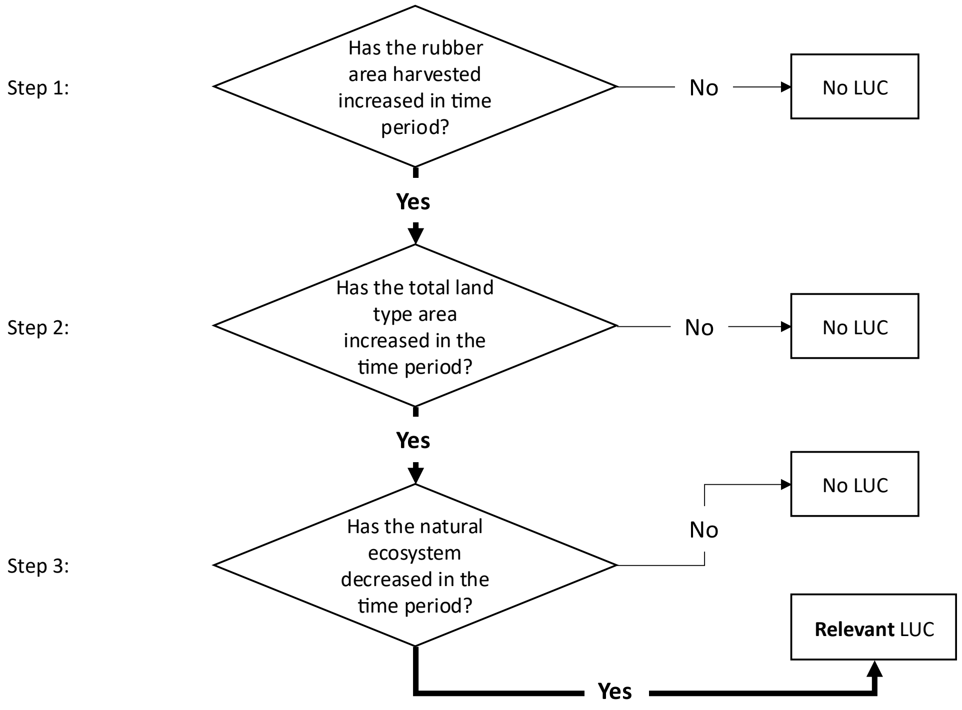

Figure 3.3: decision tree for the specific Thai NR cultivation, adapted from [128].

It is important to note that the tree presented in the Figure 3.3 slightly differs from the original generic tree found in Milà i Canals et al. [128] since a third decision is added, as third step. The rationale for this choice is that only the impacts related to changes involving natural ecosystems are considered.

The screening methodology entails three questions, whose responses should be based on country-specific and consistent information. If all the conditions are satisfied (i.e., all answers turn to be positive) then dLUC is regarded as important, and its impacts must be assessed. However, this method does not detect indirect LUC, since it is country focused [128]. In the two aforesaid studies, FAO statistics were used to accomplish the procedure; for this purpose, here, FAO FRA 2020 and FAOSTAT data, combined with other sources as needed, were considered.

Step 1: has the harvested rubber area increased in Thailand and with regard to the 2000 – 2020 period?

Harvested area, for *Hevea b.* plantations, must be obtained from FAOSTAT, since it is not present in FAO FRA. The harvested area has grown significantly from 1,462,076 ha to 3,292,671 ha, always showing a positive (increasing) trend [42]. This represents a relevant increase of more than twofold. Hence, the first condition is verified.

Moreover, it is possible to state that the area increased also in the period 1990 – 2020. At this point it may be appropriate to note that the harvested area may annually vary, according to the rubber crop characteristics. However, the positive trend would not change considering the plantation area instead of the harvested one.

Step 2: has the total land type area for rubber increased in Thailand and with regard to the 2000 – 2020 period?

Data about the total land type area for the analysed crop are here needed, thus it is pivotal to understand the related definitions and classifications and to consider the appropriate type. For instance, concerning oil palm, the permanent crop type should be considered, since oil palm is regarded as a permanent crop [128], and the land occupied by oil palm trees is excluded from the forest category but belongs to the category other land with tree cover [123]. In the specific case of rubber, the situation may appear complicated. According to FAO FRA 2020 [123], while oil palm plantations are regarded as agricultural productive systems, rubber plantations do not, since belong to the forest category (see definitions); indeed, latex and natural rubber are defined as non-wood forest products. In addition, FAO explicitly claims that "rubber plantations should always be classified as 'forest'" because the "the plantation is made up of forest tree species" [130]. It is nonetheless widely accepted that natural rubber is a perennial (or permanent crop), in particular an agricultural tree crop (e.g., [120]).

As previously observed, *Hevea b.* plantations are regarded as plantation forests, therefore it is possible to state, coherently, that they belong to that land use class. In the following, this assignment has been practically implemented thanks to the availability of data at this fine level of disaggregation (as indicated in Table 3.8); however, if data were limited to higher-level categories/types, then the forest land use class/type would be the sole viable choice with this approach.

The "plantation forest" area, which constitutes the entirety of the "planted forest" area and represents the total land use class for rubber trees, has substantially increased from 1,987,000 ha to 3,537,000 ha (see Table 3.8). Hence, the second condition is verified.

The overall "forest" area, which in the same time period has grown too, exhibits a much lower increment, and recalling that it includes the plantation area, it is thus possible to confirm that part of the rubber increase has occurred at the expense of "naturally regenerating forest" area.

Step 3: has the natural ecosystem decreased in Thailand and with regard to the 2000 – 2020 period?

This condition involves information pertaining to the natural ecosystem(s), thus, first of all, it is fundamental to understand what to consider as natural ecosystem.

The European Environment Agency (EEA) defines as natural ecosystem an "ecosystem where human impact has been of no greater influence than that of any other native species, and has not affected the ecosystem's structure since the industrial revolution. Human impact excludes changes of global proportions, such as climate change due to global warming" [131].

To be denoted as ecosystem, a bio-environmental complex must satisfy three properties: 1) functional autonomy, 2) internal dynamic equilibrium, 3) be circumscribable to contiguous complexes [132]. With respect to agricultural systems, the first characteristic is generally the most compromised due to anthropic interventions for maximising the productivity (phytosanitary treatments, fertilisation, weeding/herbicides). Thus, concerning natural ecosystems, it is suggested that agricultural systems should not be considered as ecosystems, despite the fact that are sometimes referred to as agroecosystems [133]. This is supported also by the fact that agricultural land or cropland classes are not regarded as comprising natural ecosystems [74]. In other words, agricultural systems should be deemed as artificial systems.

The Table 3.10 shows the land use FAOSTAT data [134] concerning Thailand, for the years 2000 and 2020. As can be deduced after simple calculations, it is fundamental to note that the land use type "other land" related to these data (FAOSTAT) may seem different to that presented in Table 3.8 (sourced from FAO FRA 2020), while in praxis it is absolutely consistent due to the fact that the "other land" category in the latter (Table 3.8) is defined at an higher level, and it is disaggregated into "agricultural land" type and "other land" type in the Table 3.10, thus presenting here a more detailed level of classification: e.g., 19,834 plus 12,257 give 32,091 thousand ha. Certainly, this could lead to confusion if not approached with due attention. Moreover, following this finer level of classification, it is possible to sum the values of agricultural type, forest type and other land type to obtain the total land area (51,089 thousand ha) and then adding the value of inland waters type, the total country area is correctly achieved (51,312 thousand ha).

Land use type	Year 2000	Year 2020	Unit
Agricultural land	19,834i	23,010i	1,000 ha
…of which cropland	19,034i	22,210i	1,000 ha
Forest land	18,998	19,873	1,000 ha
…of which naturally regenerating forest	17,011	16,336	1,000 ha
…of which planted forest	1,987	3,537	1,000 ha
Other land	12,257i	8,206i	1,000 ha
Inland waters	223i	223i	1,000 ha
Primary forest	6,726	n.r.	1,000 ha

Table 3.10: Thai land uses, from FAOSTAT [134], note that: 'i' denotes imputed values, the others are official figures; 'n.r.' means not reported.

FAO data, neither FAOSTAT data presented in Table 3.10, nor FAO FRA 2020 data, do not permit to resolve the query due to insufficient level of detail, as they lack recent information on primary forests and a disaggregation of data that would be beneficial for distinguishing between artificial and natural systems. Further information becomes necessary, and this can be accomplished through the sole reference identified in the literature that perfectly satisfies both the geographical and temporal system requirements/boundaries of the present study. The work of Wang et al. [135], concerning land use changes occurred in Thailand in the period 2000 – 2020, is therefore taken into consideration. It is important to underline that (i) their data are based on a global land cover product with fine classification system (denoted as GLC_FC30) which integrates Landsat imagery data and global training data [136], with specific accuracy of 82.5 % and 68.7 % for the first-level land classes and second-level land classes, respectively; (ii) the authors regarded rubber plantations as forests [74]; (iii) no distinction between artificial and natural ecosystems was made [74]. Since that study is here used as basis for data, its land use classification system is considered, composed of eight types at the first level, four of which do contain natural ecosystems, i.e., forest, shrubland, wetlands, water bodies [74]. Among the interesting results reported (e.g., forest area decreased; shrubland area, which includes shrubland, grassland, sparse vegetation and bare areas in their land use classification system, increased; etc.) they obtained that the area converted from forest, shrubland, wetlands and water bodies land types to other land use types was 2,745,000 ha; while the area transformed from other land use classes to forest, shrubland, wetland, water bodies land use types was 1,488,000 ha [135]. Therefore, considering that, in praxis, the types forest land, shrubland, wetland and water bodies all contain some natural ecosystems [74] and that (iii), a definite quantitative or qualitative statement about the change in area of natural ecosystems is not feasible, while, it is possible to attain a reference judgement on the matter: the natural ecosystem has decreased. Hence, the third condition is here deemed verified. Albeit having obtained an answer, it is crucial to emphasise the complexity of every evaluation regarding the natural ecosystem's dynamics and acknowledge the associated limitations.

Finally, since all the three conditions are verified, the direct LUC is considered as potentially relevant in this context of natural rubber production.

Some notes to the screening procedure should be here made. Another approach that could be implemented in the second step involves considering the "cropland" category as total land use class for rubber. In other words, regarding rubber tree as agricultural crop only. For instance, considering FAO data [122, 134], after some elaborations in order to preserve consistency (transferring rubber areas from the forest land use type to the cropland land use type), it would be attained that, in Thailand and in the considered time period, forest area (now without rubber areas) decreased, and cropland area (now with rubber areas) increased. Thus, the same conclusion previously deduced would be obtained and the final outcome, in terms of screening results, would not change. However, since this assignment (i.e., rubber plantations as agricultural land) would be in contrast with FAO definitions, it has been deemed unfair.

Numerous observations would be possible combining FAO statistics with information retrieved from Wang et al. [135], nonetheless, these two sources are not consistent in specific cases, thus leading to different or opposite results (e.g., forest area change is positive in one case and negative in the other). It is important, indeed, to note the diversity of the methods employed to gather data: FAO used various sources (including satellite imageries), while Wang et al. [135] relied on the GLC_FC30 dataset; consequently, divergent conclusions (both quantitative and qualitative) may stem from these methodological differences. Keeping in mind this limitation, it is possible for example to state that perhaps the rubber area (i.e., plantation area) increase of 1,550,000 ha (value from FRA 2020, see Table 3.8), registered in Thailand in the time period analysed, has occurred in part at the expense of cropland, since an area of 510,000 ha of cropland was converted to forest (value from Wang et al. [135]); moreover, since wetlands increase (due to the conversion of rainfed cropland and water bodies) and water bodies decrease (but were also converted from cropland) are very small compared to the rubber increase, they can be neglected, leading to the deduction that maybe a part of rubber area increase happened at the expense of natural ecosystems, implying the conversion of forests (other than rubber forests) and/or shrublands. Moreover, the decrease in forest area other than planted forest, obtained from FAO data (675,000 ha; see Table 3.8), is confirmed also by the decrease in forest area reported by Wang et al. [135] (720,000 ha; even though forest area comprises rubber area in their study).

An improvement that would benefit completeness and that can be implemented when data are not scarce, is the use of n-years averages to mitigate short-term fluctuations [125, 137]. In the specific case here analysed, this would not change the trend shown.

As it is possible to understand, it is mainly a matter of definitions, classification, data availability, and changes in one of these factors are not trivial since may lead to completely different results.

3.5.3 LUC and variations in carbon stocks

Land Use Change (LUC) impacts are differentiated here into transformation and occupation impacts, in line with the adopted methodology, reported in [125]. While the former pertains to variations in the carbon stocks in living and dead biomass due to a conversion of land, the latter are related to changes in soil organic carbon resulting from the occupation of already transformed land [138]. First of all, to assess these two components, it is necessary to obtain the average annual increment in land transformation related to the farming of *Hevea b.* in Thailand and during the specific time period 2000 – 2020; secondly, the emissions originated from the depletion of above-ground biomass (AGB), below-ground biomass (BGB) and dead organic matter (DOM) in the natural ecosystem are evaluated; thirdly, and finally, it is required to compute the change (loss or gain) of soil organic carbon (SOC) in mineral soil, together with its corresponding dinitrogen monoxide emission, the change (loss) of SOC retained in organic peat soil, and the potential accumulation of carbon in biomass form [125]. Hence, the methodology takes into account four carbon pools, evaluated for the new land use (i.e., *Hevea b.* cultivation) and for the former land uses, through the collection of default values from the 2006 IPCC Guidelines in the original methodology (i.e., the one proposed by [125]). In the Blonk tool used by Ecoinvent, reference data from the 2006 IPCC Guidelines, Annex V to Directive 2009/28/EC and FAO FRA 2010 are exploited for obtaining the carbon stock related to a particular land use type [137]. These sources mainly report values on carbon fraction, above-ground biomass, below-ground biomass to above-ground biomass ratios or sometimes directly the partial or total carbon stock; and are generally presented according to the different climate domains (e.g., tropical, sub-tropical, etc.), climate regions (e.g., tropical wet, tropical moist, etc.) and ecological zones (e.g., tropical dry forest, tropical shrubland, etc.), continent, soil type, type of vegetation (e.g., natural forests, forests plantations, etc.), and species. See for instance volume 4, chapter 4, section 4.5 of both the 2006 IPCC Guidelines and of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (simply 2019 Refinement, from now on). Though these data allow for estimation (denoted as IPCC tier 1 calculation method), it is important to note that they represent average data and/or proxy data, obtained at a continental scale and/or obtained at a higher-level with respect to the desired one, and thus their use may potentially lead to relevant errors in the outcomes, as demonstrated in [137]. This means that data representativeness and appropriateness must be considered, especially when dealing with these kinds of data. It is therefore suggested that data specifically focused on the considered region/geography should be used for carbon stocks' estimations, or equivalently to perform a higher tier methodology, in order to attain more precise estimates [104, 137]. Moreover, the use of species-specific data, when needed, further improves the results. In praxis, however, the choice is limited by the availability of country-specific data and the additional time/effort required. To estimate the carbon stocks associated with the four considered carbon pools, here, country-specific data have been used, when available or reasonably estimable, with some exceptions (C_{DOM} stock estimation for both natural forests and rubber plantations). For this reason, it is possible to state that the approach followed for that evaluation is in line with the tier 2 method of the 2006 IPCC (as it had not undergone refinement in 2019) [104] since it is based on geographically representative data. However, in some cases the use of country-specific information was not possible due to its absence. The methodology employed, nevertheless, can be characterised as a tier 2 approach, as it is considered good practice to use country-specific data even when they enable a more precise specification of only some components within the tier 1 default procedure [104].

The investigated parameters are carbon fraction of biomass, above-ground and below-ground biomass, root-to-shoot ratio, carbon stock in litter and dead wood (i.e., C_{DOM} stock), carbon stocks in above-ground (i.e., C_{AGB}) and below-ground (i.e., C_{BGB}) biomass, carbon stock in soil (i.e., C_{soil}), concerning Thai forests and *Hevea b.* plantations. The examined parameters are carbon fractions, above-ground and below-ground biomass, carbon stocks in biomass, in the case of Thai cropland. With regard to Thai forests, the C_{DOM} stock has been estimated using broad-scale data (thus non-specific aggregated values for specific ecological zones in Thailand), due to lack of information, while C_{AGB}, C_{BGB} and C_{soil} stocks are taken from the literature. Concerning *Hevea b.* plantations, the C_{DOM} stock has been estimated using non-Thailand-specific data (focused on other locations), due to lack of information, the C_{AGB}, C_{BGB} stocks have been estimated using country-specific data, and the C_{soil} stock is taken from the literature. Instead, considering the cropland land use type, the related C stock has been estimated on the basis of Thailand-specific literature and global data.

It is worth noting that the use of general, non-country-specific data is limited (except for crops carbon fractions) to the evaluation of the carbon stock in dead organic matter, which, as indicated in the following sections (see Section 3.5.3.4), represents a small (negligible, in practice) contribution to the overall carbon stock; therefore, it is likely to have a rather small influence on the final accuracy.

For the evaluations of carbon stocks, the guidelines of the European Commission [139] has been considered in the following. The carbon in soil is considered mainly as soil organic carbon (SOC), in line with the literature. Understory can be and it is neglected, in a consistent manner for all the cases, coherently with the FAO FRA 2020 [123]. The herb biomass and shrub biomass can be and are neglected for *Hevea b.* plantations and for the cropland, in accordance with [140].

The accuracy of C stock estimations can be enhanced using species-specific information, e.g., species-specific biomass, species-specific carbon concentrations, and can be further improved exploiting the disaggregation by plant component and also by climate, since it has been shown that plant physiology (and thus the elemental composition in the organs) is affected by climatic factors, namely temperature and precipitation [141]. Instead of selecting as biomass carbon content the usual value of 50 %, more appropriate carbon contents should be evaluated and used. In other words, the most reliable biomass C stock (i.e., in AGB + BGB) estimation procedure for a particular species would be to consider (i) the dry biomass of all its constituents (foliage, stem, roots, etc.) and (ii) the plant specific carbon fractions for all these parts. To obtain this information is generally arduous, since it is rare or unavailable in most cases. Nonetheless, in the following sections, this matter has been considered.

3.5.3.1 Assessment of LUC

Considering Tables 3.8 and 3.9, it is evident that (i) the area dedicated to rubber production (i.e., *Hevea b.* plantation area) in Thailand has experienced an increase of more than twofold, from 1,987,000 ha in the year 2000 to 3,537,000 ha in the year 2020; (ii) the rubber harvested area, which accounted to 1,462,076 ha in the year 2000, reached 3,292,671 ha in the year 2020. From (i) and (ii) the related changes (already known to be increases, from the screening procedure), calculated as difference between the final period (i.e., 2020) and the baseline period (i.e., 2000), are attained: an increment of 1,550,000 ha for the plantation area, an increase of 1,830,000 ha for the harvested area. Clearly, the difference between these values lies in the rubber crop characteristics: harvested area is always non greater than the related plantation area, depending on the tree's maturity, so on the number of trees in the establishment phase and in the productive phase. This expansion of the *Hevea b.* plantations is associated with the conversion of 675,000 ha naturally regenerating forests and of 875,000 ha "other land" area, according to the land use classification and elaborations of data from FAO FRA 2020 (Table 3.8). In other words, in the same period, in Thailand, the "naturally regenerating forest" area decreased from 17,011,000 ha in the year 2000 to 16,336,000 ha in the year 2020; and the "other land" area diminished from 32,091,000 ha in the year 2000 to 31,216,000 ha in the year 2020. It can be noted that, due to the method and definitions implemented in the FAO FRA 2020, the sum of their reductions coincides with the rubber plantation area increase. Then, it is possible to obtain that in Thailand and during the selected time period, the growth of the *Hevea b.* area occurred replacing "naturally regenerating forest" area and "other land" area to 43.6 % (i.e., 675/1,550) and 56.5 % (i.e., 875/1,550), respectively. Since in the year 2000, the rubber plantation area was 1,987,000 ha, it is possible to note that the 56.18 % (i.e., 1,987/3,537) of the plantation area concerning the year 2020 already existed in the baseline year (i.e., 2000), while the remaining 43.82 % of rubber area was planted during the following two decades. This means that, with regard to the final rubber plantation area (i.e., of 2020), the increase of rubber plantation area was to 19.1 % (i.e., (675/1,550)*0.4382) at the expense of naturally regenerating forests and to 24.7 % (i.e., (875/1,550)*0.4382) at the expense of other lands. Therefore, considering the period 2000 – 2020, the average annual increment of Thai land committed to *Hevea b.* agriculture (annual land transformations) can be computed as 0.909 % (i.e., 19.1% divided by 21) for naturally regenerating forests and 1.18 % (i.e., 24.7 % divided by 21) for other land. In other words, over each year of the period 2000 – 2020, spanning 21 years, a land area of nearly 32,151 hectare per year (i.e., 3,537,000*(0.909 %)) of "naturally regenerating forest" and a land area of 41,665 hectare per year (i.e., 3,537,000*(1.18 %)) of "other land", were converted into rubber-growing areas, with a total annual converted area of circa 73,816 hectares. Table 3.11 summarises this assessment.

			Increase 2000 - 2020			
	Unit	Rubber plantation area (baseline year)	In rubber plantation area	From "naturally regenerating forest"	From "other land"	Rubber plantation area (final year)
Land area	ha	1,987,000	1,550,000	675,000	875,000	3,537,000
Share	%	56.18	43.82	19.08	24.74	100
Annual increment	%	-	-	0.909	1.178	-

Table 3.11: rubber plantation area increase in Thailand in the period 2000 – 2020, elaborating data from [122].

It is important to underline that assessing the reduction in natural ecosystem area would be required for the evaluation, given that the focus should be on the transformation of natural land, according to the methodology. However, estimating this decrease is not feasible in this specific case due to the unavailability of more detailed data, which is related to the complexity of the topic (as previously elucidated in the discussions of the second step and of the note of the screening procedure, Section 3.5.2). To partly overcome this issue, primary forest information for the recent years (in particular for the final period, i.e., year 2020) would be beneficial, but such data are not available, as indicated in Table 3.10. Since the annual area of naturally regenerating forests (i.e., 32,151 ha/y), which do contain natural ecosystems, is used in the following calculations concerning the transformation impacts (see Section 3.5.3.6), then, this topic, which is judged as a limiting element, affects only partially the ideal results related to the conversion of land, however its influence cannot be measured. In other words, it is equivalent to say that a forced assumption is made: the whole area of natural ecosystems is considered to coincide with the entire area of "naturally regenerating forest"; that is, the "other land" contribution to the natural ecosystem, if any, is neglected due to lack of data. These are the rationales behind the use, in Section 3.5.3.6, of forests belonging to the "naturally regenerating forest" category, instead of the use of primary forests, secondary forests, shrubland and grassland as recommended by the methodology. Thus, taking into account the level of detail in the original data from FAO FRA 2020 [43, 122] and FAOSTAT [42, 134] (which are coherent with each other), the results obtained regarding this matter (i.e., transformation impacts) represent the maximum achievable, and despite they embody uncertainties, these results are still deemed representative. As a matter of fact, the annual transformed forest area here calculated (for the period 2000 – 2020) is supported by the annual loss of 60,475 ha natural forest area in Thailand during the period 2000 – 2004 reported by [142].

Furthermore, the approach here implemented based on country-specific data and on the high-level land use classification of FAO FRA 2020 (shown in Table 3.8 in this study) is consistent with the latest suggested improvements to the calculation of direct land use change emissions in LCA analyses. It is recommended, indeed, that the robustness of land transformation estimations should be improved employing high-level land use categories; also, this entails the preference of land use type data (e.g., plantation area, etc.) with respect to crop-specific data (e.g., harvested area, etc.) [137].

In the calculation of the occupation impacts (see Section 3.5.3.7), the hypothetical increase of carbon in living biomass regarding the new land use (i.e., rubber plantation) with respect to the old one, should be assessed, according to the methodology. Thus, this would require specific data on the "other land" area converted into the new land use type. However, such detailed data are not available. Considering the preference to employ high-level land use categories and the definition of "other land" category (at the highest level), two alternatives arise: to neglect the corresponding gain in carbon or to assume an increase exactly equal to the carbon stock of the new land use type. These represent two extremes, and to avoid underestimating or overestimating this carbon accumulation, a forced assumption is made here: all the area inside the "other land" category is regarded as "cropland" area, as far as the evaluation of occupation impacts is concerned. As opposed to the previous hypothesis on the natural ecosystem (regarding the transformation impacts), it is important to state that this other assumption is deemed as a significant limitation (consider indeed Table 3.10). Nonetheless, it will allow to approximate the situation, avoiding the two alternatives.

3.5.3.2 Evaluation of the carbon stock in Thai forests

The factors required for the evaluation of forest carbon stock, which is constituted by the vegetation and the soil components, are obtained in the following based on country-specific data, when available, or more general data, as previously mentioned. All biomass information is correctly reported as dry mass. The following discussion entails forest land in Thailand, excluding plantation forests.

Ecological zones

From the 2006 IPCC Guidelines (not refined in 2019) [104], the following ecological zones for the Thailand country can be deduced: tropical rain forest (code: TAr) in the southern regions (Thai peninsula), tropical moist deciduous forest (code: TAWa) and tropical dry forest (code: TAWb) in the continental region. The Table 3.12 presents briefly the classification with regard to the tropical domain only.

Climate domain	Climate region	Zone	Code	Zone criteria
Tropical	Tropical wet	Tropical rain forest	TAr	wet: ≤ 3 months dry, during winter
	Tropical moist	Tropical moist deciduous forest	TAWa	mainly wet: 3-5 months dry, during winter
	Tropical dry	Tropical dry forest	TAWb	mainly dry: 5-8 months dry, during winter
		Tropical shrubland	TBSh	semi-arid: evaporation > precipitation
		Tropical desert	TBWh	arid: all months dry
	Tropical montane	Tropical mountain systems	TM	altitudes approximately >1000 m, with local variations

Table 3.12: detail of tropical domain, extracted from [104].

A more detailed classification of zones/forests should be used for improving the assessment, but given its unavailability, the default ecological zones selected here are deemed representative of the Thai situation. Moreover, they are consistent with the climate regions that can be deduced for Thailand according to the Annex V to Directive 2009/28/EC [139], that are tropical moist in the continental region, and tropical wet in the southern region.

Nonetheless, the relative proportions of the chosen ecological zones/forest types throughout the country are not available nor easily estimable. In other words, the forest land composition, in quantitative terms and with regard to the total country land, is here not known. From the Digital Observatory for Protected Areas (DOPA) it is possible to obtain a photography of Thai protected areas as at year 2015 (this EU dataset, however, contains also the cropland class inside that protected area, so it must be managed carefully): needleleaf forests represented approximately the 0.43 % of the total protected land, while broadleaf forests (deciduous + evergreen) accounted for the 44.75 % of the total, the main part of broadleaf forests being the evergreen ones [143]. To use this information as proxy seems inadequate since the choice has to be made for tropical rain-moist-dry forest classes (so there was no information on their relative amounts). Moreover, today the protected area system in Thailand (protected forests, botanical gardens, wildlife sanctuaries, etc.) comprises circa 11 million hectares (22 % of country's total land area), while in the year 2004 it accounted for circa 6 million hectares [66].

Carbon content in dry matter

According to the 2006 IPCC Guidelines (not refined in 2019) [104], the C fraction values of AGB valid for forests belonging to the tropical climate domain are (in kg C per kg dry matter):

- 0.46 for the wood part, tree Ø < 10 cm;
- 0.49 for the wood part, tree Ø > 10 cm;
- 0.47 for the foliage part;
- 0.47 considering all the components of the tree, which represents also the default value.

Concerning Thai-specific studies, for instance, a carbon fraction of 0.50 was assumed for the AGB in three types of forest (i.e., tropical rain forest, dry evergreen forest, mixed deciduous forest) included in a protected area part of the western forest complex of Thailand, located in the Kanchanaburi province [144]. In another study, in which a thorough set of results was collected, the IPCC default forest tree C fraction of AGB of 0.47 was used for all the Thai forest types analysed [145].

In this study none of these values have been directly used in the case of forest tree species in Thailand, because, in practice, no specification was needed, since the C stocks values from the literature have been directly used, consequently there were no need to estimate them starting from the biomasses and carbon fractions.

Methodological comment concerning Dead Organic Matter pool

The 2006 IPCC Guidelines (since this methodological part has not been updated in the 2019 Refinement) tier 1 approach (i.e., use of default values since the paucity of Thai specific data) clarifies that in the case of “forest land remaining forest land” no change in DOM is assumed (therefore no difference in C_{DOM} and thus no subsequent emissions), while, in the case of forest land transformed into another land use category, the “litter and dead wood pools are zero in all” these last categories (and the loss occur entirely in the first year of conversion, whereas here annualised loss will be considered) [104, ch. 4, pp. 20 and 37]. Thus, according to tier 1 methodology, depending on the rubber plantations land use type (regarded as forestland or instead as cropland), no change in C_{DOM} or a complete loss of the starting C_{DOM}, should be considered, respectively. Nevertheless, these options represent two extremes, none of which catch the real situation: in the first case (*Hevea b.* plantations as forest land) C emissions would be underestimated; in the second case (*Hevea b.* plantations as cropland) the emissions would be overestimated (in practice it is likely that a small DOM carbon loss will occur). Thus, a modified tier 1 approach is adopted in this Section and in Section 3.5.3.4, wherein the dead organic matter carbon available in *Hevea b.* systems is considered as non-null and not necessarily equal to that of forests. Thus, the C stock in DOM of forests must be evaluated in order to estimate the change corresponding to the transformation from the old land use category (i.e., naturally regenerating forests) to the new land use category (i.e., *Hevea b.* plantations).

Estimating forest carbon in Dead Organic Matter pool

The carbon stock in dead organic matter of forests (excluding plantations) can be estimated from the default values regarding the C_{DOM} stock exhibited in the 2019 Refinement [146] (default values updated with respect to the related 2006 table), disaggregated by forest type (climate region and tree species). It must be observed that these default values are broad-scale estimates and generally incomplete since the woody debris component of the litter pool was not included due to scarcity of data [146]. In the Table 3.13, the relevant mean values (not specific for the country) from the 2019 Refinement [146], with the IPCC original terminology, are shown.

Ecological zone	Forest type	Carbon stocks [tonnes C/ha]	
		Litter	Dead wood
Tropical rainforest	broadleaf deciduous	2.5	17.7
	needleleaf evergeen	4.7	1.9
	all types	4.8	14.8
Tropical moist forest	broadleaf deciduous	4.3	8.4
	needleleaf evergeen	14.8	3.4
	all types	5.9	8.0
Tropical dry forest	broadleaf deciduous	n.a.	16.0
	needleleaf evergeen	n.a.	n.a.
	all types	2.4	9.0

Table 3.13: default values for litter and dead wood carbon stocks, extracted from [146]; note that 'n.a.' indicates the figure was not available.

The term 'all types' refers to values (which are averages themselves) corresponding to all the vegetation categories. Thus, since the scarce and incomplete information about the relative quantities of species (forest types) in the country and on their evolution with time, the average between the 'all types' values of the three ecological zones (rain, moist, dry) is evaluated and used as approximation for the dead organic matter carbon stock of Thai naturally regenerating forests: C_{DOM} stock of forest = 14,966 kg C/ha (litter C + dead wood C) ≈ 15 ton C/ha.

Equivalently, this means that Thai forest land area is thus assumed to be composed of 1/3 tropical rainforests, 1/3 tropical moist forests and 1/3 tropical dry forests, each with all the forest types considered.

Forest carbon in the other pools

The carbon stocks in AGB, BGB, and soil of tropical forests, are taken from the literature, and correspond to 235, 87, 57 ton C per ha, respectively [93].

The estimate for AGB carbon stock of 235 ton C/ha is reported in Jawjit et al. [93] referring to the 2006 IPCC Guidelines and to a study of Reijnders and Huijbregts [147]; in this last study, for the same estimate the authors cited another source, i.e., Henson [148], where, it was not possible to find explicitly that precise value, but it is clear that it regards Malaysian tropical forests. According to the 2006 IPCC Guidelines (not refined in 2019) [104], the ecological zone proper of the Malaysian country is, mainly, the tropical rain forest zone. The root-to-shoot ratio, according to the 2006 IPCC Guidelines [104], is 0.37 for the tropical (evergreen) rain forest. Therefore, considering the figures 235 and 87 ton C/ha, it is possible to deduce for which type of forest they were obtained: since the ratio of BGB stock to AGB stock is, in this case, exactly equal to 0.37, the authors considered the tropical rainforest as the reference ecological zone. In other words, it is likely that they had obtained the BGB carbon stock starting from AGB data, by using the root-to-shoot ratio specific to that vegetation type. However, since those estimates, which refer to an ecological zone present also in Thailand, are consistent with the literature values referred to Thailand forests, they are selected and used also in this study. Precisely, it can be asserted that the chosen AGB and BGB carbon stocks (i.e., 235 and 87 ton C/ha) represent relatively high estimates (indeed, are towards the higher end of the range constituted by the estimates found in the literature) and this because they reflect specifically the situation of tropical rain forests at mature condition. Biomass estimates concerning this and other types of forests presented in Thai-specific literature are, for instance, 275, 140 and 96 ton AGB/ha for tropical rain forest, dry evergreen forest, mixed deciduous forest, respectively [144]; 358, 126 and 311 ton AGB/ha for tropical rain forest, dry evergreen forest, mixed deciduous forest, respectively [144]; 120 and 129 ton AGB/ha for degraded tropical rain forest and tropical mixed deciduous forest, respectively [145]; 136 ton AGB/ha for protected forest (evergreen and mixed deciduous) [142]; thus, the corresponding AGB carbon stocks are lower than the AGB carbon stock here assumed. An AGB carbon stock as high as 350 ton C/ha is however reported for mature tropical rain forest [144]. In praxis, the above-ground biomass (and then also the below-ground biomass), which is reported on a per hectare basis, do strongly depends on the species, maturity, tree density of the forest, even under the same ecological zone. Moreover, the biomass calculation method plays a role: the allometric model used affects the results. This completely explains the variety of the evaluations. For example, the 2019 Refinement [146] reports: 413 and 132 ton AGB/ha for primary and secondary (older than 20 years) natural tropical rainforests in Asia; 68 ton AGB/ha for primary and secondary natural tropical moist deciduous forests in Asia; 185 ton AGB/ha for primary and secondary natural tropical dry forests in Asia. Instead, the Annex V to Directive 2009/28/EC [139] indicates the following vegetation carbon stocks (in living biomass plus dead organic matter) for forest land having at least 30 % canopy cover: 185 and 230 ton C/ha for tropical rain forest zone in continental Asia and insular Asia, respectively; 110 and 174 ton C/ha for tropical moist deciduous forest zone in continental Asia and insular Asia, respectively; 83 and 101 ton C/ha for tropical dry forest zone in continental Asia and insular Asia, respectively.

From this brief discussion, it is clear that the estimates, albeit in line with the other literature estimates, can be improved, and that the assumed estimate of the living biomass carbon stock is likely to be slightly overestimated.

Concerning the soil carbon stock, as soil organic carbon (SOC), the estimate here used (i.e., 57 ton C/ha) is in line with the (i) Thai specific literature, with the (ii) standard values (0 – 30 cm default depth) indicated by Annex V to Directive 2009/28/EC [139], and with (iii) the default values (0 – 30 cm default depth) reported by the 2019 Refinement [146]. To consider the appropriate climate regions/zones (tropical dry-moist-wet) and soil types, is required to refer to those standard values. The soil carbon stock estimations, specifically regarding tropical forest soils, reported in the Thailand-specific literature, are for instance: 55 ton C/ha (0 – 30 cm depth) for a degraded tropical rain forest in Songkhla province (southern Thailand, peninsula) [145]; 78 – 137 ton C/ha (0 – 30 cm depth) for a tropical mixed deciduous forest located in Maha Sarakham province (central northeastern Thailand) [145]; 59 ton C/ha (0 – 20 cm depth), 50 ton C/ha (20 – 40 cm depth) for natural forests (evergreen and mixed deciduous) in Nan province (northern Thailand) [142].

It is important to note that the estimation of SOC can be improved by considering a greater depth in the soil, provided that data are available and that the carbon at the resulting depth is significantly affected by the change in land use [104].

3.5.3.3 Evaluation of the carbon stock in Thai cropland

The factors required for the estimation of the living biomass carbon stock concerning the cropland land use type, which is constituted by the AGB and the BGB components, are obtained in the following based on country-specific data, when available, or global data, as previously mentioned. All biomass information is correctly reported as dry mass.

Due to the assumption made in the final part of Section 3.5.3.1, data on the specific cropland transformed is necessary, however, it is not available. Thus, to perform the estimation, it is assumed that all the converted cropland area is composed of an equivalent (in area) mixture of several specific local crops, as information on these is partially available. In particular, crops biomass values were taken from Gnanavelrajah et al. [140], while C contents were obtained starting from Ma et al. [141]. It is important to mention that the biomass values considered are country-specific and species-specific, while the C contents represent global assessments related to categories and not singular species (e.g., herbaceous category, woody plant category, etc.) and are disaggregated by plant organ. Then, combining this information it is possible to attain more reliable estimates (even if not the best theoretically achievable) compared to that obtainable using the default carbon fraction of 0.50.

Carbon content in dry matter

The Table 3.14 shows the carbon contents, reported for category and plant organ, directly sourced from Ma et al. [141] (each cell represents a global average over the analysed sample, of great size).

Life form	Reproductive organ	Root	Leaf	Stem	Unit
Crops	42.40	38.20	41.32	43.26	C content [%]
Woody plants	48.56	47.43	47.83	48.16	C content [%]

Table 3.14: carbon contents for categories and plant organs, from [141].

Therefore, from these starting data, it is possible to obtain a mean carbon fraction of 0.4129 for the crop category and a mean carbon fraction of 0.4799 for the woody plant category. These two C conversion factors are used in the following. It may be relevant to note that averaging over the organs is necessary due to the lack of data about their relative mass proportions.

<u>Estimating carbon in biomass pools</u>

The biomass values, regarding both above- and below-ground biomass of the several crops cultivated in Thailand, sourced from Gnanavelrajah et al. [140], are presented in the Table 3.15 below, along with the corresponding carbon stocks and their arithmetic average (estimated in this study).

Category	Land use	Total biomass (ABG+BGB) [ton/ha]	C stock [ton C/ha]	Average C stock [ton C/ha]
shrub crop	Cassava	28.89	11.93	34.1
tree crop	Coconut	139.17	66.79	
tree crop	Coconut-cassava	159.07	76.35	
tree crop	Eucalyptus	80.52	38.65	
tree crop	Mixed orchard	189.43	90.92	
shrub crop	Paddy	12.87	5.31	
shrub crop	Pineapple	25.17	10.39	
shrub crop	Pineapple-cassava	31.15	12.86	
shrub crop	Sugarcane	37.79	15.61	
shrub crop	Sugarcane-cassava	29.69	12.26	
data sourced from Gnanavelrajah et al. [122]			data elaborated in this study	

Table 3.15: biomass and C stock for several crops cultivated in Thailand, biomass values from [140].

As it is possible to note, the ten crops considered are classified into two categories, shrub type or tree type, which are perfectly consistent with the categories (life forms) of Table 3.14. In order to estimate the carbon stocks, the biomass of each crop (e.g., 28.89 ton/ha for cassava) is then multiplied by the appropriate carbon fraction (e.g., 0.4129 for shrub crop category, to which cassava belongs) previously obtained. In other words, it is assumed that all the shrub crops considered exhibit the same carbon content, equal to 41.29 % (averaged between the several plant constituents); while the considered tree crops have all the same carbon content of 47.99 % (averaged between the plant parts). Using two proper carbon conversion factors for two broad categories (tree crops and shrub crops), improves the accuracy of the estimation (better estimates can be obtained with further disaggregation, however two issues would arise: data unavailability and time-effort), as demonstrated by Ma et al. [141]. Then, after having evaluated the carbon stocks for the different land use types, it is possible to arithmetically average them to obtain the mean carbon stock of 34.1 ton C per ha. This is equivalent to consider the cropland area composed of equal shares (one tenth, since the 10 crops assumed) for the crops (i.e., 1/10 of area is under cassava land use type, 1/10 area is under coconut type, etc.) and to consider one hectare of that land with a carbon stock equal to the average (34.1 ton C/ha) between all the ten carbon stocks. The resulting mean (i.e., 34.1 ton C/ha), indeed, differs from the average carbon stock obtained with a general default carbon content of 50 % (i.e., 36.7 ton C/ha) and from the average stock obtained using a content of 55 % as reported in Gnanavelrajah et al. [140] (i.e., 40.4 ton C/ha). In the last two cases, the stocks are overestimated, while the estimation here performed using carbon fractions specifically developed for plant organs and plant categories may lead to more accurate results. To further improve the evaluation, species-specific carbon fractions should be assessed and made available. Finally, it can be noted that the BGB for the crops were obtained considering a BGB-to-AGB ratio of 0.3 in the reference study [140]; thus, also for this parameter further research could enhance the vegetation carbon stock evaluation. This comment suggests that the biomass values here employed may be slightly over- or under-estimated. However, due to the lack of more information, no further conclusions can be drawn, as a comparison is not feasible.

3.5.3.4 Evaluation of the carbon stock in Hevea b. plantations in Thailand

The factors required for the estimation of the total carbon stock concerning the rubber land use type, which is constituted by the vegetation and the soil components, are obtained in the following based on country-specific data, when available, or more general data, as previously mentioned. All biomass information is correctly reported as dry mass.

Carbon content in dry matter

Regarding the literature, in particular the Thailand-specific one, several carbon fraction values are reported and used. Bridhikitti [145] used a C fraction of AGB of the rubber tree in Thailand equal to 0.487; originally obtained however from trees in Brazil and Ghana. Wauters et al. [149] observed different C concentrations in the parts of the rubber tree, for instance: circa 46.85 % in fine and lateral roots, circa 48.2 % in tap root, circa 49.2 % in intermediate (Ø 2.5÷5.0 cm) branches, circa 48.35 % in log and circa 50.5 % in leafage (these are averaged values regarding the felled trees, of different ages and different clone types, in two specific zones: Ghana and Brazil); the resulting carbon concentration, averaged over all the tree components, was indeed 48.7 %. Hytoenen et al. [80] obtained a carbon fraction equal to 0.498 for *Hevea b.* clone RRIM 600 trees (25 year-old) in southern Thailand, which represents the mean averaged over the following C concentrations of the wood parts: 48.9 %, 50.3 %, 50.2 %, 49.8 % and 52.3 % for stump-roots, fine branches (Ø < 3 cm), intermediate branches (Ø 3÷5 cm), stem and leaves, respectively. Petsri et al. [79] used the 1997 IPCC default proportion of 50 % to convert dry biomass, in all its forms (AGB, roots, etc.), to carbon content; while Gnanavelrajah et al. [140] employed a carbon content of 55 %, for all the biomass. It is clear that converting the total tree biomass into the related C content using a fixed carbon fraction of 0.5 instead of the average carbon concentration for the constituents (which is likely to be lower, as here shown), would lead to overestimate its carbon stock. However, while using a biomass carbon percentage of 50 % is discouraged, Petsri et al. [79] decided to use this default value because the main causes of uncertainty in estimating the C stock might be far higher (e.g., allometric model) [79, 149].

The aforementioned real C shares, disaggregated by component of the tree, were obtained in one case for *Hevea b.* trees sited in two continents other than Southeast Asia, and in the other case for *Hevea b.* trees grown in Thailand. Therefore, the country-specific study of Hytoenen et al. [80] is here considered the most accurate and appropriate to represent the carbon contents in the several plant organs and the average carbon concentration of the Thai *Hevea b.* trees.

Methodological comment concerning Dead Organic Matter pool

Since the lack of specific information on the DOM carbon pool, two options can be undertaken: to estimate or to neglect it, which will mean equivalently to assume the related impacts as negligible with respect to the others. Albeit the facts that C_{DOM}, for forest land uses, represents a minor constituent of the overall total carbon stock (as can be deduced also from Section 3.5.3.2; or explicitly stated in the literature, e.g., in Blagodatsky et al. [150]) and that its value may be regarded as zero for forest plantations according to the Annex V to Directive 2009/28/EC [139], the carbon stored in the dead organic matter must be assessed also for the new land use class, i.e., *Hevea b.* plantation, as previously commented in Section 3.5.3.2 (methodological comment). However, country-specific information on DOM of rubber plantations is unavailable. In other words, the DOM carbon stock (i.e., in dead wood and litter pools) should be considered null for *Hevea b.* plantations, while it should be estimated in the case of non-plantation forests. In the case of rubber plantation land use type, neglect this carbon pool seems not appropriate, thus, it is in the following considered.

Estimating carbon in Dead Organic Matter pool

Due to the lack of data (biomass and carbon stock) about the dead organic matter in rubber plantations specifically located in Thailand, an estimation is here performed based on the only available data found in the literature, in order to allow a comparison with the corresponding stock of naturally regenerating forests calculated in Section 3.5.3.2. From the values regarding the mass of carbon in several non-tree components in [149], regarding *Hevea b.* trees in Western Ghana (age 2 – 4) and in Mato Grosso (age 15 – 26), it is possible to obtain here a mean C_{DOM} equal to circa 4.9 ton C/ha. This general (since the geographical origins, clonal varieties, ages considered) estimate for the C_{DOM} is thus used, and it represents very few percentage points (i.e., 2.9 %) of the total C stock of the plantation system analysed in this study.

Moreover, it should be noted that the values sourced from Wauters et al. [149] and then used for the estimation, refer to plantations characterised by a tree density (after 14 years) of 433 and 469 trees per ha in Western Ghana and Mato Grosso, respectively. Thus, as their results are used here to estimate the general C_{DOM} per ha, this last may be considered robust in the case of assuming a tree density of 440 trees per ha, for the reference *Hevea b.* plantation.

Carbon in the other pools

In the Thailand-specific literature, the estimates of the carbon stored in the *Hevea b.* living biomass, and in the related soil used, are not numerous, yet sufficient to permit further analysis.

For *Hevea b.* plantations, Jawjit et al. [93] used 103 and 57 ton C/ha as AGB C stock and BGB C stock, respectively. These estimates refer to a study of Gnanavelrajah et al. [140]; in which, however, it is clearly stated that the BGB for *Hevea b.* is 57 ton/ha. Therefore, it is likely that an error was made in Jawjit et al. [93], at least in the reporting of the below-ground biomass carbon stock. Moreover, Gnanavelrajah et al. [140] used 0.55 to convert biomass into biomass carbon, while, as previously indicated, a lower value should be recommended, thus leading to a slight overestimation and despite the fact this study is focused on Thailand, it does not mention several important factors, as the tree density studied, nor the age of the rubber trees analysed. Compared to other studies, the *Hevea b.* BGB figure reported by Gnanavelrajah et al. [140] (i.e., 57 ton/ha) seems considerably higher, being more than twofold with respect to the other estimations found in the literature (see Table 3.16). This resulted from the assumptions made in the cited study: "The belowground biomass of each quadrat was considered equivalent to 30 per cent of aboveground biomass as suggested for broad leaf vegetation", which means that the BGB was obtained multiplying the AGB (estimated with an equation for tropical forests of the FAO1997 and neglecting foliage) times a root-to-shoot ratio of 0.3 [140, p.245]. According to the 2019 Refinement [146], the root-to-shoot ratio for Asian planted forests belonging to the tropical rainforest zone is 0.325 ton root dry matter per tonne shoot dry matter. Several studies show that the root-to-shoot ratio decreases with the age of the rubber tree, e.g., Petsri et al. (focused on Thai *Hevea b.* trees) [79], Wauters et al. (focused on Western Ghana and Mato Grosso rubber trees) [149]. According to Petsri et al. [79], the root-to-shoot ratio in *Hevea b.* trees at different ages is as follows: 0.66 at age 1, 0.20 at age 5, 0.16 at age 10, 0.14 at age 15, 0.13 at age 20 and 0.12 at age 25. So, even if the ratio decreases with the age of the rubber tree, a value near 0.3 is reached when the tree is in its first years of life, and its related biomass is substantially lower than that which would be attained in the mature phase. Since instead the high AGB value reported by Gnanavelrajah et al. [140] (i.e., 187.53 ton/ha), it is impossible that this figure corresponded to a tree stand in the establishment stage, thus, a root-to-shoot ratio lower than 0.3 should have been used to derive the BGB. Indeed, more recent studies show that the root-to-shoot ratio in the case of rubber trees (age > 10) is close to the half of 0.3, thus, lower than the one corresponding to tropical forests. In other words, the authors may have overestimated the below-ground biomass (and therefore the related C stock) to a significant extent. For all these aforementioned reasons, the biomass C stocks here considered are based on the biomass (and directly biomass carbon) values from other studies, turning to be more realistic than the ones obtainable from Gnanavelrajah et al. biomasses.

Generally, direct measurement of tree biomass is not feasible in practice. In order to estimate rubber tree biomass, Hytoenen et al. [80] employed allometric equations specifically developed (in a previous work, [151]) for mature trees at clear-cutting age (i.e., 25 year old), based on (eighteen) trees of RRIM 600 clonal variety sited in southern Thailand. Petsri et al. [79], instead, developed an allometric model to estimate *Hevea b.* biomass depending on the age and specifically for Thailand, gathering information from numerous previous country-specific studies. Gnanavelrajah et al. (as previously commented), used the allometric model developed by FAO in 1997 [152] valid for tropical forests. Bridhikitti [145] used a modified version of the same allometric model (i.e., [152] model modified by Basuki et al. [153]), which is not developed for *Hevea b.* species and not for the Thailand region (note that, nevertheless, some inputs to the model are Thai-specific, e.g., the diameter at breast height for rubber trees measured in those studies). For these reasons, the models used by Hytoenen et al. [80] and Petsri et al. [79] are deemed to be more accurate, and representative of the biomass related to the *Hevea b.* plantations in Thailand.

Table 3.16 shows the data collected (for *Hevea b.* species and plantations) from the Thailand-specific literature (underlined in the table) along with the values deduced in this study based on these gathered data.

Tree density [trees/ha]	**Age [y]**	**root-to-shoot ratio**	**AGB [ton/ha]**	**BGB [ton/ha]**	**Total biomass [ton/ha]**	**C stock (biomass)[ton C/ha]**	**Source**
418.99	20	0.13	196.1	25.49	221.5	110.77	Petsri et al.[79]
418.99	25	0.12	229.3	27.51	256.8	128.4	Petsri et al. [79]
357	20	0.169	134.4	22.72	157.1	78.25	Hytoenen et al. [80]
357	25	0.168	147	24.67	171.7	85.49	Hytoenen et al. [80]
not declared	not declared	0.3	187.5	57.2	244.7	121.88	Gnanavelrajah et al. [140] for biomasses and Hytoenen et al. [80] for the C fraction
not declared	not declared	*0.12*	187.5	22.50	210.03	104.60	Gnanavelrajah et al. [140] for AGB, then assuming a BGB-AGB ratio of 0.12 and using Hytoenen et al. [80] C fraction
495	20	*0.13*	128.6	16.72	145.32	72.37	Bridhikitti [145]; assuming a BGB-AGB ratio of 0.13 and using Hytoenen et al. [80] C fraction
500	> 20	*0.12*	187.8	22.54	210.34	104.75	Bridhikitti [145]; assuming a BGB-AGB ratio of 0.12 and using Hytoenen et al. [80] C fraction
	average 7-25					84.74	Petsri et al. [79]
	average 1-6					18.9	Petsri et al. [79]

Table 3.16: biomass and C stocks in Thai *Hevea b.* plantations; underlined information is directly taken from the related source; italicised information denotes an assumption; and the other figures are here deduced, with simple operations, from the related sources.

From Table 3.16, it is possible to affirm that, with the exception of the lifecycle average values reported directly from Petsri et al. [79], the figures were obtained referring to mature trees at age 20 or 25. Gnanavelrajah et al. [140] AGB figure, thus, seems to be in accordance with a tree age of 18 – 20 years. Considering the root-to-shoot ratio, the values derived here starting from Hytoenen et al. [80] biomasses, converge to approximately 0.17, which is slightly higher compared to the values taken from Petsri et al. [79] related to the same tree age. This however can be explained by the fact that Hytoenen et al. [80] reported stumps and roots collectively as a single estimate, thus, in the calculations performed to obtain the Table 3.16, the root-to-shoot ratio is evaluated considering that aggregated figure as BGB, clearly leading to a higher ratio with respect to the estimation performed using roots biomass only. In any case, it can be asserted with high confidence that the rubber tree exhibits lower root-to-shoot ratios compared to those typically observed in tropical forest tree species (for comparison, see table 4.4 updated in chapter 4 of the 2019 Refinement [146]). Biomasses derived from Hytoenen et al. [80] appear to be lower than those obtained from the other studies, and the related C stocks are similar to values found in northern Thailand. The values obtained from Gnanavelrajah et al. [140], after correction, are in line with the estimates from the other studies, and thus similar values for tree ages and density (not declared in the original study) can be supposed.

It is important to note that considering factors expressed on a "per-hectare" basis, the tree density found on site (or used, as in the case of Petsri et al. [79]), i.e., number of trees per ha, plays a pivotal role on the final value obtained. Indeed, the slight differences, evident from the Table 3.16, are mainly determined by the model used for evaluating the biomass, by the tree density found or assumed, and by the age of the trees analysed. Thus, in this study, to allow better comparison between the biomass values, the biomasses per tree were obtained (dividing the biomass per area by the tree density used in the original study) and then multiplying the results by the same tree density (e.g., a density of 440 trees/ha, which is the one here assumed). The results of this procedure are presented in Table 3.17.

Age [y]	Total biomass [ton/ha]	Tree density [trees/ha]	Biomass per tree [ton/tree]	Total biomass if tree density is 440 trees/ha [ton/ha]	Source
20	221.54	418.99	0.52875	232.649	Petsri et al. [79]
25	256.80	418.99	0.61290	269.677	Petsri et al. [79]
20	157.12	357	0.44011	193.649	Hytoenen et al. [80]
25	171.67	357	0.48087	211.582	Hytoenen et al. [80]

Table 3.17: results from conversion of original data from the cited studies in order to put them on the same basis, to allow a comparison (e.g., using 357 or 419 trees/ha); here 440 trees/ha has been used; underlined information is directly taken from the related source; and the other figures are here deduced, with simple operations, from the related sources.

It is possible to observe that the values, for a fixed age, are more similar than previously detectable. In other words, the gaps between the various outcomes are clearly smaller than before. In the comparison, the further correction regarding the assumed carbon fraction to be used for Petsri et al. [79] values can be accomplished but switching from 0.5 to 0.498 leads to very small variations (i.e., 222.4 and 257.8 ton/ha would be attained for the 20 and the 25 tree stands, respectively).

From all this discussion, in particular for the wide country-specific supporting information, the work of Petsri et al. [79] is hence considered as a basis for reliable biomass estimations for the subsequent operations (and therefore also for carbon sequestration). It is important to remark that dry biomass was considered.

Table 3.18 exhibits the estimation concerning a tree stand aged 21 years, here obtained starting from data reported in Petsri et al. [79] (underlined).

Tree density [trees/ha]	Age [y]	root-to-shoot ratio	AGB [ton/ha]	BGB [ton/ha]	Total biomass [ton/ha]	C stock (biomass)[ton C/ha]	Source
418.99	21	0.13	204.8	26.62	231.4	115.2	Petsri et al. [79]

Table 3.18: biomass and C stock estimation for the case of 21 year old *Hevea b.* plantation, in Thailand.

Then, with reference to Table 3.18, the biomass per tree along with the biomass for a tree density of 440 trees per ha and its corresponding carbon stock, can be derived, as previously done in the Table 3.17: biomass per tree results to be 0.5523 ton/ha; biomass in the case of a tree density of 440 trees/ha results equal to 243.0 ton/ha; the related C stock is 121.0 ton C/ha. It is this last tree biomass for a density of 440 trees per ha (i.e., 243 ton per ha) that is regarded as accurate and representative and used in the following. To conclude, the final estimates regarding the living biomass and its accumulated carbon in the case of a 21 year old stand of *Hevea b.* trees can be obtained, as shown in Table 3.19.

Tree density [trees/ha]	Age [y]	root-to-shoot ratio	AGB [ton/ha]	BGB [ton/ha]	Total biomass [ton/ha]	C stock (biomass) [ton C/ha]
440	21	0.13	215.1	27.96	243.0	121.0

Table 3.19: living biomass and carbon stock estimates, for *Hevea b.* plantations aged 21, in Thailand; the underline denotes values directly taken from Petsri et al. [79].

Hence, the carbon bound in the living biomass can be approximated to 121 ton C/ha, of which 107 in AGB (i.e., AGB times the carbon fraction: 215*0.498) and the remainder 14 in BGB (i.e., BGB times the carbon fraction: 28*0.498). It is worth noting that the carbon fraction here used for calculating the carbon stock is directly sourced from Hytoenen et al. [80], as already specified.

Since the estimates here obtained and used about the living biomass C stocks for rubber land use type regards a density of 440 trees per ha, and the estimate of the dead mass C stock refers to densities in line with 440 trees per ha, it is possible to affirm fair consistency between the estimates of these carbon pools.

For comparison, the 2019 Refinement [146] reports that the AGB in forest plantations of *Hevea b.* with age < 20 is in the range 113-132 ton dry matter per ha. This last information is (indirectly) derived from Muhdi et al. [154], in which, using a particular allometric model (no direct information on the density per ha), the biomass and carbon stock of rubber trees aged 5,10 and 12 years located in Indonesia (North Sumatra province) were estimated. This may explain the slight discrepancy between the IPCC values, which are lower, and the ones quoted here from Thailand-specific literature.

Concerning the soil carbon stock, as soil organic carbon (SOC), the estimate here used is 40 Ton per ha and is taken from the Thai-specific study of Gnanavelrajah et al. [140] (which was also employed by Jawjit et al. [140]), since it is consistent with the other country-specific literature. The soil carbon stock estimations, specifically regarding *Hevea b.* plantations soil, reported in the Thailand-specific literature, are for example: 27 ton C/ha (0 – 30 cm depth) for a 20 year old stand in Buriram province (northeastern Thailand) [145]; 34 ton C/ha (0 – 30 cm depth) for a stand older than 20 years, located in Songkhla province (southern Thailand, peninsula) [145]; 38 ton C/ha (0 – 30 cm depth) for a two year old plantation in Songkhla province (southern Thailand, peninsula) [145].

3.5.3.5 Summary of results on carbon stocks

The information validated or estimated in Sections 3.5.3.2 – 3.5.3.4 necessary for the subsequent calculations, is summarised in Table 3.20.

Land use	**C_{AGB} [ton/ha]**	**C_{BGB} [ton/ha]**	**C_{soil} (SOC) [ton/ha]**	**C_{DOM} [ton/ha]**	**Total C stock [ton C/ha]**
Tropical forests	235	87	57	15	394
Hevea b.	107	14	40	5	166
	Average living biomass C stock [ton C/ha]				
Crops	34.1				

Table 3.20: results on carbon stocks, used in this study; approximated figures.

3.5.3.6 Transformation impacts

To model the emissions resulting from the clear cutting of naturally regenerating forests the following assumptions are made: **(i)** 20 % of AGB is burned, **(ii)** 8 % of AGB is harvested, **(iii)** 72 % of AGB decays, **(iv)** BGB and DOM decay, consistently with the adopted methodology (indicated in Section 3.5). The last two assumptions (iii, iv) mean that all the C accumulated in the BGB, in the DOM and in the 72 % of AGB, is released to the atmosphere in the form of CO_2, coherently with the default tier 1 assumptions of the IPCC [125]. Emissions of GWP are calculated also in kg CO_2-eq per ha (GWP 100 years), for the conversions occurred, in accordance with [125]. Thus, in this study that relative GHG emission metric is followed, expressing emissions in carbon dioxide equivalents. In particular, the GWPs 100-year from the sixth assessment report of the IPCC (i.e., AR6) [155] were used: 1 for CO_2; 27 for non-fossil CH_4; 273 for N_2O.

From the results obtained in Section 3.5.3.1 and the results summarised in Section 3.5.3.5, it is thus possible to calculate the transformation impacts.

Assumption (**i**): burning of 20 % AGB

In order to calculate the emissions resulting from forest fires, in this work, the guidelines of the European Environment Agency developed under the cooperative programme for monitoring and evaluation of the long-range transmission of air pollutants (EMEP/EEA), are employed. These guidelines are incorporated in the EMEP/EEA Guidebook 2019 [156], to which is here made reference. The generic methodology of the 2006 IPCC Guidelines (in practice not refined in 2019) [104] has a similar structure and would in practice lead to coherent results. Specifically, the 'tier 2 technology-specific' approach is selected and used for estimating the emissions derived from biomass burning. In praxis, in order to take into account the geography-specific and land-use-specific data relevant to the case, these are directly employed, thus enhancing the overall estimation. The method involves the evaluation of the carbon emitted, and then, the evaluation of the other gases using emission ratios with respect to carbon [156]. This detailed methodology requires indeed specific data as inputs; thus, it is consistent with the approach previously followed for gathering/calculating detailed information (that now serves as input). The emissions corresponding to the burning of the twenty percent of the above-ground biomass related to the former land use type area, i.e., forest land, which was then converted, amount to $5.630 \cdot 10^6$ ton CO_2-eq/y. That is to say that the CO_2-eqivalent emissions per hectare of forest land burned per year are $8.340 \cdot 10^3$ kg CO_2-eq/(ha*y). See Appendix A.3 for details. The emission factors used for the species CO, CH_4, NMVOC, NO_x, NH_3, N_2O, SO_x, are sourced from Table 3-3 of the EMEP/EEA Guidebook 2019 [156] of the European Environment Agency; particulate emission factors are taken from the same source, but they were derived from U.S. Environmental Protection Agency (US EPA) data. It is important to note that as burning efficiency (with EMEP/EEA terminology), denoted also as combustion factor (with IPCC nomenclature), which is dimensionless, representing the fraction of biomass burnt, the value reported in the Thailand-specific study by Petsri et al. [79] is here selected and used. In other words, it is assumed that the combustion factor is equal to 0.9; this is in line with the estimate of 0.8 for tropical biomes reported in the EMEP/EEA Guidebook 2019 [156].

However, considering the 2019 Refinement [146] values, it may result high, thus leading to a potential overestimation of the emissions.

<u>Assumption (**ii**): harvesting of 8 % AGB</u>

A naturally regenerating forest biomass equivalent to 18.8 ton C per hectare of forest land converted is harvested. Therefore, considering the annual transformed area, this leads to the conclusion that a biomass equivalent to $6.044\cdot10^5$ ton carbon per year is harvested in the considered time span.

<u>Assumption (**iii**): decay of 72 % AGB</u>

The decay of the seventy-two percent of the above-ground biomass, related to the tropical forests land use type, leads to the release of $1.995\cdot10^7$ ton CO_2/y in the time period analysed. That is to say $2.955\cdot10^4$ kg CO_2/(ha*y), thus per hectare of forestland converted and per year (in the selected time period).

<u>Assumption (**iv**): decay of BGB and DOM</u>

The complete decay of both the below-ground biomass and the dead organic matter, related to the tropical forests land use type, leads to the release of $1.202\cdot10^7$ ton CO_2/y in the time period analysed. That is to say $1.781\cdot10^4$ kg CO_2/(ha*y), thus per hectare of forestland converted and per year (in the analysed time period).

<u>Results</u>

The total emissions associated with the removal of naturally regenerating forests in Thailand during the specific time period 2000 – 2020 are $3.760\cdot10^7$ ton CO_2-eq/y. This means that the CO_2-eqivalent emissions per hectare of forest land converted per year are $5.570\cdot10^4$ kg CO_2-eq/(ha*y).

3.5.3.7 Occupation impacts

According to the implemented methodology [125], these impacts concern: (a) the change of organic carbon in mineral soils and the associated nitrous oxide emissions (potential loss is considered only when the former land use type consisted of natural vegetation, potential accumulation is considered only in cases where the former area was already in use); (b) the depletion of carbon in organic peat soils; (c) the increase of carbon in living biomass on the new land use which is not reaped (this accumulation of C is considered only for permanent crops and when the land is transformed into a different land use type). It is pivotal to note that soil carbon represents a significant part of the total C stored in forests and *Hevea b.* systems, not only dependent on carbon inputs or outputs (as CO_2 releases in organic matter mineralisation) but also on the depth taken into account. According to

Blagodatsky et al. [150], rubber plantations SOC accounts for the 41÷72 % of the total ecosystem carbon (TEC), varying in time throughout the rotation cycle. From the results obtained in Section 3.5.3.1 and the results summarised in Section 3.5.3.5, it is thus possible to calculate the occupation impacts.

Point (**a**): change of organic C in mineral soils

Since the comments and assumptions previously given, it is possible to recognise that the change in SOC due to the conversion from natural forests to *Hevea b.* plantations amounts to a loss. Indeed, generally, the transformation from forests to *Hevea b.* plantations (mainly monocultural) leads to a decrease in SOC stock [150]. On the contrary, after some land use changes to *Hevea b.* systems, the soil carbon may exhibit an increase (e.g., conversion of agricultural land into rubber area). This enrichment in soil carbon, however, is generally smaller compared to the carbon increase due to tree biomass accumulation. Since the insufficient knowledge on the land use change effects on soil carbon stocks (i.e., paucity of data), the potential SOC gain due to the transformation of cropland into rubber plantations is here not considered, thus neglected. The loss of soil organic carbon is quantitatively computed with an IPCC tier 2 approach [104], which practically means that country-specific values where used, instead of default ones, when available, leading to the emission of $2.202 \cdot 10^6$ ton CO_2-eq/y, that are equivalent to $3.261 \cdot 10^3$ kg CO_2-eq/(ha*y). These emissions in carbon dioxide equivalents contains also the emissions into air due to the nitrogen mineralisation caused by the loss of soil organic carbon stemming from the change in land use. See Appendix A.4 for details.

Point (**b**): reduction of C in organic peat soils

This particular impact is considered null/negligible because peat soils in Thailand represent a very small amount of the total land. Therefore, even if a peat soil area had been transformed into rubber area, such converted area would be negligible compared to the total area transformed into rubber (1,550,000 ha in 2000 – 2020). Hence, even regarding this potential case it would be reasonable to neglect its impacts. If, instead, that conversion had not occurred, then its impacts would be null and this assumption would be completely right. Specifically, the total area of peatland in Thailand is approximately 60,331 hectares, mostly concentrated in the coastal plain of the peninsula, thus in the southern regions [157]. Given that rubber cultivation was initially established in the southern regions, any potential conversion would have occurred in the last century, well outside the considered time period. As a result, the assumption made is deemed fair.

Point (**c**): carbon increase in biomass

Since the comments and assumptions previously given, it is possible to state that a carbon gain, in tree biomass, occurred following the transformation from cropland area to rubber plantation area. The accumulation (per hectare) is here calculated as the difference between the total living biomass carbon of *Hevea b.* land use category (i.e., 121 ton C/ha) and the total living biomass carbon of cropland land use category (i.e., 34.1 ton C/ha). The resulting gain for all the cropland area transformed into rubber plantations during the specific time period is $1.328 \cdot 10^{7}$ ton CO_2/y, that are equivalent to $1.517 \cdot 10^{4}$ kg CO_2/(ha*y). Calculation has been performed equivalently to the stock – difference method by IPCC [104, 146].

3.6 Field emissions

In the context of the natural rubber plantation, field emissions refer to the release of substances into the atmosphere, the soil, or the waters, from the activities (mainly agricultural) conducted in the field. These emissions can arise from various practices, including the application of fertilisers, manure management, soil cultivation, and other activities that involve the use of land for farming. In this case, emissions stemming from fertilisation, maintenance, and replanting activities are considered and estimated according to the following. Results are comprised in the inventory (Section 5.1.1).

The emissions derived from the use of ammonia, employed in the preservation of latex (see Sections 3.3.5.1 and 5.1.2), are not included due to the paucity of information. This lack of data is also indicated in the accurate work of Birnbach et al. [97], in which the authors hypothesise a possible volatilisation related to the collection of latex. It is important to underline that, in addition to the impacts from the cultivation/maintenance of the plantations, the dLUC impacts (calculated in Section 3.5) must also be considered. Indeed, the direct land use change (dLUC) emissions are inventoried in Section 5.1.1.

3.6.1 Agrochemicals

With regard to Section 3.3.4 (where the fertilisation practice is introduced), in the following, the models/methodologies for calculating the emissions originated from the use of fertilisers and herbicide are presented. The results are shown in the Appendix A.5. Emissions of heavy metals, to soil and waters, are not estimated due to information unavailability in the literature.

3.6.1.1 Fertilisers

The use of nitrogen fertilisers produces NH_3, NO_X, and N_2O [158, 159]. The use of phosphorus fertilisers releases particles containing P and phosphates [160, 161].

The following assumptions have been made, consistently with the rest of this study: (1) no organic fertiliser (i.e., animal manure) is used in the plantations, (2) the cultivation occurs on mineral soils (i.e., managed soils are mineral soils), and (3) the emissions due to crop residues are negligible, due to lack of needed data for rubber, in particular about the contents of total N in crop residues. These hypotheses can also be found in the Thai-specific study of [93].

Application of nitrogen fertiliser

The emissions of N considered, stemming from the use of nitrogen fertiliser only, are: (i) direct emissions of N_2O into air (i.e., directly from the fertilised soil); (ii) indirect N_2O emissions due to volatilisation of NH_3 and NO_x and their succeeding deposition on soil and water surfaces; (iii) indirect N_2O emissions due to leaching and runoff of the nitrogen from the inorganic fertilisation to soil and water; (iv) emissions into air of the parts of NH_3 and NO_x which do not convert into N_2O; (v) emissions into soil and water of the part of nitrogen (mainly in NO_3^- form) which do not convert into N_2O [104, 146]. With regard to points (iii) and (v), the part of N lost via leaching and runoff has been fairly assumed as NO_3^-. Thus, the fraction of NO_3^- which does not convert into N_2O is assumed to remain in the soil and water. For the point (iv), the emissions of NH_3 and NO_x into air have been calculated, without considering further successive wet/dry depositions due to lack of data; while, for the parts of NH_3 and NO_x which do convert into N_2O (point (ii)), the subsequent deposition on soils and waters has been taken into account. For evaluating these emissions, the IPCC tier 1 method has been employed [146], both for the direct and indirect pathways, in compliance with the [125]. Emission factors and fractions are sourced from tables 11.1 and 11.3, chapter 11 of the 2019 Refinement [146], and represent aggregated default values, which are not country-specific. All the detailed calculations are briefly presented in the Appendix A.5.1.

Note: N_2O emissions due to mineralised N as a result of soil C loss because of land use change are not included in this Section but are correctly included in point (a) of Section 3.5.3.7.

Application of phosphorus fertiliser

Phosphorus, essential nutrient for plant growth, can become a concern when it enters water bodies in excessive amounts, potentially leading to eutrophication. Eutrophication is the process by which nutrient enrichment, particularly P and N, causes an overgrowth of algae and other aquatic plants. This excessive growth can disrupt the balance of aquatic ecosystems, leading to oxygen depletion and harmful algal blooms. Phosphorus is transported from soil to water both in particulate and dissolved forms, and the possible loss pathways are (i) leaching, (ii) run-off/drainage, and (iii) erosion [160, 161]. Therefore, three types of P emissions are here considered: (i) leaching of dissolved phosphorus (soluble phosphate) to ground water; (ii) runoff of dissolved phosphorus (soluble phosphate) to surface water; (iii) erosion of soil particulate phosphorus (P-containing soil particles) to surface water [160, 161]. For modelling these emissions, the SALCA – P method (SALCA stands for Swiss Agricultural Life Cycle Assessment) has been employed, in compliance with the Ecoinvent database [126, 160, 162]. It is worth noting that this approach, albeit being more feasible and rapid than complex models, generates a rough estimate of the impacts [161]. Indeed, it entails mean default values, adjusted with correction factors, and its geographical scope is restricted to Europe, since it was developed for Swiss climate and soil conditions [163]. In praxis, some of the standard input values, necessary for the calculus, are Swiss focused, and, with few exceptions, it was not possible to find or obtain refinements representative of the considered region or continent (i.e., Thailand, Asia). Moreover, it has been pointed out that, in some cases (read as some geographies), the Ecoinvent methodology on P emissions may lead to underestimations, due to how the method was developed [164]. All the detailed calculations are presented in the Appendix A.5.2.

It should be noted that wind erosion is here neglected, since, according to Faist Emmenegger et al. [161], the wind erosion vulnerability of the analysed country is generally minimal.

3.6.1.2 Glyphosate

The glyphosate applied for weed control is considered to end up as emission to the soil, in accordance with Ecoinvent [126, 160, 162].

3.6.2 Biomass burning due to replanting

The *Hevea b.* 25 year old stands undergo two end of life options (which are not mutually exclusive): use as raw material in the wood industry and on-site combustion (see Section 3.3.3.3).

It is here assumed that the rubber area which is incinerated each year in the period 2000 – 2020 is equal to 11,455 hectares per year [79]. For the quantity of biomass to be incinerated (i.e., AGB residues, roots) and for the quantity of biomass to be used in the wood industry (i.e., stem), no direct reference to the Thai-specific literature is possible. From Hytoenen et al. [80], a mass of 44.68 ton/ha can be deduced for the biomass to be combusted, by summing the mass of the appropriate components of 25 year old trees. Nonetheless, this result is based on a tree density equal to 357 trees per ha. In the study of Petsri et al. [79], a mass of 43.54 ton/ha can be obtained for the biomass to be incinerated, by summing the AGB residues mass and the roots mass of 25 year old trees. However, in this case the authors reported that their estimation was based on studies and surveys focused on southern Thailand, but without clarifying explicitly the corresponding tree density value. In light of these, and to ensure consistency with the previous estimations of Section 3.5.3.4, the mass for a 25 year old *Hevea b.* tree is deduced from Petsri et al. [79] (see Table 3.17), and the mass percentages for all the components are directly sourced from Hytoenen et al. [80]. In this manner the estimation has been performed based on the tree density of 440 tree per ha, thus guaranteeing coherency, and on the correct organs that are burnt, obtaining a mass of 70.21 ton/ha to be incinerated, and a mass of 199.47 ton/ha for the rubberwood output.

For the burning of *Hevea b.*, the 'tier 2 technology-specific' approach from the EMEP/EEA Guidebook 2019 [156] is selected and, after some improvements, used for estimating the subsequent emissions. In praxis, this means that the method has been slightly modified in order to take into account the geography-specific and land-use-specific data relevant to the case. This is the rationale for the use of the specific carbon fraction (i.e., 0.498), and of the total mass of residues (i.e., 70.21 Ton/ha), which enhances the overall estimation. Emission factors used for the species CO, CH_4, NMVOC, NO_x, NH_3, N_2O, SO_x, are sourced from table 3-3 of the EMEP/EEA Guidebook 2019 [156]; particulate emission factors are taken from the same chapter, but they were derived from U.S. Environmental Protection Agency (US EPA) data. The burning efficiency is considered as written in the part (i) of Section 3.5.3.6. Further details are shown in the Appendix A.2 and A.5.3.

Chapter 4

Goal and Scope Definition

4.1 Goal definition

The rationales for this Life Cycle Assessment are to quantitatively evaluate the environmental impacts related to the life cycles of (i) retreaded truck tyres subjected to the retreading process implemented by Metalepsi Proteron (Ofir, Europe), and of (ii) virgin truck tyres. This study is therefore intended to:

- attain comparative conclusions between those two product systems (not for public disclosure);
- conduct a thorough environmental analysis on the most important raw material for (truck) tyres, i.e., natural rubber, for developing a specific and original LCI results dataset.

The Product Category Rule (PCR) of tyres (UL 10006) is considered for this cradle to grave assessment, performed with the SimaPro Software (v. 9.5) supplied from 2B S.r.l. (Mogliano Veneto, Italy). The LCI database employed in this work is the Ecoinvent database (version 3.9).

4.2 Scope definition

4.2.1 Systems description

4.2.1.1 Retreaded truck tyre

Metalepsi Proteron developed the Hapax legomenon specifically for tyres of size 385/65R22.5, on which it is applied replacing their worn treads.

The system is first characterised by the transport of worn truck tyres (carcasses or casings) from the collection centre in Ponto (Europe) to the Metalepsi manufacturing plant sited in Ofir (Europe). The retreading process implemented by the company is structured into three macro-stages: production of the elastomeric compounds, which takes place in the Ofir plant; production of the pre-moulded tread (jointless tread ring) at the Metalepsi manufacturing plant located in Paflagonia (Europe); cold retreading of the tyre in the Ofir plant.

Three elastomeric compounds are produced in the Ofir factory: the ring compound, the solution compound (also denoted as unvulcanised rubber solvent), and cushion compound (or substrate compound). Two of these, namely the ring and the cushion compounds, are sent to Bitinia, where the manufacturing (moulding) of the ring and of the cushion (substrate) gum is executed. Since no information about the packaging concerning this first trip were provided, it is here fairly assumed that the elastomeric compounds are transported without packaging. Afterwards, the ring and the substrate are sent back to the Ofir retreading plant along with the corresponding packaging. Then, the retreading process takes place according to the following ordered steps:

- visual inspection and shearography (a non-destructive testing), for selecting the old tyre structures (carcasses/casings), rejecting the damaged ones;
- automated buffing, to remove the residual old tread, obtain a peculiar surface roughness for enhancing adhesion, and attain the appropriate dimensions;
- skiving and repairing (manual operations) damages, if any, to the carcass;
- automated building, which entails the application, onto the casing surface, of the solution compound, of the (uncured) cushion (for improving the bonding between the tyre structure and the new tread), and of the (uncured) pre-moulded ring;
- enveloping the resulting tyre, using two rubber envelopes for homogeneously press the new parts (newly applied tread) on the tyre structure;
- curing, that occurs in autoclave at temperatures in the range 100 – 115 °C, pressures near 6 atm, and for 2 – 3 hours;
- final inspection, to guarantee the desired quality.

After, the retreaded tyres are sent towards the customers to be safely used again, extending the overall service life of the tyre structure (for its original application). At the end of this additional service life (use phase), the tyre undergoes a specific end-of-life (EOL) scenario.

4.2.1.2 New truck tyre

After the procurement of the necessary raw materials, the virgin truck tyre production entails: compounding and mixing (blending), forming, assembling/building, curing, and finishing. In this study, these manufacturing steps are assumed to occur in a factory located in Ofir. Each of the different rubber compounds used for the tyre is separately obtained by mixing specific raw materials in a Banbury machine. The blended compounds are then squeezed in rolling mills (heated rolls) in order to obtain rubber sheets. In a calendar machine (heated rollers), some of these sheets are pressed onto and within high-strength steels cords, obtaining sheets of steel reinforced rubber, which are then cut at precise angles required for making the body plies and the belts. Bead cores are instead made embedding annular steel wires into rubber. Other rubber sheets are employed for producing the inner liner, made by calendaring or extrusion. Some other rubber slabs, instead, are used to coat the reinforcing fabrics, previously obtained from textile synthetic fibres. In this way, the textile cord ply is manufactured. Simultaneously, different rubber compounds are extruded in order to obtain different components, for the different uses and parts of the final tyre. Indeed, the tread is extruded (screw-type extrusion), and with the extrusion process also parts of the sidewalls are shaped. Afterwards, all the components are ready for the assembling, which occurs in the tyre assembly machine. Onto this machine, similar to a big drum, wire beads are placed at the extremities, while sidewalls, inner liner and body ply are added at the centre, and the building machine starts to rotate. Then, the bladder present inside this new tyre is inflated and the belts are laid out, followed by the tread. At this point, bladders on each side inflate pushing the components into the correct shape. Special rollers press all the parts together (stitching process) in order to obtain the green tyre. This green tyre undergoes curing into heated presses containing moulds (curing presses), according to a precise vulcanisation scheme. Inside the air cavity of the tyre, an inner tube (rubber bladder) inflates to press the tyre against the mould. In this way, the tread pattern and sidewalls design are achieved. It can be stated that, generally, high pressure steams provide the required heat, and that sometimes they generate also electricity. When the virgin cured tyre is obtained it must be inspected, and then, in case of positive responses, it can be used for its intended application. At the end of its service life (use phase), the worn tyre undergoes a particular end-of-life (EOL) scenario.

4.2.1.3 Functional unit and reference flow

According to the PCR of tyres [165], the functional unit (FU) for truck tyres is one tyre driven one thousand kilometres. The tyre's performance is achieved through the manufacturing and utilisation of a specific tyre portion, i.e., the reference flow [165]. In this case, the portion of tyre is evaluated per functional unit (No per FU) according to the Equation (1):

$$No\ per\ FU\ \left[\frac{unit}{FU}\right] = \frac{1{,}000\ [km/FU]}{Reference\ service\ life\ of\ tyre\ [km]} \tag{1}$$

For the new tyre, the reference service life is assumed to be 160,000 km. For the retreaded tyre, the reference service life is given by the sum of the service life of the virgin tyre and its supplementary service life due to the retreading, considering the number of retreads [165]. In this work, one instance of the retreading process is assumed, along with an additional service life of 160,000 km. Therefore, the resulting reference service life of a retreaded tyre is 320,000 km.

Consequently, the reference flows for a virgin truck tyre and a retreaded truck tyre are exhibited in Table 4.1, along with the functional unit.

Functional Unit	
One tyre driven 1,000 km	
Reference flow [unit/FU]	
New tyre	6.25E-03
Retreaded tyre	3.13E-03

Table 4.1: functional unit and fraction of tyre per functional unit, for the studied product systems.

4.2.2 System boundaries

4.2.2.1 Technical system boundary

The cut-off criterion implemented in this study is consistent with the tyre PCR guidelines [165], hence, the contribution of the included elementary flows linked to the product systems (inflows/outflows) represents at least the 99 % of the environmental impacts. This implies that, with reference to the PCR of tyres [165], the following activities are excluded from the system boundaries of this study, for both the virgin and the retreaded truck tyres systems: equipment assets; mounting operations – viz., transport of tyre from manufacturing/retreading plant to the location where it is positioned, installation, transport of the ready-to-use truck to final customers – collected under information modules A4 to A6; maintenance and repairing during service, covered in information modules B2 and B3; removal of the product, at its EOL, from the truck, indicated in information module C1. The life cycle activities that lie within the system boundaries can be showed in Figure 4.1.

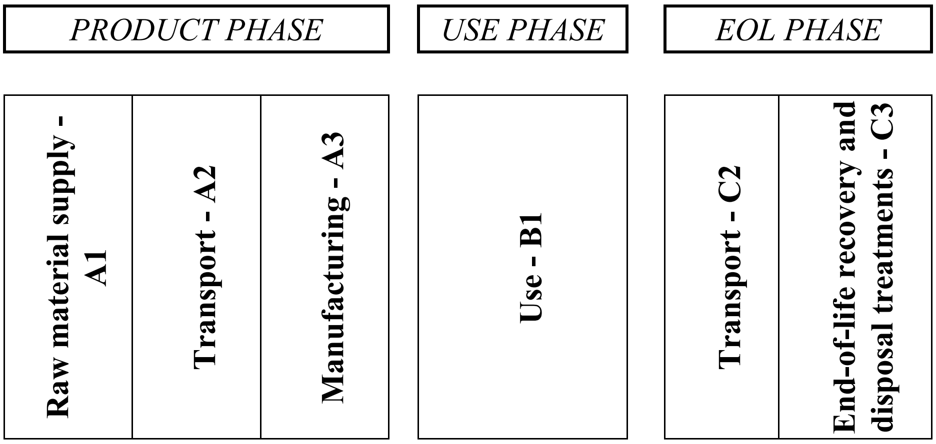

Figure 4.1: life cycle of tyres, as considered in this work, showing the information modules that constitute that scope, while the out-of-scope activities are not presented.

The same life cycle stages, as indicated in Figure 4.1, are included in both the product systems, as crucial for comparative studies. The descriptions that follow, regards the contributions considered in this study, for the two systems.

The “raw material supply – information module A1” comprises the extraction, the refinement, and the processing of resources and materials, the production and the use of energy from primary or secondary sources, the auxiliary products (e.g., envelopes used in the retreading) or their raw materials, and of packaging. The “transport – information module A2” entails the transport of raw materials, ancillary materials, and packaging materials, to the production factory. The manufacturing of the material inputs into the completed tyre (new or retreaded), along with the related energy consumption, the manufacturing of the auxiliary products used, the internal transports, the EOL of production residues, and the EOL of packaging, are all included in the “manufacturing – information module A3”. The “use - information module B1” comprises the release of tyre and road wear particles (TRWP), which are clusters composed of tyre material and road material, due to abrasion; whereas the contribution of the energy demand (i.e., fuel consumption) to the impacts that can be imputable to the tyre, is here excluded from the scope. The “transport – information module C2” concerns the transfer of the end-of-life tyre (ELT) to the treatment plants. The EOL processing is included in the “end-of-life recovery and disposal treatments – information module C3”.

Regarding the retreaded tyre system, the residues (granulate scraps) generated in the buffing of the old casing, in the building, and in the curing, are sent to a factory in Pomerania (Europe) to be recycled, for then returning to the Ofir plant and being used as secondary raw material to produce the compounds. Hence, in this case of closed loop recycling, these scraps are considered; in other words, they are included in this system boundary (however, since lack of primary data specific for the process, no energy consumption is assumed, but only transport). The discarded tyres, from the first inspection stage of the retreading process, are not accounted for in this study. For the other types of waste, in particular for the ones directed to recycling, the polluter pays principle (PPP) is employed, leading to the inclusion in the boundary of the related transport only.

In the new tyre system, no packaging materials for semi-finished products are assumed, due to the hypothesis that the virgin tyre production occurs in one factory, without transports from or to other plants.

4.2.2.2 Geographical system boundary

In this study, the geographical scope is the tyre retreading and the virgin tyre manufacturing in northern Europe, specifically in Ofir. The raw materials used for the retreaded tyre product are modelled as sourced by the Metalepsi company. This implies a global supply network, with suppliers located in Europe as well as in Asia, Africa, and Americas. The corresponding distances and means of transport are considered and modelled. The same transport (distances and means of) characterising those raw materials, is assumed also for each of those raw materials (or as in one case, for a similar substance but with the same function – flame retardant) included in the new tyre system. This is due to the unavailability of primary data concerning the materials procurement of the virgin tyre product. For instance, since the availability of primary information about the carbon black used for the ring compound (retreaded tyre system), the same sourcing (same distances and means of transports) is fairly assumed for the carbon black employed in the compounding required for the virgin tyre manufacturing. For the raw materials used for the new tyre and not for the retreaded tyre (for which, thus, neither primary nor secondary information is available), a distance of 1,000 km covered by truck is assumed. Therefore, for these last raw materials, sourcing from the EU is considered. The only exception being the transport of the synthetic fibres used for the new tyre structure, which are assumed to be sourced from India, due to the precise geography on which the related Ecoinvent process was developed. Hence, all the choices and assumptions done, guarantee coherency and comparability.

The retreaded truck tyre is produced in the factory located in Ofir. The carcasses to be retreaded are sourced from Ponto. The elastomeric compounds are manufactured in the Ofir factory, while the new tread and the substrate are manufactured in the plant at Bitinia site. For the packaging materials used for the semifinished products of the retreaded tyre (viz., ring and substrate), the primary data provided by the company are used; in praxis, they are sourced from local near plants.

The virgin tyre is manufactured in one factory only, assumed to be situated in Ofir. The rationale for this arbitrary choice, is that it allows better consistency and comparability of the two systems.

The end-of-life treatments, considered identical for both the products, are assumed to take place in factories located at distances of 50 km, which is assumed to be covered by a generic waste collection truck.

4.2.2.3 Temporal system boundary

The primary data used in this study are obtained from Metalepsi Proteron, and specifically refer to the year 2021. The secondary data employed in this study for characterising the mass composition of the new tyre relate to the year 2021 (data from the Japan Automobile Tyre Manufacturers Association – JATMA [166]), the ones for the production of the new tyre (see Section 5.2) refer to few years earlier (2017 year). This gap is fairly deemed irrelevant, thereby comparability/consistency is regarded as ensured. Data on the EOL scenario are focused on the last years (2020 – 2022).

The results obtained for natural rubber are based on data other than primary (secondary data from the literature) and estimations, all referring to years within the time period 2000 – 2023.

In conclusion, the considered data and the final outcomes concerning the tyre products, are regarded to hold validity in the time span between 2010 and the present year at least.

4.2.3 General assumptions, data sources and quality

The reference mass of the truck tyre (virgin or retreaded) considered in this study is 79.94 kg, as retrieved from the Metalepsi company. The composition of the retreaded tyre (information module A1) is considered according to primary data specified by the Metalepsi company itself, while the composition of the new tyre (A1) is derived from the guidelines developed by the Japan Automobile Tyre Manufacturers Association (JATMA) [166], since the paucity of primary data on that matter. Furter details are explicated in the LCI (Sections 5.2 – 5.3). Table 4.2 shows the original data and the resulting mass composition, assumed in this study, of the new tyre of mass 79.94 kg.

Raw material	Mass ratio [phr]	Mass ratio [%]	Mass composition (new tyre) [kg]
Natural rubber	78.8	37.08	29.64
Synthetic rubber	21.2	9.98	7.98
(thus, new rubber is)	100	47.06	37.62
Carbon black	47.3	22.26	17.79
Process oil	1.8	0.85	0.68
Total of organic rubber chemicals	8.3	3.91	3.12
Zinc oxide	4.4	2.07	1.66
Sulphur	2.7	1.27	1.02
Silica	2.8	1.32	1.05
Total of fibres	0.4	0.19	0.15
Steel cord	31.5	14.82	11.85
Bead wire	13.3	6.26	5.00
Total	212.5	100	79.94

Table 4.2: raw material composition of virgin tyre, based on JATMA [166], and with reference to the tyres of mass 79.94 kg considered in this work.

Note that the organic rubber chemicals (not specified in Table 4.2, which is based on JATMA data, as previously declared) required further assumptions to obtain a more precise composition that takes into account also these chemicals. These hypotheses are clearly stated in the LCI (Sections 5.2 – 5.3), and are based on the literature and, when possible, on the primary information concerning the retreading system. This means that, among the most common rubber chemicals reported in the literature, the ones utilised also for the retreaded tyre, are here selected. For example, N-1,3-

dimethylbutyl-N'-phenyl-p-phenylenediamine (i.e., 6PPD) and 2,2,4-Trimethyl-1,2-dihydroquinoline (i.e., TMQ), employed for producing the ring compound in the retreaded tyre system (primary data from Metalepsi), are assumed to be used also as chemicals in the production of the compound for the new tyre, since both are the most used antioxidants/antiozonants in the tyre industry. This ensures further coherency between the studied systems, which improves their comparison, but of course represents a limitation, due to the lack of primary data regarding the virgin tyre system.

For the activities in the information modules A2 and A3, primary data (from Metalepsi company) are used for the retreaded tyre system, and secondary data (see Section 5.2 for details) are used for the new tyre system. The information used for the latter product system, i.e., virgin tyre, was obtained particularly for the European tyre production, thus, it is here deemed as valid and representative of the studied new tyre manufacturing (as it is assumed to occur in northern Europe).

A wear rate equal to QQ %, with respect to the total mass of the tyre, is reported by Metalepsi Proteron and therefore used during the service of the retreaded tyre. The same tread wear rate proper of the retreaded tyre is fairly assumed and employed for the new tyre use phase.

The end of life scenario considered in this study is shown in Table 4.2, along with the EOL of the packaging.

	[%]				
	Rubber (tyre)	Plastic packaging	Paper and Cardboard	Steel	Pallet wood
Reused	-	-	-	-	12.3
Recycled	52.4	45.5	71.6	90.0	80.0
Incinerated	39.8	37.2	28.4	5.7	5.7
Landfilled	4.3	17.3	-	2.0	2.0
Backfilled	3.6	-	-	-	-

Table 4.3: ELT and packaging EOL (EU-specific) data, pallet EOL (USA-specific) data, taken from [167-171].

This EOL scenario is used for both the virgin and the retreaded tyres, after their useful lives. The mass to consider for ELT is obtained subtracting the mass loss due to wear from the reference mass of 79.94 kg (which is the mass of a new truck tyre and of a newly retreaded truck tyre). It must be noted that, the information about the waste generated during the new tyre manufacturing, retrieved from the literature, is general, so not distinguishing between waste types, but referring to a total mass of scraps. Therefore, this waste mass disposal pathway is modelled as a mix of treatment according to Ecoinvent database: landfilling (55.22 % of the total mass), incineration (44.11 %) and open burning (0.67 %). The EOL of the waste (cured) rubber obtained during the retreading process is instead modelled according to the assumed scenario (Table 4.3).

For foreground processes, the collected data were validated considering their representativeness with respect to the temporal, geographical, and technological system boundaries assumed in this study. The validated information was then used as basis for the LCI of this work. In other words, data quality, concerning time, geography, and technology is ensured. Background processes relied on generic data(sets) drawn from the Ecoinvent database (version 3.9), the utilisation of which in this study was coherent and identical for the two analysed product systems, sustaining their comparability. Moreover, these generic data, sourced from the mentioned database, were controlled in terms of temporal, geographical, and technological representativeness, to guarantee the consistency of their underlying assumptions with those of this work.

Finally, it is deemed that in this study (i) the completeness (all the pertinent processes related to the products have been incorporated, reflecting the specific scenarios of the virgin and of the retreaded tyre), (ii) the reliability (required information – obtained in the preferred order: primary data, secondary data, estimations – was verified), (iii) the consistency (data with the same level of detail have been employed, when possible, following identical methodological assumptions), (iv) the transparency and reproducibility (information and methodologies employed have been thoroughly documented to facilitate validation and reproducibility), and (v) the representativeness (data characteristic of the specific geography and of the current practices have been used), are ensured.

One last relevant point to mark, is that the research, assumptions, and estimates made in this study, regarding the critical raw material natural rubber, not present in the Ecoinvent database, have led to a cradle-to-gate assessment, for which the economic partitioning rule was required and coherently performed.

Chapter 5
Life Cycle Inventory Analysis

This chapter offers a detailed insight of the inventory data employed for modelling the *Hevea b.* plantation system (Section 5.1.1), the unsmoked sheets (a primary rubber product; Section 5.1.4), the technically specified rubber (the primary rubber product used in the tyre industry; Section 5.1.5), the virgin tyre (Section 5.2), and the retreading system (retreaded tyre; Section 5.3).

The modelling of the systems in SimaPro LCA software has requested some further calculations, mainly to convert the measurement units. These additional steps, together with the specific assumptions needed, are shown in the following, to ensure consistency, transparency, and reproducibility. Note that the inventoried data (as inflows/outflows) refer, when explicitly declared, to one unit of the related product or manufacturing process (e.g., raw material inputs for producing one new tyre, energy consumption for obtaining one retreaded tyre). The rationale for this choice is to improve the clarity and simplicity of the reporting. Moreover, it is fundamental to mark that this represents a reporting decision, and it must be clearly stated that under no circumstances these "reporting units" have substituted the correct functional unit in the execution of the assessment (recall that the FU is not "one tyre").

5.1 LCI of natural rubber

The geographical, temporal, and technical coverage of the inventory analysis of natural rubber is the current status of the natural rubber agricultural practices and primary processing in Thailand. The system boundary entails the *Hevea b.* cultivation (site preparation, fertilisation, weeding, maintenance, harvesting of the biomass (co-product) at tree end-of-life, burning of a part of it, emissions due to the use of fertilisers, and impacts due to changes in land use), the transport of latex/coagulum to primary processing facilities, the manufacturing of the unsmoked rubber sheets, and the manufacturing of the technically specified rubber (as STR 20 grade), including energy consumptions, wastes or avoided products, when possible. The equipment used for tapping (note that it is a manual operation, specific knives are used) is out of the scope; no packaging is assumed for the internal transports. The co-products of the fresh latex tapping are the field coagulum, the stem biomass (once harvested), and the rubber seeds. A qualitative system flow chart, along with the system boundary, is shown in Figure 5.1, where, for the sake of clarity, some inflows/outflows are not depicted (e.g., energy inputs, water, releases).

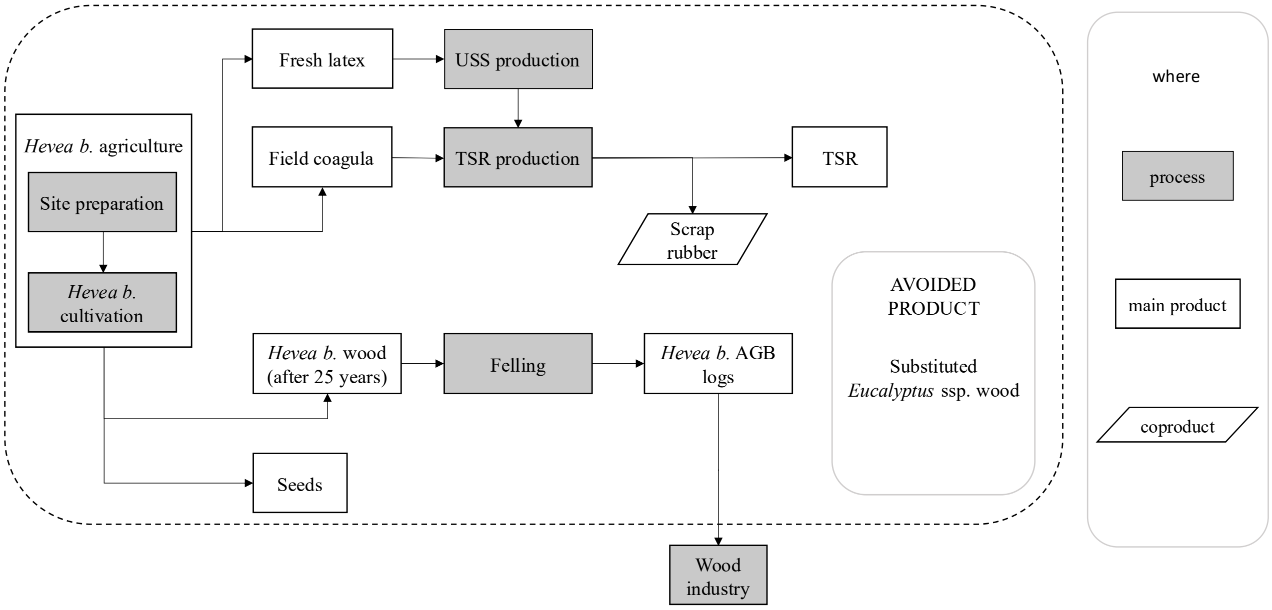

Figure 5.1: natural rubber system flow chart and boundary. Note that TSR is used as raw material in the tyre industry.

For completeness, Figure 5.2 exhibits the SimaPro model, from the natural rubber forms obtained in Thailand, to the tyre-grade rubber transported to the European tyre manufacturers.

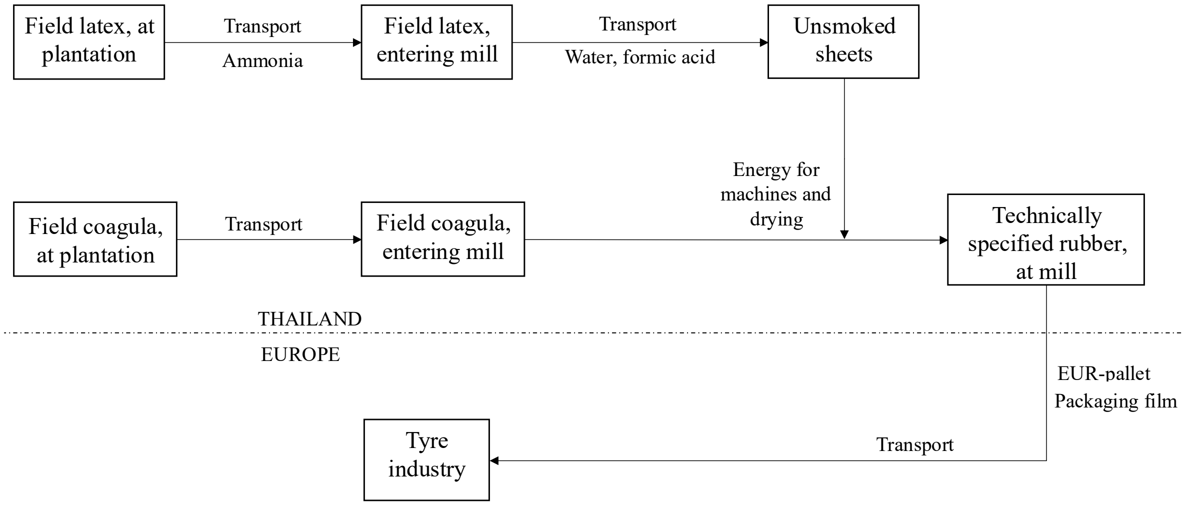

Figure 5.2: overview of SimaPro modelling, from NR at plantation exit to the NR supplied to the tyre industry.

Regarding this inventory, secondary data from Thai-specific literature (generally obtained from surveys, interviews, case studies, Thai governmental agencies) and estimates (performed in this work) have been collected/evaluated, validated, and then used, since the unavailability of primary data. The only exception to the use of country-specific data regards the information used for evaluating the mass of rubber seeds (Section 5.1.1.13 for details). Table 5.1 summaries the data quality requirements evaluated.

Data quality category	Requirement
Geospatial	Country-specific data (Thailand)
Temporal	Recent data; data from 2000 – 2020 period for land use change topics
Technological	Most common practices

Table 5.1: data quality requirements for the acquisition of the information required for the NR system.

When allocation was necessary, the partitioning problem was solved considering the economic worth of the products, evaluated by price. In other words, economic allocation was chosen and performed, consistently across the system. Regarding the natural rubber plantation products, the economic allocation factors used are taken from Birnbach et al. [97] and are consistent with the Thai-specific ones reported in Jawjit et al. [92]. The rationale for this choice is that all the co-products are considered in the former study, while not in the latter. Refer to Appendix A.6.1. Concerning the manufacturing of the technically specified rubber, economic partitioning has been performed in this study, for details consult Appendix A.6.2. The origins of the employed data are clearly declared when introduced in the text. The order here presented resembles the production flow: the agriculture of rubber trees (Section 5.1.1) leads to the collection of latex (in both forms: field latex and field coagulum), which is then partly transported to the sites where unsmoked sheets are produced (Section 5.1.4), and partially to the factories where technically specified rubber is obtained (Section 5.1.5), using as input also the USS. For a comprehensive explanation of the *Hevea b.* plantations, the primary processing, and the field emissions, please refer to Chapter 3 of this work.

Finally, the quality of the resulting dataset(s) is deemed as high, in terms of representativeness, completeness, and transparency.

5.1.1 Natural rubber plantation

The natural rubber plantation is modelled at the plantation exit, per hectare of plantation and over its lifecycle (i.e., 25 years, as stated in Section 3.3.3.3).

5.1.1.1 Power sawing

The assumptions performed are:

i. the gasoline consumed by the sawing machine is 125 litres/ha, from Petsri et al. (2013);
ii. the density of gasoline is equal to 750 kg/m^3.

With regard to the SimaPro modelling, the process *"Power sawing, with catalytic converter {GLO}| market for | Cut-off, S"* has been employed, which requires further conversion so as to express the input as working hours. Thus, an additional assumption is required:

iii. the average consumption per hour is equal to 1.6 kg, from Ecoinvent 3.8 dataset documentation [172]. This modelled activity satisfies the time requirements of this assessment, and it refers to Europe, however, the information here needed (i.e., consumption per hour) it is fairly considered valid/is representative also for the analysed region. (Note that for the SimaPro modelling, another activity, referring to global geography is used, which is more proper).

Therefore, it is possible to obtain:

1.6 kg divided by 750 kg/m^3 = $2.13 \cdot 10^{-3}$ m^3 = 2.13 L/hour

that means 2.13 litres for one hour working. Then, the consumption assumed in (i) of 125 L/ha corresponds to 58.68 hour/ha (obtained dividing 125 L/ha by 2.13L/hour) and using a 25 year life cycle we obtain 2.347 hour/(ha*y) (obtained dividing 58.68 hour/ha by 25 y) which is equal to 8449.2 seconds per ha per year.

5.1.1.2 Diesel used in tillage

The assumptions performed are:

i. diesel use equivalent to 0.78 L/(ha*y), from Jawjit et al. [93];
ii. the density of diesel is equal to 850 kg/m^3.

Therefore, it is possible to obtain:

(0.78/1000) m^3/(ha*y) and then multiplying this value for the density, assumed in (ii), a value of 0.663 kg/(ha*y) is obtained.

Assumption (i) is consistent with the range reported by Petsri et al. [79] of 56.25 ÷ 92.75 L per ha (then to be considered for the plantation lifecycle).

With regard to the SimaPro modelling, the process *"Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery | Cut-off, S"* has been employed, which requires further calculations: following the conversion given in the Ecoinvent process itself, i.e., 1 MJ = 0.0222 kg, it yields that 0.66 kg = 29.7297 MJ.

5.1.1.3 Diesel used by truck during thinning

The assumptions performed are:

i. the diesel consumed by the truck in the thinning is 84 L/ha, from Petsri et al. [79];
ii. the density of diesel is equal to 850 kg/m^3.

Therefore, it is possible to obtain:

since the value assumed in (i) refers to the total, it is possible to divide by 25 years obtaining 3.36 L/(ha*y); that is equal to (3.36/1000) m^3/(ha*y) and then multiplying by the density assumed in (ii), the figure 2.856 kg/(ha*y) is obtained.

With regard to the SimaPro modelling, the process *"Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery | Cut-off, S"* has been employed, which requires further calculations: following the conversion given in the Ecoinvent process itself, i.e., 1 MJ = 0.0222 kg, it yields that 2.856 kg= 128.8288 MJ.

5.1.1.4 Land occupation and transformation

The assumptions performed are:

i. data, literature, and observations about land use change as specified in Section 3.5;
ii. production yield, production cycle as considered in this study (Chapter 3);
iii. calculation performed according to the Ecoinvent database [173, 174].

Therefore, it is possible to obtain:

Land occupation = total area of plantation/product extracted per year = $3.91 \cdot 10^{10}$ [m^2] / $4.31 \cdot 10^{10}$ [kg/y] = $9.08 \cdot 10^{-1}$ (m^2*y)/kg extracted.

Land transformation = total area of plantation/total lifetime production = $3.91 \cdot 10^{10}$ [m^2] / ($4.31 \cdot 10^{10}$ [kg/y] * 25 [y]) = $3.63 \cdot 10^{-2}$ m^2/kg extracted.

Where for product harvested per year, the overall output (latex, cup lump and biomass) of the plantation has been considered (while options for seeds are not modelled in this study). When multiple-products systems are considered, also land occupation and transformation may be partitioned [173], this motivates the calculus performed, since it permits subsequent allocation.

With regard to the SimaPro modelling, the exchanges *"Occupation, permanent crop, TH"*, *"Transformation, from agriculture + forest"* and *"Transformation, to permanent crop, TH"*, have been employed, which do not require any further conversion.

It is important to mark that the land transformation exchange does not capture LUC emissions [174].

5.1.1.5 Biomass residue in post harvested area

The assumptions performed are:

i. total residues for burning account for 70.21 ton/ha, as specified in Section 3.6.2.

Therefore, it is possible to obtain:

dividing by 25 years plantation cycle a value of 2.81 ton biomass/(ha*y) is attained.

5.1.1.6 Nitrogen fertiliser used

The assumed amount of nitrogen fertiliser used is 70 kg/(ha*y), from Jawjit et al. [93], as nutrient supplied to the Hevea b. trees (in accordance with Ecoinvent process documentation and Ecoinvent practices).

With regard to the SimaPro modelling, the process *"Inorganic nitrogen fertiliser, as N {TH}| market for inorganic nitrogen fertiliser, as N | Cut-off, S"* has been employed, which does not require any further conversion. It should be noted that in this Ecoinvent process the output is supplied as mass of nutrient (read corresponding documentation); coherency is thus ensured.

5.1.1.7 Phosphorus fertiliser used

The assumed quantity of phosphorus fertiliser consumed is 35 kg/(ha*y), from Jawjit et al. [93], as nutrient supplied to the Hevea b. trees (in accordance with Ecoinvent process documentation).

With regard to the SimaPro modelling, the process *"Inorganic phosphorus fertiliser, as* P_2O_5 *{TH}| market for inorganic phosphorus fertiliser, as* P_2O_5 *| Cut-off, S"* has been employed, which does not require any further conversion. It should be noted that in this Ecoinvent process the output is supplied as mass of nutrient (read corresponding documentation); coherency is thus ensured.

5.1.1.8 Potassium fertiliser used

The assumed quantity of potassium fertiliser consumed is 70 kg/(ha*y), from comments in Section 3.3.4.

With regard to the SimaPro modelling, the process *"Inorganic potassium fertiliser, as* K_2O *{TH}| market for inorganic potassium fertiliser, as* K_2O *| Cut-off, S"* has been employed, which does not require any further conversion. It should be noted that in this Ecoinvent process the output is supplied as mass of nutrient (read related documentation); coherency is thus ensured.

5.1.1.9 Glyphosate

The assumptions performed are:

i. the amount of glyphosate used specifically in Thailand is 3 kg glyphosate/ton fresh latex, from Jawjit et al. [92]. Note that this is the allocated value, so it is fundamental to consider the allocation factor used in that study (i.e., 0.6) and the reported fresh latex yield in that study (i.e., 1800 kg/(ha*y)) in order to calculate, going backwards, the general unallocated value;

ii. glyphosate is used in 1 vol.% water solution, that is 1 litre to 100 litres of water, deduced from Petsri et al. [79];
iii. glyphosate density as 1000 kg/m^3, as in Petsri et al. [79].

Therefore, it is possible to obtain:

(0.003 [kg glyphosate/kg fresh latex] *1800 [kg fresh latex/(ha*y)])/0.6= 9 kg glyphosate/(ha*y).

This value is also in line with the figure reported in Petsri et al. [79] of 6.25 kg glyphosate/(ha*y) that they sourced from the Department of Agriculture (DOA) of Thailand; it is worth mentioning that they reported, in addition, the application of another herbicide (i.e., paraquat) at a rate of 2.5 kg/(ha*y), thus resulting in a total herbicide amount of 8.75 kg, which is very similar to the herbicide consumption here assumed.

With regard to the SimaPro modelling, the process *"Glyphosate {GLO}| market for | Cut-off, S"* has been employed, which does not require any further conversion.

The water for the glyphosate solution can be obtained considering (ii) and (iii): 99 L per kg glyphosate * 9 kg glyphosate = 891 L water.

In the SimaPro modelling, this water input has been considered with the process *"Water, unspecified natural origin/m^3, TH"*.

5.1.1.10 Planting operation

The assumptions performed are:

i. calculation in accordance with Ecoinvent database [175];
ii. tree density and lifetime as assumed in this study (Sections 3.3.3.1 and 3.3.3.3, respectively).

Therefore, it is possible to obtain:

Planting tree [tree/kg] = tree density [tree/ha] / crop lifetime [y] / yield [kg/(ha*y)] = 440 [tree/ha] / 25 [y] / $1.10 \cdot 10^4$ [kg/ha*y] = $1.6 \cdot 10^{-3}$ tree/kg of output (i.e., fresh latex, field coagulum, harvested biomass).

With regard to the SimaPro modelling, the process *"Planting tree {GLO}| market for planting tree | Cut-off, S"* has been employed, which does not require any further conversion.

5.1.1.11 Fresh latex and field coagulum

The assumptions performed are:

i. field latex yield and coagulum yields of 2.795 ton/ha and 0.243 ton/ha, respectively, as specified in part A.1 of the Appendix.

With regard to the SimaPro modelling, the processes *"Field latex, at plantation"* and *"Field coagula, at plantation"* have been created.

5.1.1.12 Rubberwood

The assumption performed is:

i. output biomass of *Hevea b.* as calculated in Section 3.6.2 (i.e., 199.473 ton/ha).

Therefore, it is possible to obtain:

199.473 t/ha divided by 25 leads to 7978.936 kg/(ha*y).

With regard to the SimaPro modelling, the process *"Hevea wood, at plantation"* has been created.

5.1.1.13 Rubber seeds

The assumptions performed are:

i. the annual quantity of seeds produced by one *Hevea b.* tree equals 2.6 kg, from Eka et al. [176];
ii. a reference plantation density of 440 trees per hectare, as selected in this study.

Therefore, it is possible to obtain:

440 trees/ha * 2.6 kg seeds/tree*y = 1144 kg seeds/(ha*y).

Regarding the first assumption it should be noted that the source of information [176] is a Malaysian-based study in which, however, no stated geospatial reference to a country nor to a specific clone are done with respect to that information. Considering that the clone RRIM 600 is largely spread both in Malaysia (the name reminds its origin) and in Thailand, the value here obtained is considered valid with respect to the geospatial requirement.

It is worth mentioning that a value of 114 kg seeds/(ha*y) has been calculated in the work of Birnbach et al. [97], focused on Malaysia. Nevertheless, the figure here proposed seems appropriate, being in good accordance with the range 800 – 1200 kg seeds/(ha*y), reported in Eka et al. [176] citing a study which was unavailable, and with the one obtained considering different countries in Oluodo et al. [177] spanning from 150 to 2000 kg/(ha*y).

With regard to the SimaPro modelling, the process *"Hevea seeds, at plantation"* has been created.

5.1.1.14 *Eucalyptus* ssp. wood

The assumptions performed are:

i. rubber wood output as calculated in this study (Sections 5.1.1.12, 3.6.2);
ii. timber use from Eucalyptus species represents the 48.2 % of Thailand total wood use [66], being the most important feedstock for the wood industry; thus, it is considered that *Eucalyptus* ssp. biomass, from local Thai production, is offset by *Hevea b.* biomass.

The Ecoinvent process "*Sawlog and veneer log, eucalyptus ssp., measured as solid wood under bark {TH}| hardwood forestry, eucalyptus ssp., sustainable forest management | Cut-off, S"* refers to (iii) the volume of wood with the exception of the bark, which accounts for the 10% of the total volume, and to (iv) a density of 825 kg/m^3 at zero moisture content (no further details on the density reported); to (v) temporal, geospatial system boundaries and included activities coherent with the ones considered here for the *Hevea b.* plantation model (i.e., are comparable systems).

This process has been employed for the model in SimaPro. To overcome the lack of further information on the volume regarding the density specified in (iv) (e.g., green volume, oven-dry volume, etc.) (not found also in other searches), the oven-dry volume (i.e., volume at zero moisture content) is here assumed for both *Eucalyptus* and *Hevea* wood (thus oven-dry density). A further assumption is thus needed: (vi) oven-dry density (mass and volume, oven-dry conditions) of *Hevea* wood equal to 700 kg/m^3.

Therefore, it is possible to obtain:

Volume V = 7978.94/700 = 11.4 m^3 of *Hevea* wood, and then 11.4 m^3 – volume of bark = 11.4 m^3 – (0.01*11.4) m^3 = 10.26 m^3 without bark, which replace an equal volume of *Eucalyptus* wood.

Thus, referring to density values reported in Section 3.3.3.3, assumption (vi) seems reasonable, since it is evident that density values based on oven-dry volume are greater than the values obtained with green volume. In addition, the density values at 12 % moisture content (MC) reported above, endorse the aforesaid assumption, being the mass at 12 % MC higher than the oven-dry mass and the volume at 12 % MC higher than the oven-dry volume.

5.1.1.15 Emissions from the application of fertilisers

With regard to the SimaPro modelling, the processes *"Use of nitrogen fertiliser"* and *"Use of phosphorus fertiliser"* have been created, on the basis of the Section 3.6.1.1 (calculation in Appendix A.5.1 and A.5.2). These processes refer to emissions resulting from the application of one kg of the N and one of the P fertilisers, respectively, annualised over the plantation cycle.

5.1.1.16 Emissions from the burning of residues due to replanting

With regard to the SimaPro modelling, the process *"Burning of residues due to replanting"* has been created. The emissions reported are discussed in Section 3.6.2 (calculated in Appendix A.5.3) and are here annualised over the plantation cycle.

5.1.1.17 LUC impacts

With regard to the SimaPro modelling, the processes "*LUC_Transformation impacts*" and "*LUC_Occupation impacts*" have been created. The impacts employed are discussed in Sections 3.5.3.6 and 3.5.3.7 (calculated in Appendix A.3 – A.4) and are annualised over the plantation cycle.

5.1.1.18 Natural rubber plantation dataset

Table 5.2 exhibits the natural rubber plantation dataset used in the inventory analysis, with specific reference to one hectare of plantation and to one year of the plantation cycle.

Flow category	**Inflows/Outflows**	**Quantity [unit/(ha*y)]**	**Unit**	**SimaPro process**
Fuel use	Power sawing	8.45E+03	s	Power sawing, with catalytic converter {GLO}| market for | Cut-off, S
	Diesel used in tillage	2.97E+01	MJ	Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery | Cut-off, S
	Diesel used by truck during thinning	1.29E+02	MJ	Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery | Cut-off, S
Planting trees	Planting operation	1.76E+01	tree	Planting tree {GLO}| market for planting tree | Cut-off, S
Land use	Land occupation	9.08E-01	m^2*y	Occupation, permanent crop, TH
	Land transformation	3.63E-02	m^2	Transformation, from agriculture + forest; Transformation, to permanent crop, TH
Fertilisation	N fertiliser	7.00E+01	kg	Inorganic nitrogen fertiliser, as N {TH}| market for inorganic nitrogen fertiliser, as N | Cut-off, S
	P fertiliser	3.50E+01	kg	Inorganic phosphorus fertiliser, as P2O5 {TH}| market for inorganic phosphorus fertiliser, as P2O5 | Cut-off, S
	K fertiliser	7.00E+01	kg	Inorganic potassium fertiliser, as K2O {TH}| market for inorganic potassium fertiliser, as K2O | Cut-off, S
Herbicide	Glyphosate	9.00E+00	kg	Glyphosate {GLO}| market for | Cut-off, S
Water use	Water for herbicide solution	8.91E-01	m^3	Water, unspecified natural origin/m3, TH
Products	Field latex, at plantation	2.79E+03	kg	-
	Field coagula, at plantation	2.43E+02	kg	-
	Hevea wood, at	7.98E+03	kg	-

	plantation			
	Hevea seed, at plantation	1.14E+03	kg	-
Avoided products	*Eucalyptus* ssp. wood	1.03E+01	m^3	Sawlog and veneer log, eucalyptus ssp., measured as solid wood under bark {TH}| hardwood forestry, eucalyptus ssp., sustainable forest management | Cut-off, S
Field emissions	Use of fertilisers	7.00E+01	kg	Use of nitrogen fertiliser
		3.50E+01	kg	Use of phosphorus fertiliser
	Burning of residues due to replanting	1.00E+00	ha	Burning of residues due to replanting
	direct Land Use Change	1.00E+00	ha*y	LUC_Transformation impacts
		1.00E+00	ha*y	LUC_Occupation impacts

Table 5.2: NR plantation LCI dataset modelled at plantation exit, over plantation cycle, not allocated.

5.1.2 Field latex entering mill

5.1.2.1 Ammonia

The assumption performed is: consumption of ammonia is equal to the 0.3 % of the latex wet mass, from Birnbach et al. [97].

Therefore, it is possible to obtain:

1*0.003= 0.003 kg ammonia per kg latex.

As anti-coagulant, in alternative, sodium sulphite can be used in 1.2 g per kg dry rubber content (DRC). This means, considering 35% DRC of fresh latex, that 1 kg DRC implies 2.857 kg latex, so as to have 1.2 g sodium sulphite per 2.857 kg fresh latex. Finally, this leads to 0.42 g sodium sulphite per kg fresh latex. However, with this anti-coagulant the attained quality of the rubber is lower, thus, for preservation, ammonia is selected in this study.

With regard to the SimaPro modelling, the process *"Ammonia, anhydrous, liquid {UN-SEASIA}| market for ammonia, anhydrous, liquid | Cut-off, S"* has been employed, which does not require any further conversion.

5.1.2.2 Field latex transport

The assumptions performed are:

i. fresh latex is moved from plantation to primary processing factory;
ii. 30 km one way trip with vehicle of 2.5 tons capacity, following Jawjit et al. [46].

Therefore, it is possible to obtain: 30.003 kg*km.

With regard to the SimaPro modelling, the process *"Transport, freight, lorry 3.5-7.5 metric ton, euro3 {RoW}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, S"* has been employed, which requires only the mass-distance unit of measure.

5.1.2.3 Field latex entering mill dataset

Table 5.3 shows the *"Field latex, entering mill"* process modelled in SimaPro and used in the inventory analysis.

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process
Raw materials	Field latex, at plantation	1.00E+00	kg	Field latex, at plantation
	Ammonia	3.00E-03	kg	Ammonia, anhydrous, liquid {UN-SEASIA}| market for ammonia, anhydrous, liquid | Cut-off, S
Transport	Latex transportation	1.003*30	kg*km	Transport, freight, lorry 3.5-7.5 metric ton, euro3 {RoW}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, S
Products	Field latex, entering mill	1.003	kg	-

Table 5.3: *"Field latex, entering mill"* dataset.

5.1.3 Field coagula entering mill

Regarding the field coagula entering the mill, the same transport assumption of field latex has been selected (Section 5.1.2.2).

5.1.3.1 Field coagula entering mill dataset

Table 5.4 shows the *"Field coagula, entering mill"* process modelled in SimaPro and used in the inventory analysis.

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process
Raw materials	Field coagula, at plantation	1.00E+00	kg	Field coagula, at plantation
Transport	Coagula transportation	3.00E+01	kg*km	Transport, freight, lorry 3.5-7.5 metric ton, euro3 {RoW}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, S
Products	Field coagula, entering mill	1.00E+00	kg	-

Table 5.4: *"Field coagula, entering mill"* dataset.

5.1.4 Unsmoked Sheets

5.1.4.1 Fresh latex

The assumption performed is:

i. the mass ratio proper of RSS (i.e., 3.3 : 1) is here considered, thus 3.3 ton of fresh latex for 1 ton of USS, as reported in Section 3.4.2.

Therefore, it is possible to obtain: 3.3 kg of fresh latex per kg of USS produced.

5.1.4.2 Water use for dilution

The assumption performed is:

i. water is added to latex with a volume ratio of 2 L water for 3 L of latex, according to the Rubber Research Institute of Thailand (RRIT) [116].

Therefore, it is possible to obtain:

2/3 litres of water for 1 litre of latex, thus, for 3.3 L of latex, a volume of 2.2 L of water is used, equivalent to 0.0022 cubic metres.

With regard to the SimaPro modelling, the process *"Water, unspecified natural origin/m^3, TH"* has been employed.

5.1.4.3 Formic acid for coagulation

The assumption performed is:

i. a 300 mL of 2 % formic acid solution is used to coagulate the diluted latex, according to the Rubber Research Institute of Thailand (RRIT) [116].

Therefore, it is possible to obtain:

2 mL of solute are present in 100 mL solution, thus, a total of 2 mL *3 = 6 mL in 300 mL solution; therefore, this leads to obtain 6 mL formic acid and 294 mL of water.

With regard to the SimaPro modelling, the process *"Formic acid {RoW}| market for | Cut-off, S"* has been employed, which requires further conversion since it models formic acid as pure substance, in mass unit. Thus, an additional assumption is required:

ii. density of formic acid as 1.22 g/mL.

Considering assumption (ii), a mass equal to 6*1.22 = 7.32 g is obtained. Moreover, the amount of water for the formic acid solution is added to the water used for dilution (Section 5.1.4.2) in order to consider the whole water consumption (i.e., 2.2 L + 0.294 L).

5.1.4.4 Unsmoked sheet (USS)

The quantity of 1 kg is obtained, as output.

With regard to the SimaPro modelling, the process *"Unsmoked sheet (USS)"* has been created.

5.1.4.5 USS dataset

Table 5.5 shows the unsmoked sheet dataset used in the inventory analysis, with reference to 1 kg of product.

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process
Raw materials	Field latex, entering mill	3.30E+00	kg	Field latex, entering mill
	Formic acid for coagulation	7.32E-03	kg	Formic acid {RoW}| market for | Cut-off, S
Water use	Water for dilution	2.20E-03	m^3	Water, unspecified natural origin/m3, TH
	Water for formic acid solution	2.94E-04	m^3	Water, unspecified natural origin/m3, TH

Products	Unsmoked sheet (USS)	1.00E+00	kg	-

Table 5.5: dataset used to model the production of unsmoked sheets.

5.1.5 Technically specified rubber

Technically Specified natural Rubber (TSR), employed in tyres applications (see Section 3.4.3) is modelled as Standard Thai Rubber grade twenty (STR 20).

5.1.5.1 Water used

The assumption performed is:

i. 23 m^3 of water per ton of STR20 are used, as reported by the Block rubber Industrial Sector Committee [115].

Therefore, it is possible to obtain: 0.023 m^3 per kg of STR 20 produced (or 23 L H_2O per kg STR).

With regard to the SimaPro modelling, the process *“Water, unspecified natural origin/m3, TH”* has been employed, which does not require any further conversion.

5.1.5.2 Unsmoked sheets

The assumption performed is:

i. 0.367 ton of USS are needed for producing a tonne of STR 20, from [96].

Therefore, it is possible to obtain: 0.367 kg USS per kg STR 20 produced.

5.1.5.3 Field coagula entering mill

The assumption performed is:

i. 1.18 tons are needed per 1 ton of STR 20, according to [96].

Therefore, it is possible to obtain: 1.18 kg field coagulum per kg STR 20 produced.

5.1.5.4 Electricity used

The assumption performed is:

i. electricity consumption is equal to 220 kWh/ton STR as reported in [93] (originally obtained by questionnaires to Thai producers, technicians’ interviews, Thai mill visits); which is in line with the value of 200 kWh/ton STR 20 (median value between factories of the survey of 2001) reported by the Block rubber Industrial Sector Committee [115].

Therefore, it is possible to obtain: 0.22 kWh per kg of STR 20 produced.

With regard to the SimaPro modelling, the process *“Electricity, low voltage {TH}| market for | Cut-off, S”* has been employed, which does not require any further conversion.

5.1.5.5 Diesel used

The assumption performed is:

i. diesel use equivalent to 1000 MJ/ton STR, from [93] (originally obtained by questionnaires to Thai producers, technicians' interviews, Thai mill visits); which is in line with the consumption of 29 litres/ton STR 20 (median value between factories of the survey of 2001) reported by the Block rubber Industrial Sector Committee [115].

Therefore, it is possible to obtain: 1 MJ per kg of STR 20 produced.

With regard to the SimaPro modelling, the process *"Diesel, burned in diesel-electric generating set, 18.5kW {GLO}| market for | Cut-off, S"* has been employed, which does not require any further conversion.

5.1.5.6 Liquefied Petroleum Gas (LPG) used

The assumption performed is:

i. LPG use equivalent to 1252 MJ/ton STR, from [93] (originally obtained by questionnaires to Thai producers, technicians' interviews, Thai mill visits).

Therefore, it is possible to obtain: 1.252 MJ per kg of STR 20 produced.

In the process *'Liquefied petroleum gas, combusted in industrial boiler/US'* a quantity measured in litres is required, thus considering that (ii) LPG used in rubber industry has an heating value near 50 MJ/kg, according to a report of the Thai Ministry of Energy [178], and that (iii) its density at 15 °C and 1 atm is equal to 1.9 kg/m^3, it is possible to attain the volume of 13.1789 litres of LPG to be used. However, because this activity is not from the Ecoinvent database (belongs to US LCI database), its use has been avoided, instead the following input activity taken from the Ecoinvent database *"Propane, burned in building machine {GLO}| market for | Cut-off, S"*, has been preferred and used in order to ensure coherency and consistency (so having 1.252 MJ from propane, burned).

5.1.5.7 Technically Specified Rubber (STR 20)

The quantity of 1 kg is obtained, as main product.

With regard to the SimaPro modelling, the process *"Technically specified rubber (TSR), at mill"* has been created.

5.1.5.8 Scrap rubber

The quantity of scrap rubber (i.e., the co-product) equal to 0.024 kg, per unit kg of STR produced, is obtained [96].

With regard to the SimaPro modelling, the process *"Scrap rubber, at mill"* has been created.

5.1.5.9 Wastewater

The quantity of 0.023 m^3 of wastewater is assumed to be discharged, per kg of STR 20 produced.

This Thai-specific value is in line with the only other reference found in literature on wastewater discharged in the rubber industry. This quantity ranges between 25 – 35 m^3 per ton of block rubber manufactured in Vietnamese mills [179].

With regard to the SimaPro modelling, the process *"Wastewater, average {RoW}| treatment of wastewater, average, wastewater treatment | Cut-off, S"* has been employed, which does not require any further conversion.

5.1.5.10 Technically Specified Rubber (TSR) dataset

Table 5.6 shows the dataset employed in the inventory analysis regarding the technically specified rubber at mill, with reference to 1 kg of this main product.

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process
Raw materials	Unsmoked sheet (USS)	3.67E-01	kg	Unsmoked sheet (USS)
	Field coagula, entering mill	1.18E+00	kg	Field coagula, entering mill
Water use	Water	2.30E-02	m^3	Water, unspecified natural origin/m3, TH
Electricity use	Electricity	2.20E-01	kWh	Electricity, low voltage {TH}| market for | Cut-off, S
Fuel use	Diesel	1.00E+00	MJ	Diesel, burned in diesel-electric generating set, 18.5kW {GLO}| market for | Cut-off, S
	LPG	1.25E+00	MJ	Propane, burned in building machine {GLO}| market for | Cut-off, S
Products	Technically Specified Rubber (TSR), at mill	1.00E+00	kg	-
	Scrap rubber, at mill	2.40E-02	kg	-
Wastewater	Wastewater	2.30E-02	m^3	Wastewater, average {RoW}| treatment of wastewater, average, wastewater treatment | Cut-off, S

Table 5.6: dataset used for modelling the production of 1 kg of technically specified rubber (TSR).

5.2 LCI of new tyre

This inventory refers to a virgin 385/65R22.5 truck tyre of mass 79.94 kg, and it is built upon: (i) the raw material configuration mass ratios sourced from the Tyre $LCCO_2$ Calculation Guidelines v3.0 published by JATMA in 2021 [166]; (ii) assumptions made in this work for the organic rubber chemicals, based on literature research and available company data, since the lack of precise information on the amounts of the chemicals used in the virgin tyre industry; (iii) the energy consumption of the manufacturing process derived from De Bortoli (2018) [180]. Regarding (i), conversion from mass ratios in PHR (i.e., per hundred rubber) to mass ratios in kg was performed. The contents of zinc oxide (i.e., vulcanisation activator) and sulphur (i.e., main vulcanising agent) were derived from (i); however, further research was necessary to grasps the other chemicals employed and their amounts. With reference to Section 4.2.3 of the Goal and Scope Definition Chapter, the chemicals used in the manufacturing are here assumed to be: stearic acid (i.e., activator, part of the curing system); 6PPD (i.e., the most used antiozonant, part of the protective system); TMQ (i.e., the most used antioxidant, part of the protective system); TBBS (i.e., one of the two most used accelerators, component of the curing system); phenolic resin (i.e., one of the most employed tackifiers); chlorinated paraffins (as the first constituent of the flame retardant system); zinc borate hydrate (as the second constituent of the flame retardant system). These chemicals were thus roughly modelled using the software (catalysts and byproducts generally neglected). The flame retardant system is generally composed of chlorinated paraffins (halogenated retardant) with the addition of another constituent. This last can be antimony oxide (not present in the Ecoinvent database, and not of feasible modelling), zinc hydroxy stannate [181] (not of feasible modelling since the absence, in the Ecoinvent database, of its raw materials: zinc chloride and tin tetrachloride), and zinc borate hydrate (of easily modelling). These are the rationales for the selection of zinc borate hydrate as the second component of the flame retardant system.

In the following, the inventory is presented according to Product Category Rule for Tires (UL 10006).

5.2.1 Inventory of module A1

In the Table 5.7 the dataset used in the inventory analysis of module A1 is presented, with specific reference to one new tyre to manufacture.

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
Elastomeric compound	Natural rubber	2.96E+01	kg	Technically specified rubber (TSR), at mill; see Table 5.6	Process not present in Ecoinvent, modelled in this study
	Synthetic rubber	7.98E+00		Synthetic rubber {RER}| synthetic rubber production | Cut-off, S	
	Carbon black	1.78E+01		Carbon black {GLO}| carbon black production | Cut-off, S	
	Silica	1.05E+00		Sodium silicate, spray powder, 80% {RER}| sodium silicate production, spray powder, 80% | Cut-off, S	
	Process oil	6.80E-01		Lubricating oil {RER}| lubricating oil production | Cut-off, S	
	Zinc oxide	1.66E+00		Zinc oxide {RER}| zinc oxide production | Cut-off, S	
	Stearic acid	8.30E-01		Stearic acid {GLO}| stearic acid production | Cut-off, S	
	Sulphur	1.02E+00		Sulfur {Europe without Switzerland}| sulfur production, petroleum refinery operation | Cut-off, S	
	6PPD	7.50E-01		6PPD; see Table 5.9	Process not present in Ecoinvent, modelled in this study

	TMQ	7.50E-01		TMQ; see Table 5.11	Process not present in Ecoinvent, modelled in this study
	TBBS	3.80E-01		TBBS; see Table 5.12	Process not present in Ecoinvent, modelled in this study
	Phenolic resin	2.10E-01		Phenolic resin {RER}| phenolic resin production | Cut-off, S	
	Chlorinated paraffins	1.00E-01		Chlorinated paraffins; see Table 5.14	Process not present in Ecoinvent, modelled in this study
	Zinc borate hydrate	1.00E-01		Zinc borate hydrate; see Table 5.15	Process not present in Ecoinvent, modelled in this study
Wires	Steel cord	1.19E+01	kg	Steel cord; see Table 5.8	Process not present in Ecoinvent, modelled in this study
	Bead wire	5.00E+00		Steel cord; see Table 5.8	Process not present in Ecoinvent, modelled in this study
	Synthetic textile fabrics	1.50E-01		Textile, nonwoven polyester {RoW}| textile production, nonwoven polyester, needle-punched | Cut-off, S	Assuming only polyester textile fabric; the process here chosen is used as proxy

Table 5.7: information module A1 dataset for one new tyre.

In Table 5.8 the dataset used for modelling 1 kg of steel cord, and employed also for the bead wire, is shown.

Flow category	**Inflows/Outflows**	**Quantity**	**Unit**	**SimaPro process**	**Observation**
Steel cord	Steel (cast)	1	kg	Steel, unalloyed {RER}| steel production, converter, unalloyed | Cut-off, S	
	Hot rolling	1	kg	Hot rolling, steel {Europe without Austria}| hot rolling, steel | Cut-off, S	
	Wire drawing	1	kg	Wire drawing, steel {GLO}| market for wire drawing, steel | Cut-off, S	

Table 5.8: dataset for modelling 1 kg of steel cord, used also for the bead wire.

In Table 5.9 the dataset used for modelling the production of 1 kg of 6PPD is reported. 6PPD (i.e., N-1,3-dimethylbutyl-N'-phenyl-*p*-phenylenediamine) is obtained from 4-ADPA (i.e., 4-aminodiphenylamine) and MIBK (i.e., methyl isobutyl ketone or also called 4-Methyl-2-pentanone) [18, 182]. Since the paucity of information about the stoichiometry of the reaction, in this case a 1 to 1 reaction is assumed. Furthermore, catalysts are neglected.

Flow category	**Inflows/Outflows**	**Quantity**	**Unit**	**SimaPro process**	**Observation**
6PPD	4-ADPA	6.86E-01	kg	4-ADPA; see Table 5.10	Process not present in Ecoinvent, modelled in this study
	4-methyl-2-pentanone	3.73E-01	kg	4-methyl-2-pentanone {RoW}| 4-methyl-2-pentanone production | Cut-off, S	Perfect match

Table 5.9: dataset of 6PPD used.

In Table 5.10 the dataset used for modelling the production of 1 kg of 4-ADPA is presented. The 4-ADPA (1 mol) is synthesised from aniline (4 mol) and *p*-chloronitrobenzene (1 mol), and this dataset is based on the production route (method 1) stated in [183]. Thus, raw materials and yield are taken from that cited study. Catalysts are neglected. The isomer (*o*-chloronitrobenzene or 1-chloro-2-nitrobenzene) has been used as a proxy for *p*-chloronitrobenzene, chosen as the most suitable match available.

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
4-ADPA	Aniline	1.08E+00	kg	Aniline {RoW}| aniline production | Cut-off, S	Perfect match
	p-chloronitrobenzene	4.57E-01	kg	Chloronitrobenzene {RoW}| chloronitrobenzene production | Cut-off, S	1-Chloro-2-nitrobenzene, that is an isomer of the 4-nitrochlorobenzene

Table 5.10: dataset of 4-ADPA used.

In Table 5.11 the dataset used for modelling the production of 1 kg of TMQ is listed. TMQ, i.e., 2,2,4-Trimethyl-1,2-dihydroquinoline, is synthesised by one mol aniline and two mols of acetone [18].

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
TMQ	Aniline	5.38E-01	kg	Aniline {RoW}| aniline production | Cut-off, S	Perfect match
	Acetone	6.70E-01	kg	Acetone, liquid {RoW}| acetone production, from isopropanol | Cut-off, S	Perfect match

Table 5.11: dataset of TMQ used.

In Table 5.12 the dataset used for modelling the production of 1 kg of TBBS is shown. TBBS, i.e., N-*t*-butyl-2-benzothiazole sulfenamide, is obtained (2 mol) reacting t-butylamine (2 mol) with benzothiazyl disulfide (i.e., MBTS; 1 mol), which is obtained from MBT (1 mol), sodium hydroxide (1 mol), and sodium hypochlorite (1 mol) [18].

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
TBBS	Mercaptobenzothiazole	3.51E-01	kg	Mercaptobenzothiazole (MBT); see Table 5.13	Process not present in Ecoinvent, modelled in this study
	Sodium hydroxide	8.39E-02	kg	Sodium hydroxide, without water, in 50% solution state {GLO}| market for sodium hydroxide, without water, in 50% solution state | Cut-off, S	
	Sodium hypochlorite	1.56E-01	kg	Sodium hypochlorite, without water, in 15% solution state {RER}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, S	
	Tert-butyl amine	3.07E-01	kg	Tert-butyl amine {GLO}| market for tert-butyl amine | Cut-off, S	

Table 5.12: dataset of TBBS used.

In Table 5.13 the dataset used for modelling the production of 1 kg of mercaptobenzothiazole (MBT) is shown. One mol of MBT is produced from the reaction of aniline (1 mol), carbon disulfide (1 mol), and sulphur (1 mol) [18].

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
Mercaptobenzothiazole (MBT)	Aniline	5.57E-01	kg	Aniline {RER}| market for aniline | Cut-off, S	
	Carbon disulfide	4.55E-01	kg	Carbon disulfide {GLO}| market for carbon disulfide | Cut-off, S	
	Sulphur	1.92E-01	kg	Sulfur {GLO}| market for sulfur | Cut-off, S	

Table 5.13: dataset of MBT used.

In Table 5.14 the dataset used for modelling the production of 1 kg of chlorinated paraffins (CP) is presented. Chlorinated paraffins with almost 70 % chlorine, and chain length C10 – 13, were preferred by the rubber industry (to be used as flame retardants), however, in the last decades it has been shown that these small chains are toxic [184, 185]. Therefore, this dataset considers single chain C18 chlorinated paraffins, as synthesised according to [185, 186]. Due to the absence, in the Ecoinvent database, of the reagent n-octadecane, a generic paraffin (which refers to C20 – C30) has been used as a proxy.

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
Chlorinated paraffins	Paraffin	5.05E-01	kg	Paraffin {RER}| paraffin production | Cut-off, S	Proxy
	Dichloromethane	1.68E+00	kg	Dichloromethane {RER}| dichloromethane production | Cut-off, S	
	Sulfuryl chloride	5.27E+00	kg	Sulfuryl chloride {GLO}| sulfuryl chloride production | Cut-off, S	

Table 5.14: dataset of chlorinated paraffins used.

In Table 5.15 the dataset used for modelling the production of 1 kg of zinc borate hydrate is presented. The resolved oxide formula of the product is sourced from [187], the production route here followed as basis for the dataset is taken from [18]: zinc oxide (2 mol) reacts with boric acid (6 mol).

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
Zinc borate hydrate	Zinc oxide	3.83E-01	kg	Zinc oxide {RER}| zinc oxide production | Cut-off, S	
	Boric acid	8.73E-01	kg	Boric acid, anhydrous, powder {RER}| boric acid production, anhydrous, powder | Cut-off, S	

Table 5.15: model of zinc borate hydrate used.

5.2.2 Inventory of module A2

In Table 5.16 the dataset used in the inventory analysis of module A2 is listed, referring to 1 kg of transported material.

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
Transport of raw materials used for the elastomeric compound	Natural rubber	1.39E+04	kg*km	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	Refer to Section 3.4.3.1 of this work
		1.83E+02		Transport, freight train {RER}| market group for transport, freight train | Cut-off, S	
		1.21E+02		Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, S	
	Synthetic rubber	1.00E+03		Transport, freight train {Europe without Switzerland}| market for transport, freight train | Cut-off, S	Refer to Section 4.2.2.2
	Carbon black	7.54E+02		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Refer to Section 4.2.2.2
		2.19E+03		Transport, freight train {Europe without Switzerland}| market for transport, freight train | Cut-off, S	Refer to Section 4.2.2.2
	Silica	1.00E+03		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Refer to Section 4.2.2.2
	Process oil	1.58E+02		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Refer to Section 4.2.2.2
	Zinc oxide	1.75E+02		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Refer to Section 4.2.2.2
	Stearic acid	1.58E+02		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Refer to Section 4.2.2.2
	Sulphur	1.14E+03		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Refer to Section 4.2.2.2
	6PPD	8.67E+03		Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	Refer to Section 4.2.2.2
		3.25E+02		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Refer to Section 4.2.2.2
	TMQ	8.67E+03		Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	Refer to Section 4.2.2.2
		3.25E+02		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Refer to Section 4.2.2.2
	TBBS	6.41E+02		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Refer to Section 4.2.2.2
	Phenolic resin	6.73E+02		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Assuming same sourcing as for the retardant used for retreading
	Chlorinated paraffins	1.00E+03		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Refer to Section 4.2.2.2; distance that is similar to the one of the paraffinic oil used for the retreading compound
	Zinc borate hydrate	1.00E+03		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Refer to Section 4.2.2.2
Transport of wires	Steel cord	1.00E+03	kg*km	Transport, freight train {RER}| market group for transport, freight train | Cut-off, S	Refer to Section 4.2.2.2
	Bead wire	1.00E+03		Transport, freight train {RER}| market group for transport, freight train | Cut-off, S	Refer to Section 4.2.2.2
	Synthetic textile fabrics	8.67E+03		Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	Refer to Section 4.2.2.2

		3.25E+02		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Assuming distance covered by lorry

Table 5.16: information module A2 dataset for new tyre; refers to 1 kg of transported material.

5.2.3 Inventory of module A3

In Table 5.17 the datasets employed in the inventory analysis of module A3 are exhibited. The inputs refer to one tyre manufactured (of mass 79.94 kg).

Flow category	**Inflows/Outflows**	**Quantity**	**Unit**	**SimaPro process**	**Observation**
Production of the virgin tyre	Electricity	2.54E+02	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	
	Steam	5.07E+01	kg	Steam, in chemical industry {RER}| market for steam, in chemical industry | Cut-off, S	
	Heat	2.55E+02	MJ	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW | Cut-off, S	
	Water	1.88E+02	kg	Water, process, unspecified natural origin/kg	
EOL of manufacturing scrap	Treatment mix	1.07E+00	kg	Municipal solid waste {IT}| market for municipal solid waste | Cut-off, U	Modified adding a 50 km transport

Table 5.17: information module A3 dataset for new tyre.

It should be noted that the Ecoinvent process chosen for the disposal pathways of the manufacturing scrap represents a 'market' activity. Therefore, it was modified replacing its transports with the correct (from this study's perspective) transport of 50 km. Then, considering the treatments declared in Section 4.2.3, the scrap quantity of 1.07 kg goes to landfill (0.588 kg), incineration (0.47 kg), and open burning (0.007 kg).

5.2.4 Inventory of module B1

In Table 5.18 the dataset used in the inventory analysis of the module B1 is displayed, with reference to one service life (160,000 km).

Flow category	**Inflows/Outflows**	**Quantity**	**Unit**	**SimaPro process**	**Observation**
Use phase	Wear	WWE+00	kg	Tyre wear emissions, lorry {RER}| treatment of tyre wear emissions, lorry | Cut-off, S	Mass loss

Table 5.18: information module B1 dataset for new tyre.

5.2.5 Inventory of modules C2 – C3

The Table 5.19 represents the dataset concerning the ELT modules C2 and C3, with specific reference to the end of life of one new tyre, after its service life.

Flow category	**Inflows/Outflows**	**Quantity**	**Unit**	**SimaPro process**	**Observation**
End-of-life	Rubber granulation and	2.74E+01	kg	Granulation (recycling); see Table 5.20	Process not present in Ecoinvent, modelled

	recycling				in this study
	Tyres incineration	2.08E+01		Waste rubber, unspecified {Europe without Switzerland}| treatment of waste rubber, unspecified, municipal incineration | Cut-off, S	Modified adding a 50 km transport; rubber incinerated
	Tyres landfilling	2.25E+00		Municipal solid waste {CH}| treatment of, sanitary landfill | Cut-off, S	Proxy for the RER process (not found); modified adding a 50 km transport
	Tyres backfilling	1.83E+00		Hazardous waste, for underground deposit {DE}| treatment of hazardous waste, underground deposit | Cut-off, S	Proxy for the RER process (not found); modified adding a 50 km transport
	Steel recycling	1.52E+01		Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, S	Modified adding a 50 km transport
	Steel landfilling	1.68E+00		Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Cut-off, S	Modified adding a 50 km transport
	Textile incineration	1.50E-01		Waste textile, soiled {CH}| treatment of waste textile, soiled, municipal incineration | Cut-off, S	Modified adding a 50 km transport

Table 5.19: information modules C2 and C3 dataset for the end of life of new tyre.

In Table 5.20 the dataset used to model the rubber granulation and recycling is shown, with reference to 1 kg of rubber. The PPP is employed, thus only the electricity required for the process is considered, as sourced from [166].

Flow category	**Inflows/Outflows**	**Quantity**	**Unit**	**SimaPro process**	**Observation**
Granulation (recycling)	Electricity	6.60E-01	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	PPP is here considered
	Transport	5.00E+01	kg*km	Municipal waste collection service by 21 metric ton lorry {CH}| municipal waste collection service by 21 metric ton lorry | Cut-off, S	Proxy for the RER process (not found); adding a 50 km transport

Table 5.20: dataset for modelling granulation and recycling of rubber.

5.3 LCI of retreaded tyre

This inventory refers to a retreaded 385/65R22.5 truck tyre of mass 79.94 kg, and it is built upon primary data collected by Metalepsi Proteron (Ofir, Europe) concerning (i) the raw materials used for the retreading process (including the specific rubber chemicals employed), (ii) the related packaging and transport, and (iii) the energy consumption of the production processes. Moreover, (iv) assumptions on the end-of-life were needed and made (see Section 4.2.3).

In the following, the inventory is presented according to Product Category Rule for Tires (UL 10006).

5.3.1 Inventory of module A1

In Table 5.21 the datasets employed in the inventory analysis of module A1 are exhibited, with reference to one tyre retreaded.

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
Carcass	Carcass	1	piece	1 new tyre after use phase	Mass of YYYY kg (79.94 - ZZZZ)
Ring compound	Natural rubber (TSR)	XXE+00	kg	Technically specified rubber (TSR), at mill; see Table 5.6	Process not present in Ecoinvent, modelled in this study
	NR regenerated	XXE-00		-	Waste natural rubber that is purchased - no input
	Carbon black	XXE+00		Carbon black {GLO}| carbon black production | Cut-off, S	
	Paraffinic plasticiser oil	XXE-00		Paraffin {RER}| paraffin production | Cut-off, S	
	Zinc oxide	XXE+00		Zinc oxide {RER}| zinc oxide production | Cut-off, S	
	Stearic acid	XXE+00		Stearic acid {GLO}| stearic acid production | Cut-off, S	
	6PPD	XXE+00		6PPD; see Table 5.9	Process not present in Ecoinvent, modelled in this study
	TMQ	XXE+00		TMQ; see Table 5.11	Process not present in Ecoinvent, modelled in this study
	Sulphur	XXE+00		Sulfur {Europe without Switzerland}| sulfur production, petroleum refinery operation | Cut-off, S	
	CBS	XXE+00		CBS; see Table 5.22	Process not present in Ecoinvent, modelled in this study
	CTP	XXE+00		Chemical, organic {GLO}| chemical production, organic | Cut-off, S	Chemical organic used as a proxy
	Organozinc	XXE+00		Zinc {GLO}| market for zinc | Cut-off, S	Modified to consider correct transport
	DBD	XXE+00		Chemical, organic {GLO}| chemical production, organic | Cut-off, S	Chemical organic used as a proxy
	Ubuntu	XXE+00		-	Rubber particles from carcass buffing that are reused after treatment in Ariston - no input
Solution compound	Natural rubber (TSR)	XXE+00	kg	Technically specified rubber (TSR), at mill; see Table 5.6	Process not present in Ecoinvent, modelled in this study
	Aromatic hydrocarbon resin	XXE+00		Chemical, organic {GLO}| chemical production, organic | Cut-off, S	Chemical organic used as a proxy
	Naphtha - Hydrocarbons, C6-C7	XXE+00		Naphtha {Europe without Switzerland}| naphtha production, petroleum refinery operation | Cut-off, S	Proxy
	Paraffinic plasticiser oil	XXE+00		Paraffin {RER}| paraffin production | Cut-off, S	
	Carbon black	XXE+00		Carbon black {GLO}| carbon black production | Cut-off, S	
	Process oil	XXE+00		Lubricating oil {RER}| lubricating oil production | Cut-off, S	
Cushioning compound	Natural rubber (TSR)	XXE+00	kg	Technically specified rubber (TSR), at mill; see Table 5.6	Process not present in Ecoinvent, modelled in this study
	SBR	XXE+00		Synthetic rubber {RER}| synthetic rubber production | Cut-off, S	Proxy
	AAAA copolymer	XXE+00		Acetylene {RER}| acetylene production | Cut-off, S	Proxy
	SSS	XXE+00		Bitumen seal {RER}| bitumen seal production | Cut-off, S	Proxy
	Naphtha	XXE+00		Naphtha {Europe without Switzerland}| naphtha production, petroleum refinery operation | Cut-off, S	
	Carbon black	XXE+00		Carbon black {GLO}| carbon black	

				production | Cut-off, S	
	Insoluble sulphur	XXE+00		Sulfur {IN}| sulfur production, petroleum refinery operation | Cut-off, S	
	Zinc oxide	XXE+00		Zinc oxide {RER}| zinc oxide production | Cut-off, S	
	Stearic acid	XXE+00		Stearic acid {GLO}| stearic acid production | Cut-off, S	
	MBTS	XXE+00		MBTS; see Table 5.24	Process not present in Ecoinvent, modelled in this study
	DPG	XXE+00		DPG; see Table 5.25	Process not present in Ecoinvent, modelled in this study
	DDTS	XXE+00		DDTS; see Table 5.26	Process not present in Ecoinvent, modelled in this study
	TMQ	XXE+00		TMQ; see Table 5.11	Process not present in Ecoinvent, modelled in this study
	6PPD	XXE+00		6PPD; see Table 5.9	Process not present in Ecoinvent, modelled in this study
Envelopes	External envelope	4.39E-02	kg	Envelope; see Table 5.27	Process not present in Ecoinvent, modelled in this study
	Internal envelope	4.44E-02		Envelope; see Table 5.27	Process not present in Ecoinvent, modelled in this study
Packaging for the transport of the ring and cushion compounds	Box	XXE+00	kg	Corrugated board box {RER}| market for corrugated board box | Cut-off, S	
	EUR pallet	XXE+00		EUR-flat pallet {RER}| EUR-flat pallet production | Cut-off, S	Considering both ring and cushion
	Label	XXE+00		Graphic paper, 100% recycled {GLO}| market for graphic paper, 100% recycled | Cut-off, S	Considering both ring and cushion packaging
	Packaging film (PE)	XXE+00		Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, S	Considering both ring and cushion packaging
	Cardboard	XXE+00		Particleboard, uncoated {RER}| particleboard production, uncoated, average glue mix | Cut-off, S	Elaborating primary data
	Adhesive tape	XXE+00		Solid bleached and unbleached board carton {RER}| solid bleached and unbleached board carton production | Cut-off, S	Considering both ring and cushion packaging
		XXE+00		Packaging film, low density polyethylene {RER}| packaging film production, low density polyethylene | Cut-off, S	Considering both ring and cushion packaging

Table 5.21: information module A1 datasets for retreaded tyre system.

In Table 5.22 the dataset used for modelling the production of 1 kg of CBS is presented. CBS, i.e., N-cyclohexyl-2-benzothiazole sulfenamide, is obtained (2 mol) reacting MBT (1 mol), sodium hydroxide (1 mol), sodium hypochlorite (1 mol), and cyclohexylamine (2 mol) [18].

Flow category	**Inflows/Outflows**	**Quantity**	**Unit**	**SimaPro process**	**Observation**
CBS	Mercaptobenzothiazole (MBT)	3.16E-01	kg	Mercaptobenzothiazole (MBT); see Table 5.13	Process not present in Ecoinvent, modelled in this study
	Sodium hydroxide	7.56E-02		Sodium hydroxide, without water, in 50% solution state {GLO}| market for sodium hydroxide, without water, in 50% solution	

				state | Cut-off, S	
	Sodium hypochlorite	1.41E-01		Sodium hypochlorite, without water, in 15% solution state {RoW}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, S	
	Cyclohexylamine	3.75E-01		Cyclohexylamine; see Table 5.24	Process not present in Ecoinvent, modelled in this study

Table 5.22: dataset of CBS used.

Table 5.23 shows the dataset employed for modelling the production of 1 kg of Cyclohexylamine, which is obtained (1 mol) from aniline (1 mol) and gaseous hydrogen (3 mol), through catalytic hydrogenation [18].

Flow category	**Inflows/Outflows**	**Quantity**	**Unit**	**SimaPro process**	**Observation**
Cyclohexylamine	Aniline	9.39E-01	kg	Aniline {RoW}| market for aniline | Cut-off, S	Perfect match
	Hydrogen	6.10E-02		Hydrogen, gaseous {GLO}| market for hydrogen, gaseous | Cut-off, S	Perfect match

Table 5.23: dataset of cyclohexylamine used.

In Table 5.24 the dataset used for modelling the production of 1 kg of MBTS is listed. MBTS, i.e., benzothiazyl disulfide (or benzothiazole disulfide), is synthesised from MBT (1 mol), sodium hydroxide (1 mol), and sodium hypochlorite (1 mol).

Flow category	**Inflows/Outflows**	**Quantity**	**Unit**	**SimaPro process**	**Observation**
MBTS	Mercaptobenzothiazole (MBT)	5.03E-01	kg	Mercaptobenzothiazole (MBT); see Table 5.13	Process not present in Ecoinvent, modelled in this study
	Sodium hydroxide	1.20E-01		Sodium hydroxide, without water, in 50% solution state {RoW}| chlor-alkali electrolysis, diaphragm cell | Cut-off, S	
	Sodium hypochlorite	2.24E-01		Sodium hypochlorite, without water, in 15% solution state {RoW}| sodium hypochlorite production, product in 15% solution state | Cut-off, S	

Table 5.24: dataset of MBTS used.

In Table 5.25, the dataset used for modelling the production of 1 kg of DPG is shown. DPG, i.e., Diphenyl guanidine, is synthesised (1 mol) by reacting aniline (2 mol) with cyanogen chloride (1 mol) [18].

Flow category	**Inflows/Outflows**	**Quantity**	**Unit**	**SimaPro process**	**Observation**
DPG	Aniline	8.82E-01	kg	Aniline {RoW}| aniline production | Cut-off, S	Perfect match
	Cyanogen chloride	2.91E-01		Cyanogen chloride {RoW}| cyanogen chloride production | Cut-off, S	

Table 5.25: dataset of DPG used.

In Table 5.26, the dataset employed for modelling the production of 1 kg of DDTS is presented. DDTS, i.e., N, N'-Dimethyl-N, N'-diphenylthiuram disulfide, is obtained from N-methyl aniline and carbon disulfide [188-190]. Since the lack of clarity about the stoichiometry of the reaction, in this case 2 mol of aniline are assumed to react with 2 mol of carbon disulfide, to give 1 mol of the product.

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
DDTS	N-methyl aniline	5.11E-01	kg	Aniline {RoW}| aniline production | Cut-off, S	Proxy
	Carbon disulfide	4.18E-01		Carbon disulfide {GLO}| carbon disulfide production, from natural gas | Cut-off, S	

Table 5.26: dataset of DDTS used.

In Table 5.27 the dataset used for modelling 1 kg of envelope is exhibited (primary data).

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
Envelope	Chlorobutyl rubber	WWE-00	kg	Polybutadiene {GLO}| market for polybutadiene | Cut-off, S	Proxy
	Carbon black	WWE-00		Carbon black {GLO}| carbon black production | Cut-off, S	
	Paraffinic oil	WWE-00		Paraffin {RER}| paraffin production | Cut-off, S	
	Chemicals	WWE-00		Chemical, organic {GLO}| market for chemical, organic | Cut-off, S	Proxy

Table 5.27: dataset of the envelopes used.

5.3.2 Inventory of module A2

In Table 5.28 the datasets used in the inventory analysis of module A2 are exhibited, specifically referring to 1 kg of transported material. For simplicity, only one instance of material transport is shown for substances, sourced from the same supplier (location/site) and thus with the same distances and means of transport, utilised in various processes. For this reason, the superscript '*' is employed for flow categories in the Table 5.28, denoting the fact that some raw materials of that particular flow category are also used (exactly the same material and equal distances/transport) as raw materials for another compound or product (in praxis for the ring compound or for the solution compound), and therefore, are not reported separately. For clarity and transparency, the materials not reported are: carbon black for the solution compound, because it is the same (i.e., same distances and transport means) as the one used for the ring compound; natural rubber (TSR) for the cushioning compound, since it is the same as the TSR for ring; carbon black for the cushioning compound, since it is same as the carbon black reported for the ring; zinc oxide for the cushioning compound, because it is same as the one used for the ring; stearic acid for the cushioning compound, as it is same of the one used for the ring; 6PPD and TMQ for the cushioning compound, since are the same as those used for the ring. Moreover, also the carbon black and the paraffinic oil both used as raw materials of the envelope are not reported since they are the same as those used for the solution compound.

Flow category	**Inflows/Outflows**	**Quantity**	**Unit**	**SimaPro process**	**Observation**
Carcass transport	Carcass	KKE+00	kg*km	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	From Ponto, to Ofir
Transport of raw materials for ring compound	Natural rubber (TSR)	KKE+00	kg*km	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	NR regenerated	KKE+00		Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	Carbon black	KKE+00		Transport, freight train {Europe without Switzerland}| market for transport, freight train | Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	Paraffinic plasticiser oil	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	Zinc oxide	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	Stearic acid	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	6PPD	KKE+00		Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	TMQ	KKE+00		Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	Sulphur	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	CBS	KKE+00		Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	CTP	KKE+00		Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	Organozinc	KKE+00		Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	

	DBD	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	Ubuntu	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Distance from Pomerania to Ofir (927 km) is doubled to consider the whole round trip (Section 4.2.2.1)
Transport of raw materials for solution compound*	Natural rubber (TSR)	KKE+00	kg*km	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	Aromatic hydrocarbon resin	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	Naphtha - Hydrocarbons, C6-C7, n-alkanes, isoalkanes, cyclics, <5% nhexane	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	Paraffinic plasticiser oil	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	Process oil	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
Transport of raw materials for cushioning compound*	SBR	KKE+00	kg*km	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	AAAA copolymer	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	SSS	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	Naphtha	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	Insoluble sulphur	KKE+00		Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	MBTS	KKE+00		Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	DPG	KKE+00		Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
	DDTS	KKE+00		Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship |	

				Cut-off, S	
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	
Transport for the packaging (to Bitinia site where it is used)	Box	KKE+00	kg*km	-	Already in Bitinia site, hence no transport is assumed. This input is then used for the packaging of the cushion, to be sent to Ofir
	EUR pallet	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	This input is then used for the packaging of the ring and also in that of the cushion, before the transport to Ofir
	Label	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	This input is then used for the packaging of the ring and also in that of the cushion, before the transport to Ofir
	Packaging film (PE)	KKE+00		-	Already in Bitinia site, hence no transport is assumed. This input is then used for the packaging of the ring, to be sent to Ofir
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	This input is then used for the packaging of the ring and also in that of the cushion, before the transport to Ofir
	Cardboard	KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	This input is then used for the packaging of the ring , before the transport to Ofir
	Adhesive tape	KKE+00		-	Already in Bitinia site, hence no transport is assumed. This input is then used for the packaging of the cushion, to be sent to Ofir
		KKE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	This input is then used for the packaging of the ring, before the transport to Ofir
Transport of raw materials for envelopes* (to Ofir)	-	-	kg*km	-	Chlorobutyl rubber and the rubber chemicals are already modelled as 'market', thus, transport is already accounted for; see Table 5.28

Table 5.28: information module A2 datasets for retreaded tyre system.

5.3.3 Inventory of module A3

In Tables 5.29 and 5.30, the datasets employed in the inventory analysis of module A3 are presented. The inputs refer to one retreaded tyre, therefore, the energy consumptions are reported with respect to: one ring tread; one cushioning strip; one instance of the retreading process (obtaining one retreaded tyre); the quantity of envelopes allocated for one instance of the retreading process (one envelope serves for 180 vulcanisation cycles); and the mass of pallet attributable to one retreading process.

Primary data from the Metalepsi Proteron company have been used, except for those referring to the Euro-pallet manufacturing, sourced from [191].

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
Production of the ring	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Mixing line 1
	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for	Mixing line 2

				electricity, low voltage | Cut-off, S	
	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Extrusion (extruder/trimming)
	Steam	BBE+00	kg	Steam, in chemical industry {RER}| market for steam, in chemical industry | Cut-off, S	Press
	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Buffing
Production of the cushion strip	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Mixing line 1
	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Mixing line 2
	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Extrusion (extruder)
Retreading	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Visual inspection-NDT
	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Shearography
	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Buffing
	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Building-Cushion
	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Building-Ring
	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Curing
	Steam	BBE+00	kg	Steam, in chemical industry {RER}| market for steam, in chemical industry | Cut-off, S	
	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Shearography
Production of the external envelope	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Considering alfa/eta [kg]
	Heat	BBE+00	kWh	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW | Cut-off, S	
Production of the internal envelope	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Considering beta/eta [kg]
	Heat	BBE+00	kWh	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW | Cut-off, S	
Production of the EUR pallet	Electricity	BBE+00	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	Assuming production in the place from which it is sourced. These inputs are needed since not included in the process EUR-pallet of Ecoinvent, which includes only the materials
	Heat	BBE+00	kWh	Heat, district or industrial, other than natural gas {IT}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, S	

Table 5.29: information module A3 datasets for retreaded tyre system (first part).

Flow category	**Inflows/Outflows**	**Quantity**	**Unit**	**SimaPro process**	**Observation**
Transport of the ring	Transport of ring compound to Bitinia	LLE+00	kg*km	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Production of the ring (tread) occurs in Bitinia
	Transport of ring to Ofir	LLE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Retreading process occurs in Ofir
Transport of the cushion	Transport of the cushioning compound to Bitinia	LLE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Production of the cushion occurs in Bitinia

	Transport of the cushion to Ofir	LLE+00		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	Retreading process occurs in Ofir
EOL of waste (cured) rubber from retreading process	Scrap rubber recycling	LLE+00	kg	Waste rubber recycling; see next "Observation"	Waste rubber already as granulate; PPP is applied; hence it is empty process modified adding a 50 km transport
	Scrap rubber incineration	LLE+00		Waste rubber, unspecified {Europe without Switzerland}| treatment of, unspecified, municipal incineration | Cut-off, S	Modified adding 50 km transport
	Scrap rubber landfilled	LLE+00		Municipal solid waste {CH}| treatment of municipal solid waste, sanitary landfill | Cut-off, S	Modified adding 50 km transport
	Scrap rubber backfilling	LLE+00		Hazardous waste, for underground deposit {DE}| treatment of hazardous waste, underground deposit | Cut-off, S	Modified adding 50 km transport
EOL of the used packaging	Paper	LLE+00	kg	Waste graphical paper {CH}| treatment of waste graphical paper, municipal incineration | Cut-off, S	Incinerated; modified adding 50 km transport
		LLE+00		Paper (waste treatment) {GLO}| recycling of paper | Cut-off, S	Recycled; modified adding 50 km transport
	PE packaging film	LLE+00		Waste polyethylene {CH}| treatment of waste polyethylene, sanitary landfill | Cut-off, S	Landfilled; modified adding 50 km transport
		LLE+00		Waste polyethylene {CH}| treatment of waste polyethylene, municipal incineration | Cut-off, S	Incinerated; modified adding 50 km transport
		LLE+00		PE (waste treatment) {GLO}| recycling of PE | Cut-off, S	Recycled; modified adding 50 km transport
	Cardboard	LLE+00		Waste paperboard {CH}| treatment of waste paperboard, municipal incineration | Cut-off, S	Incinerated; modified adding 50 km transport
		LLE+00		Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	Recycled; modified adding 50 km transport
	Wood (pallet)	LLE+00		Waste wood, untreated {GLO}| treatment of waste wood, untreated, unsanitary landfill, moist infiltration class (300mm) | Cut-off, S	Landfilled; modified adding 50 km transport
		LLE+00		Waste wood, untreated {CH}| heat production, untreated waste wood, at furnace 1000-5000 kW | Cut-off, S	Incinerated; modified adding 50 km transport
		LLE+00		Recycling wood pallet	Recycled; PPP is applied, hence it is **empty** process modified adding a 50 km transport
		LLE+00		Reuse wood pallet	Reused; is an **empty** process including only the avoided product 'EUR pallet' and its production

Table 5.30: information module A3 datasets for retreaded tyre system (second part).

5.3.4 Inventory of module B1

In Table 5.31 the dataset used in the inventory analysis of the module B1 is displayed, with reference to one additional service life (160,000 km).

Flow category	**Inflows/Outflows**	**Quantity**	**Unit**	**SimaPro process**	**Observation**

Use phase	Wear	WWE+00	kg	Tyre wear emissions, lorry {RER}| treatment of tyre wear emissions, lorry | Cut-off, S	Mass loss

Table 5.31: information module B1 dataset for retreaded tyre.

5.3.5 Inventory of modules C2 – C3

The Table 5.32 represents the dataset concerning the end of life modules C2 and C3, with specific reference to the retreading materials, after the additional service life provided.

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
End-of-life	Rubber granulation and recycling	3.56E+00	kg	Granulation (recycling); see Table 5.33	Process not present in Ecoinvent, modelled in this study
	Tyres incineration	2.70E+00		Waste rubber, unspecified {Europe without Switzerland}| treatment of waste rubber, unspecified, municipal incineration | Cut-off, S	Modified adding a 50 km transport
	Tyres landfilling	2.92E-01		Municipal solid waste {CH}| treatment of municipal solid waste, sanitary landfill | Cut-off, S	Proxy for the RER process (not found); modified adding a 50 km transport
	Tyres backfilling	2.38E-01		Hazardous waste, for underground deposit {DE}| treatment of hazardous waste, underground deposit | Cut-off, S	Proxy for the RER process (not found); Modified adding a 50 km transport

Table 5.32: information modules C2 and C3 dataset for retreaded tyre.

In the Table 5.33 the dataset used to model the rubber granulation and recycling is shown, with reference to 1 kg of rubber. The PPP is employed, thus, only the electricity required for the process is considered, as taken from [166].

Flow category	Inflows/Outflows	Quantity	Unit	SimaPro process	Observation
Granulation (recycling)	Electricity	6.60E-01	kWh	Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, S	PPP is here considered
	Transport	5.00E+01	kg*km	Municipal waste collection service by 21 metric ton lorry {CH}| municipal waste collection service by 21 metric ton lorry | Cut-off, S	Proxy for the RER process (not found); adding a 50 km transport

Table 5.33: dataset for modelling granulation and recycling of rubber.

Chapter 6
Life Cycle Impact Assessment and Interpretation

6.1 Impact categories, category indicators, and characterisation model

The impact categories, indicators, and methods onto which this assessment is based are listed in Table 6.1, chosen to thoroughly entail the significant environmental concerns pertaining to the analysed systems, and in accordance with the PCR of tyres [165].

Impact category	Impact indicator	Unit	Characterisation model	Source
Acidification, terrestrial and freshwater	Accumulated Exceedance (AE)	mol H^+ eq	Seppala et al. 2006, Posch et al. 2008	EF 3.1
Climate change	Global Warming Potential (GWP100 years)	kg CO_2 eq	Baseline model of IPCC 2021	EF 3.1
Ecotoxicity freshwater	Comparative Toxic Unit for ecosystems	CTUe	USEtox model	EF 3.1
Particulate matter	Disease incidence due to kg of PM2.5 emitted	Disease incidence	PM method	EF 3.1
Eutrophication, marine	Nitrogen equivalents	kg N eq	EUTREND model	EF 3.1
Eutrophication, freshwater	Phosphorus equivalents	kg P eq	EUTREND model	EF 3.1
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	Seppala et al. 2006, Posch et al. 2008	EF 3.1
Human toxicity, cancer	Comparative Toxic Unit for human	CTUh	USEtox model	EF 3.1
Human toxicity, non-cancer	Comparative Toxic Unit for human	CTUh	USEtox model	EF 3.1
Ionising radiation	Ionizing Radiation Potentials	kBq ^{235}U eq	Dreicer et al. 1995, Frischknecht et al. 2000	EF 3.1
Land Use	Soil quality index	Pt (dimensionless)	Baseline model of LANCA v2.2	EF 3.1
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC11 eq	1999 WMO assessment	EF 3.1
Photochemical ozone formation	Photochemical Ozone Creation Potential (POCP)	kg NMVOC eq	LOTUS-EUROS (Van Zelm et al. 2008)	EF 3.1
Resource use, energy carriers	Abiotic resource depletion fossil fuels (ADP-fossil)	MJ	Van Oers et al. 2002, CML Guinée et al. 2002	EF 3.1
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserve)	kg Sb eq	Van Oers et al. 2002, CML Guinée et al. 2002	EF 3.1
Water use	User deprivation potential	m^3 eq	AWARE model	EF 3.1
Particulate matter	PM10 formation	kg PM10 eq	ReCiPe 2008 v1.13 midpoint, H	Supplementary
Particulate matter	PM2.5 formation	kg PM2.5 eq	ReCiPe 2016 v1.1 midpoint, H	Supplementary

Table 6.1: selected impact categories, indicators and characterisation methods, for performing the LCIA.

6.2 Results

The Life Cycle potential environmental impacts of the studied systems are exhibited in the following, along with insights concerning the virgin tyre system, the retreaded tyre system, and the critical raw material natural rubber. The results are referred to the correct functional unit through the use of the corresponding reference flows (Section 4.2.1.3).

6.2.1 Comparison between new tyre and retreated system

Table 6.2 and Figure 6.1 present the results of the comparison between the environmental potential impacts of the virgin truck tyre and of the retreaded tyre (which entails the new tyre plus one retreading, recall that a number of retreads equal to one is considered in this study).

Impact category	**Unit**	**Life Cycle New Tyre**	**Life Cycle Retreaded Tyre**	**Difference [%]**
Acidification	mol H+ eq	1.95E-02	1.23E-02	-37%
Climate change	kg CO_2 eq	3.16E+00	1.93E+00	-39%
Ecotoxicity, freshwater	CTUe	2.42E+01	1.63E+01	-33%
Particulate matter	disease inc.	1.16E-06	1.12E-06	-4%
Eutrophication, marine	kg N eq	4.57E-03	2.94E-03	-36%
Eutrophication, freshwater	kg P eq	4.81E-04	2.76E-04	-43%
Eutrophication, terrestrial	mol N eq	6.80E-02	4.40E-02	-35%
Human toxicity, cancer	CTUh	2.40E-09	1.44E-09	-40%
Human toxicity, non-cancer	CTUh	1.05E-07	9.68E-08	-8%
Ionising radiation	kBq U-235 eq	1.35E-01	7.48E-02	-45%
Land use	Pt	-1.54E+01	-9.63E+00	-37%
Ozone depletion	kg CFC11 eq	1.24E-07	6.68E-08	-46%
Photochemical ozone formation	kg NMVOC eq	2.58E-02	1.65E-02	-36%
Resource use, fossils	MJ	3.42E+01	2.03E+01	-41%
Resource use, minerals and metals	kg Sb eq	1.66E-05	9.99E-06	-40%
Water use	m^3 depriv.	3.33E-01	1.29E-01	-61%
PM10	kg PM10 eq	5.31E-03	5.25E-03	-1%
PM2.5	kg PM2.5 eq	4.89E-03	4.43E-03	-9%

Table 6.2: comparison of the potential environmental impacts of the new tyre LC and of the retreaded tyre LC; LC stands for life cycle.

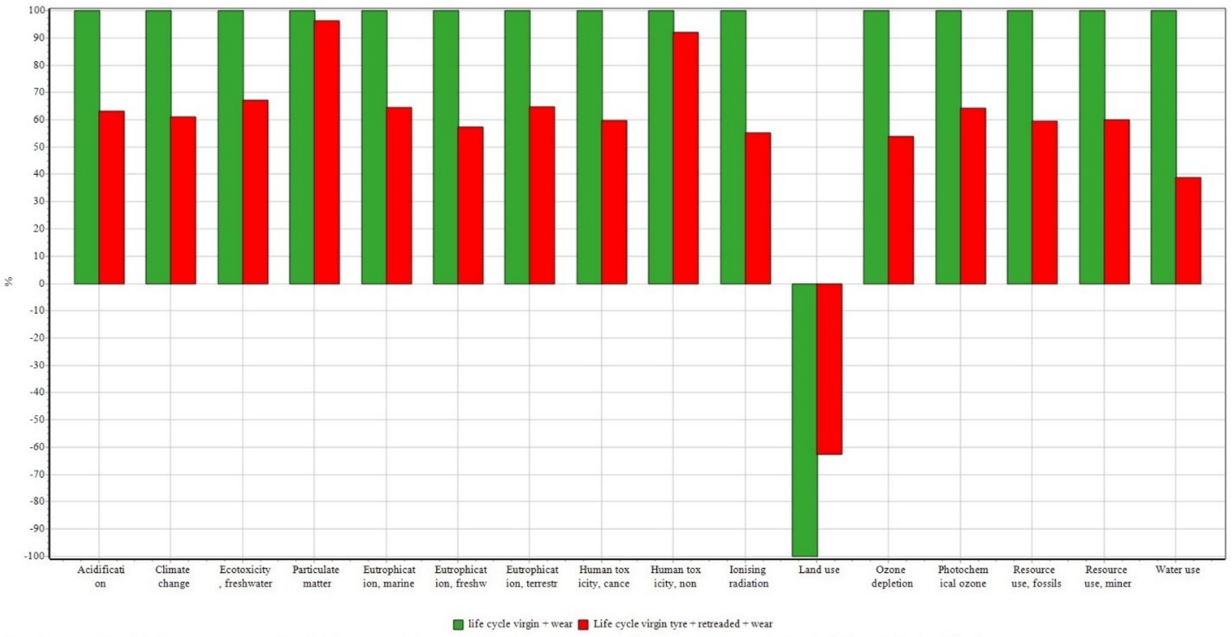

Figure 6.1: graphical comparison of the potential environmental impacts of the new tyre LC (highlighted in green) and of the retreaded tyre LC (coloured in red).

In light of these outcomes, it is possible to reach comparative conclusions about the two analysed systems, therefore fulfilling the main goal for which the study was conducted. Indeed, it can be clearly stated that the retreaded tyre outperforms the virgin tyre for each of the considered impact categories, over the entire life cycle. Comparing the retreaded tyre system with the new tyre system, it is possible to assert that the potential impacts of the former represent the 63 % of those of the latter, in the acidification category; the 61 % in the climate change category; the 67 % in the ecotoxicity freshwater category; the 96 % in the particulate matter category; the 64 % in the eutrophication marine category; the 57 % in the eutrophication freshwater category; the 65 % in the eutrophication terrestrial category; the 60 % in the human toxicity cancer category; the 92 % in the human toxicity non cancer category; the 55 % in the ionising radiation category; the 63 % in the land use category; the 54 % in the ozone depletion category; the 64 % in the photochemical ozone formation category; the 59 % in the resource use fossil category; the 60 % in the resource use minerals and metals category; the 39 % in the water use category; the 99 % in the PM10 category; the 91 % in the PM2.5 category.

Table 6.2 exemplifies the corresponding environmental savings that characterise the retreaded tyre system with respect to the new tyre system. The main savings of the retreaded truck tyre, over the life cycle of the tyre, are achieved in the water use (- 61 %), ozone depletion (- 46 %), and ionising radiation (- 45 %) categories. As far as the water use is concerned, this is mainly due to the lower energy and material demand that characterise the retreaded tyre system, and, specifically, the overall saving lies into the lower electricity consumption, lower natural rubber use (which implies a lower use of nitrogen fertiliser), lower consumption of synthetic rubber. Moreover, the water savings related to the steel wire drawing and the production of the new tyre play a secondary role in decreasing the impact of the retreaded tyre system over the water category. The reduced potential impacts in the ozone depletion category, for the retreaded tyre system, are caused by the avoided raw materials production processes and by the lower energy consumption proper of the retreading process; in particular, mostly by the avoided synthetic fabric production (required instead for the synthetic fabrics used in the new tyre system), by the avoided steel production and processing, by the reduced electricity and heat demands, and by the lack, in the elastomeric compounds employed for retreading, of the chlorinated paraffins (in particular, the impacts are related to the dichloromethane production), the use of which was instead assumed for manufacturing the virgin tyre compound. Hence, this last contribution due to the use of chlorinated paraffins as part of the flame retardant system of the new tyre rubber components, is here pointed out as a limiting factor due to the assumption made, even if it has a small effect on the overall ozone depletion comparison between the two tyre systems. From the emissions/substances perspective, the lower impact onto the ozone depletion of the retreaded tyre system stems from its lower emissions of: CFC–12 ($2.58 \cdot 10^{-8}$ kg CFC11-eq *versus* $5.16 \cdot 10^{-8}$ kg CFC11-eq of the new tyre system); of Halon–1301 ($1.93 \cdot 10^{-8}$ kg CFC11-eq *versus* $3.18 \cdot 10^{-8}$ kg CFC11-eq of the new tyre system); of Halon–1001 ($8.05 \cdot 10^{-9}$ kg CFC11-eq *versus* $1.60 \cdot 10^{-8}$ kg CFC11-eq of the new tyre system); and of CFC–10 ($7.40 \cdot 10^{-9}$ kg CFC11-eq *versus* $1.30 \cdot 10^{-8}$ kg CFC11-eq of the new tyre system); and it may be relevant to note that the emissions of these four substances account for nearly the 91 % of the total ozone depletion impact of the retreaded tyre system (and also to the 91 % for the new tyre system).

The decreased consumption of materials and energy, in praxis the prevention of further materials and energy production that the tyre reuse allows, is the key reason for the better environmental performance of the retreaded system. Indeed, it is exactly because of such factors that the retreaded tyre system ionising radiation is lower than that derived from the new tyre system; specifically, this saving is due to the consumption of less electricity and less synthetic rubber, leading to reductions in Radon–222 emitted (- 45 %), Carbon–14 (- 44 %), Radium–226 (- 36 %), Uranium – 234 (- 35 %), note that these four emitted substances contribute for over the 99 % to the ionising radiation impact of both the systems (the Radon–222 alone makes up to the 70 % of the total ionising radiation impact). Nearly the seventy percent of the emitted Radon–222, and this is valid for both the systems, is due to the electricity used (58 %) and to the synthetic rubber production (12 %).

Focusing on the climate change impacts, the new tyre system entails the emission of 3.16 kg CO_2-eq, while the retreaded tyre system results in the emission of 1.93 kg CO_2-eq. The 78 % of both those carbon footprints is emitted carbon dioxide, of fossil origin for approximately the 81 %. This fossil–carbon dioxide emission derives from the electricity used (for the 25 % considering the new system, for the 21 % considering the retreaded system), from the incineration treatment of waste rubber (for the 20 % considering the new system, for the 19 % considering the retreaded system), from the carbon black production (for the 10 % considering the new system, for the 11 % considering the retreaded system), from the steel cord production (for the 10 % considering the new system, for the 9 % considering the retreaded system), from the synthetic rubber production (for the 5 % considering the new system, for the 4 % considering the retreaded system), and from other smaller contributing processes (together summing up to the remainder).

The comparative results here obtained are in line with the existing literature, which, however, is scarce. Potential impacts on the climate change, the acidification, the eutrophication, the photochemical oxidation, and the abiotic resource depletion categories were considered in [192], and in that work, the retreaded tyre exhibited lower impacts, where these benefits increased with the number of retreads performed. Another study [29] pointed out that retreading truck tyres leads to lower energy consumption in the manufacturing stage, while its performance considering the whole life cycle strongly depends on the retreaded tyre rolling resistance: if this increases due to the retreading process, so as to results higher than that of a new tyre, then the tyre energy consumed during the service will augment, leading to higher potential impacts in the use phase, potentially leading to overall life cycle negligible or worse results. It should be remarked that in this study, the new tyre and retreaded tyre service performances are considered identical, based on primary data from Metalepsi Proteron, indicating that the coefficient of rolling resistance of the retreaded tyres is equivalent to that of the new tyres.

6.2.2 New tyre

Table 6.3 reports the life cycle impact assessment results for the virgin tyre system, with respect to the selected categories.

Impact category	Unit	Total
Acidification	mol H+ eq	1.95E-02
Climate change	kg CO_2 eq	3.16E+00
Ecotoxicity, freshwater	CTUe	2.42E+01
Particulate matter	disease inc.	1.16E-06
Eutrophication, marine	kg N eq	4.57E-03
Eutrophication, freshwater	kg P eq	4.81E-04
Eutrophication, terrestrial	mol N eq	6.80E-02
Human toxicity, cancer	CTUh	2.40E-09
Human toxicity, non-cancer	CTUh	1.05E-07
Ionising radiation	kBq U-235 eq	1.35E-01
Land use	Pt	-1.54E+01
Ozone depletion	kg CFC11 eq	1.24E-07

Photochemical ozone formation	kg NMVOC eq	2.58E-02
Resource use, fossils	MJ	3.42E+01
Resource use, minerals and metals	kg Sb eq	1.66E-05
Water use	m^3 depriv.	3.33E-01

Table 6.3: LCIA results for virgin tyre.

Figure 6.2 shows the network flow chart (as Sankey diagram) of the life cycle of the virgin tyre, regarding the climate change impact category only, and with a cut-off value of 1 %.

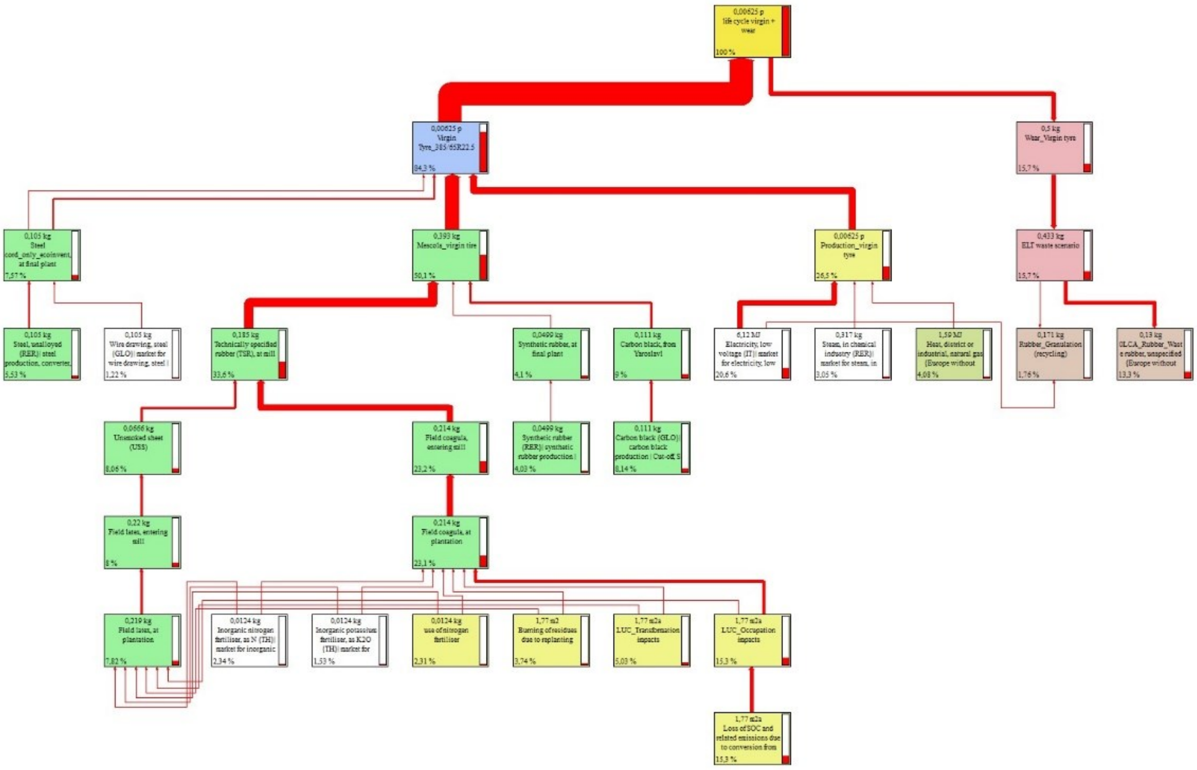

Figure 6.2: Network flow chart of the new tyre life cycle, impact category climate change, cut-off of 1 %.

Note that (i) the thicker the line, the greater the environmental burden contribution, that (ii) the red bars present in the right part of the boxes visually display the contribution of each of those boxes, and that (iii) green bars, if present, indicate negative impacts, that are environmental benefits. It is therefore possible to observe that the main contribution to the climate change impact is that related to the elastomeric mixture (50 %), followed by the contributions of the manufacturing (27 %), of the end of life (16 %), and of the steel cord (near 7 %). Regarding the virgin rubber compound, the natural rubber contribution to climate change impact should be highlighted, since it accounts for nearly the 34 % of the total.

As far as the climate change impact is concerned (total carbon dioxide equivalents emitted of 3.16 kg CO_2-eq), it is possible to obtain the following detailed process contribution hierarchy (in descending order, with a cut-off value of 1 %): (1) electricity used in the production stage of new tyre (19.2 %); (2) loss of soil organic carbon and related emissions due to the conversion of forests (15.3 %); (3) end-of-life incineration of waste rubber (12.8 %); (4) production of carbon black (8.1 %); (5) production of steel cords (7.4 %); (6) heat and steam consumed in the production phase of the new tyre (7.1 %); (7) land use change transformation impacts (5.0 %); (8) synthetic rubber production (4.0 %); (9) burning of *Hevea b.* residues for replanting (3.7 %); (10) production of nitrogen fertiliser (2.3 %); (11) application of nitrogen fertiliser (2.3 %); (12) production of potassium fertiliser (1.5 %); (13) electricity used for rubber granulation in the end-of-life stage (1.4 %); and the other processes are responsible for the remainder (10.3 %) of the impact on the climate change category. Already from this ranking, the importance of the raw material production, in particular of the TSR, and that of the energy demand of the new tyre manufacturing can be appreciated (further analyses are provided in this Section and in Sections 6.2.3, 6.2.4).

Figure 6.3 shows an analysis of groups to understand the contribution, to the total environmental potential impacts, of some groups of processes, in this case defined as:

- “Production” group: entails the activities belonging to the information module A3 (Section 5.2.3);
- “Use” group: corresponds to the information module B1 (Section 5.2.4), hence, it includes the tyre wear emissions only;
- “Transport” group: incorporates all the transport processes which occur throughout the life cycle;
- “ELT waste scenario” group: considers the waste scenario of the tyre, thus, matching with the modules C2 – C3 (Section 5.2.5);
- “TSR” group: includes the technically specified rubber, net of transport towards the tyre manufacturing plant;
- “Steel cord” group, “carbon black” group, “synthetic rubber” group, and “synthetic fabric” group: entail the steel cord, the carbon black, the synthetic rubber, and the synthetic fabric, respectively, net of transport towards the tyre manufacturing plant;
- “Other compounding ingredients” group: includes all the ingredients used for the new tyre compound except for the TSR, the carbon black, and the synthetic rubber (see Section 5.2.1).

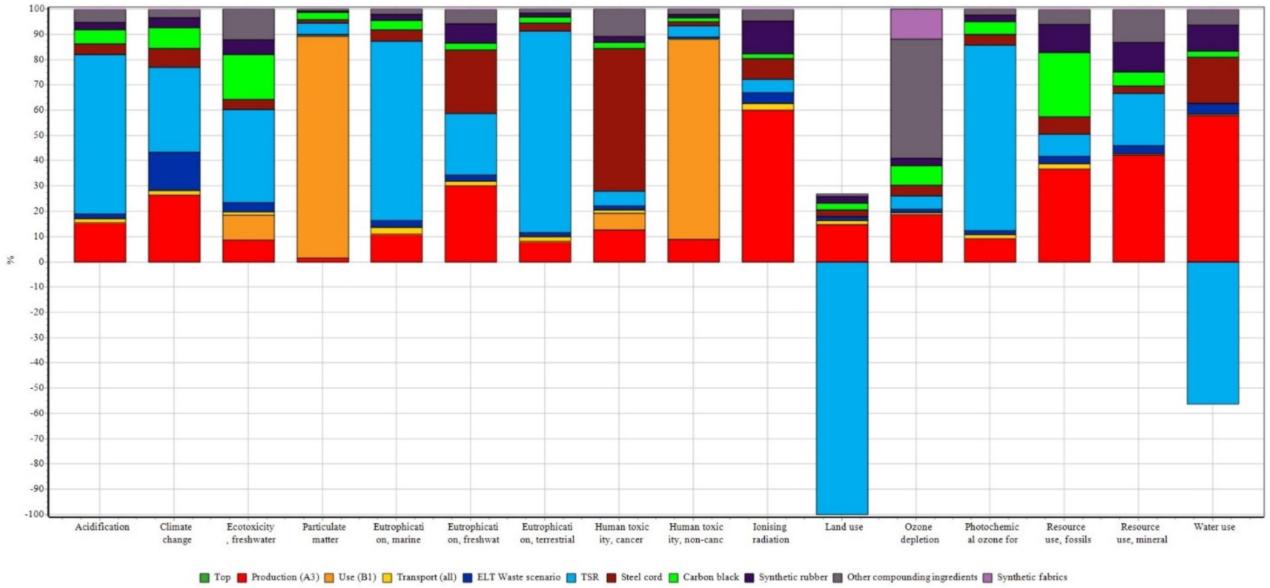

Figure 6.3: graphical representation of the impact assessment according to the groups created, covering the whole new tyre life cycle.

It must be noted that the selected groups comprise all the processes, thus, the “Top” group is empty. Moreover, they resemble the life cycle stages, but highlighting separately the contribution of the transports required during the complete life cycle and specifying the individual contributions of the raw materials. The corresponding quantitative results, related to the aforementioned groups, are shown in Table 6.4 as absolute values, while in Table 6.5 the contribution analysis is reported in shares. Table 6.5 exhibits, for each impact category, the contribution of the chosen groups in percentage of the total impact on that category. It is therefore possible to significantly notice that the raw material acquisition phase represents a relevant part of the overall life cycle burden, accounting for the 81 % of the total acidification impact, for the 57 % of the total climate change impact, for the 77 % of the total ecotoxicity freshwater impact, for the 10 % of the total particulate matter impact, for the 84 % of the total eutrophication marine impact, etc., being the technically specified natural rubber the main driver for almost all the categories (not all). Finally, among the several comments that can be made, it can be concluded that: transports do have a relative negligible contribution for all the impact categories, in a life cycle perspective; the use phase (remind that only the tyre particle emissions of the B1 module have been considered in this study) mostly impacts the particulate matter and human toxicity non cancer categories; the manufacturing stage of the life cycle is responsible for noteworthy impacts, largely affecting the ionising radiation, resource use and water use categories; the end of life phase holds low influence on the whole life cycle impacts, except for the climate change category (indeed, the contribution of the rubber incineration has been already identified); the raw materials production dominates the life cycle impacts.

Impact category	Unit	Total	Production (A3)	Use (B1)	Transport	ELT Waste scenario (C2-C3)	TSR	Steel cord	Carbon black	Synthetic rubber	Other compounding ingredients	Synthetic fabrics
Acidification	mol H+ eq	1.95E-02	2.96E-03	5.01E-05	3.21E-04	3.51E-04	1.23E-02	8.48E-04	1.07E-03	5.93E-04	9.81E-04	2.64E-05
Climate change	kg CO_2 eq	3.16E+00	8.36E-01	0.00E+00	5.35E-02	4.83E-01	1.06E+00	2.35E-01	2.57E-01	1.27E-01	1.00E-01	5.16E-03
Ecotoxicity, freshwater	CTUe	2.42E+01	2.08E+00	2.37E+00	3.34E-01	9.01E-01	8.87E+00	9.99E-01	4.27E+00	1.43E+00	2.92E+00	2.51E-02
Particulate matter	disease inc.	1.16E-06	1.62E-08	1.02E-06	4.74E-09	3.70E-09	5.31E-08	1.54E-08	3.17E-08	8.62E-09	7.66E-09	3.30E-10
Eutrophication, marine	kg N eq	4.57E-03	4.84E-04	1.88E-05	1.18E-04	1.22E-04	3.24E-03	2.04E-04	1.74E-04	1.05E-04	9.64E-05	5.09E-06
Eutrophication, freshwater	kg P eq	4.81E-04	1.45E-04	0.00E+00	8.06E-06	1.18E-05	1.18E-04	1.21E-04	1.24E-05	3.76E-05	2.65E-05	1.40E-06
Eutrophication, terrestrial	mol N eq	6.80E-02	5.39E-03	8.24E-05	1.26E-03	1.06E-03	5.43E-02	2.10E-03	1.65E-03	1.05E-03	1.02E-03	6.51E-05
Human toxicity, cancer	CTUh	2.40E-09	2.99E-10	1.64E-10	3.16E-11	3.76E-11	1.37E-10	1.36E-09	5.76E-11	6.24E-11	2.55E-10	3.11E-12
Human toxicity, non-cancer	CTUh	1.05E-07	9.27E-09	8.30E-08	4.14E-10	7.71E-10	4.86E-09	1.64E-09	1.45E-09	1.40E-09	2.28E-09	5.40E-11
Ionising radiation	kBq U-235 eq	1.35E-01	8.12E-02	0.00E+00	3.58E-03	5.84E-03	7.09E-03	1.10E-02	2.72E-03	1.75E-02	6.13E-03	3.13E-04
Land use	Pt	-1.54E+01	3.09E+00	0.00E+00	3.62E-01	3.16E-01	-2.11E+01	5.74E-01	5.43E-01	5.32E-01	2.42E-01	2.40E-02
Ozone depletion	kg CFC11 eq	1.24E-07	2.31E-08	0.00E+00	1.01E-09	1.80E-09	6.35E-09	5.24E-09	9.76E-09	3.47E-09	5.84E-08	1.49E-08
Photochemical ozone formation	kg NMVOC eq	2.58E-02	2.35E-03	3.10E-06	4.41E-04	3.94E-04	1.89E-02	1.10E-03	1.27E-03	7.04E-04	5.71E-04	2.43E-05
Resource use, fossils	MJ	3.42E+01	1.26E+01	0.00E+00	7.33E-01	9.81E-01	2.96E+00	2.42E+00	8.65E+00	3.85E+00	1.95E+00	9.50E-02
Resource use, minerals and metals	kg Sb eq	1.66E-05	7.01E-06	0.00E+00	1.28E-07	5.23E-07	3.42E-06	5.02E-07	9.32E-07	1.93E-06	2.16E-06	4.01E-08
Water use	m^3 depriv.	3.33E-01	4.40E-01	0.00E+00	3.84E-03	3.23E-02	-4.28E-01	1.39E-01	1.87E-02	7.76E-02	4.79E-02	1.22E-03

Table 6.4: impact assessment according to the groups created, covering the whole new tyre life cycle.

Impact category	Production (A3)	Use (B1)	Transport (all)	ELT Waste scenario	TSR	Steel cord	Carbon black	Synthetic rubber	Other compounding ingredients	Synthetic fabrics
Acidification	15.2	0.3	1.6	1.8	63.1	4.4	5.5	3.0	5.0	0.1
Climate change	26.5	0.0	1.7	15.3	33.6	7.4	8.1	4.0	3.2	0.2
Ecotoxicity, freshwater	8.6	9.8	1.4	3.7	36.7	4.1	17.6	5.9	12.1	0.1
Particulate matter	1.4	87.8	0.4	0.3	4.6	1.3	2.7	0.7	0.7	0.0
Eutrophication, marine	10.6	0.4	2.6	2.7	70.9	4.5	3.8	2.3	2.1	0.1
Eutrophication, freshwater	30.1	0.0	1.7	2.5	24.4	25.1	2.6	7.8	5.5	0.3
Eutrophication, terrestrial	7.9	0.1	1.9	1.6	79.9	3.1	2.4	1.5	1.5	0.1
Human toxicity, cancer	12.5	6.8	1.3	1.6	5.7	56.4	2.4	2.6	10.6	0.1
Human toxicity, non-cancer	8.8	78.9	0.4	0.7	4.6	1.6	1.4	1.3	2.2	0.1
Ionising radiation	60.0	0.0	2.6	4.3	5.2	8.1	2.0	12.9	4.5	0.2
Land use	20.1	0.0	2.4	2.1	-136.9	3.7	3.5	3.5	1.6	0.2
Ozone depletion	18.7	0.0	0.8	1.4	5.1	4.2	7.9	2.8	47.1	12.0
Photochemical ozone formation	9.1	0.0	1.7	1.5	73.4	4.3	4.9	2.7	2.2	0.1
Resource use, fossils	36.7	0.0	2.1	2.9	8.7	7.1	25.3	11.3	5.7	0.3
Resource use, minerals and metals	42.1	0.0	0.8	3.1	20.5	3.0	5.6	11.6	13.0	0.2
Water use	132.2	0.0	1.2	9.7	-128.5	41.8	5.6	23.3	14.4	0.4

Table 6.5: contribution analysis according to the groups created, covering the whole new tyre life cycle; all the figures are expressed as percentages.

6.2.3 Retreaded tyre

Table 6.6 reports the life cycle impact assessment results for the retreaded tyre system, with respect to the selected categories.

Impact category	Unit	Total
Acidification	mol H+ eq	1.23E-02
Climate change	kg CO^2 eq	1.93E+00
Ecotoxicity, freshwater	CTUe	1.63E+01
Particulate matter	disease inc.	1.12E-06
Eutrophication, marine	kg N eq	2.94E-03
Eutrophication, freshwater	kg P eq	2.76E-04
Eutrophication, terrestrial	mol N eq	4.40E-02
Human toxicity, cancer	CTUh	1.44E-09
Human toxicity, non-cancer	CTUh	9.68E-08
Ionising radiation	kBq U-235 eq	7.48E-02
Land use	Pt	-9.63E+00
Ozone depletion	kg CFC11 eq	6.68E-08
Photochemical ozone formation	kg NMVOC eq	1.65E-02
Resource use, fossils	MJ	2.03E+01
Resource use, minerals and metals	kg Sb eq	9.99E-06
Water use	m^3 depriv.	1.29E-01

Table 6.6: LCIA results for retreaded tyre.

Figure 6.4 shows the network flow chart (as Sankey diagram) of the life cycle of the retreaded tyre, regarding the climate change impact category only, and with a cut-off value of 1 %.

Information withheld for confidentiality

Figure 6.4: Network flow chart of the retreaded tyre life cycle, impact category climate change, cut-off of 1 %.

Hence, it is immediately clear that the dominant contribution to the climate change impact is that related to the virgin tyre (69 %), followed by the contributions of the reuse (18 %), and of the end of life (13 %). Concerning the climate change impact (total carbon dioxide equivalents emitted of 1.93 kg CO_2-eq), it is possible to obtain a detailed process contribution hierarchy (in descending order, with a cut-off value of 1 %) that, due to the declared main contribution associated with the virgin tyre, resembles the one related to the new tyre system, but few differences emerge: (1) loss of soil organic carbon and related emissions due to the conversion of forests (16.5 %); (2) electricity used in the production stage of new tyre (15.7 %); (3) end-of-life incineration of waste rubber (11.8 %); (4) production of carbon black (8.6 %); (5) production of steel cords (6.0 %); (6) heat and steam consumed in the production phase of the new tyre (5.8 %); (7) land use change transformation impacts (5.4 %); (8) burning of *Hevea b.* residues for replanting (4.0 %); (9) synthetic rubber production (3.4 %); (10) production of nitrogen fertiliser (2.5 %); (11) application of nitrogen fertiliser (2.5 %); (12) transports, lorry (2.2 %); (13) production of potassium fertiliser (1.7 %); (14) incineration of scrap rubber obtained during buffing (1.3 %); (15) electricity used for rubber granulation in the end-of-life stage (1.3 %); and the other processes are responsible for the remainder (12.8 %) of the impact on the climate change category.

Figure 6.5 presents an analysis of groups to understand the relative contribution of some groups of processes (resembling the life cycle stages) to the total environmental potential impacts of the analysed system. The groups in this analysis are defined as:

- “Retreading” group: consists of the retreading process in strict sense, from the visual inspection to the tests after curing (Sections 4.2.1.1, 5.3.3);
- “Use” group: corresponds to the information module B1 (Section 5.3.4), hence, it includes the tyre wear emissions only;
- “Production (RCE)” group: entails the energy consumption for manufacturing the ring, the cushion, and the envelopes;
- “Raw material supply” group: involves the modules A1 – A2, hence, the procurement of the ring compound, the substrate (or cushion) compound, the solution compound, and the envelopes (related transports included);
- “New tyre LC” group: contains the life cycle of the tyre before the reuse through retreading (related transports included);
- “Packaging (materials + EOL)” group: relates to the packaging materials employed, their processing (when required, i.e., for the pallet), and their EOLs;

- “Transport (packaging, internal)” group: involves the transport used for procuring packaging and the internal transports needed for the manufacturing stage;
- “EOL retreaded” group: concerns the end of life of the retreaded tyre (modules C2 – C3);
- “EOL scrap rubber from retreading” group: entails the end of life of the retreading rubber residues.

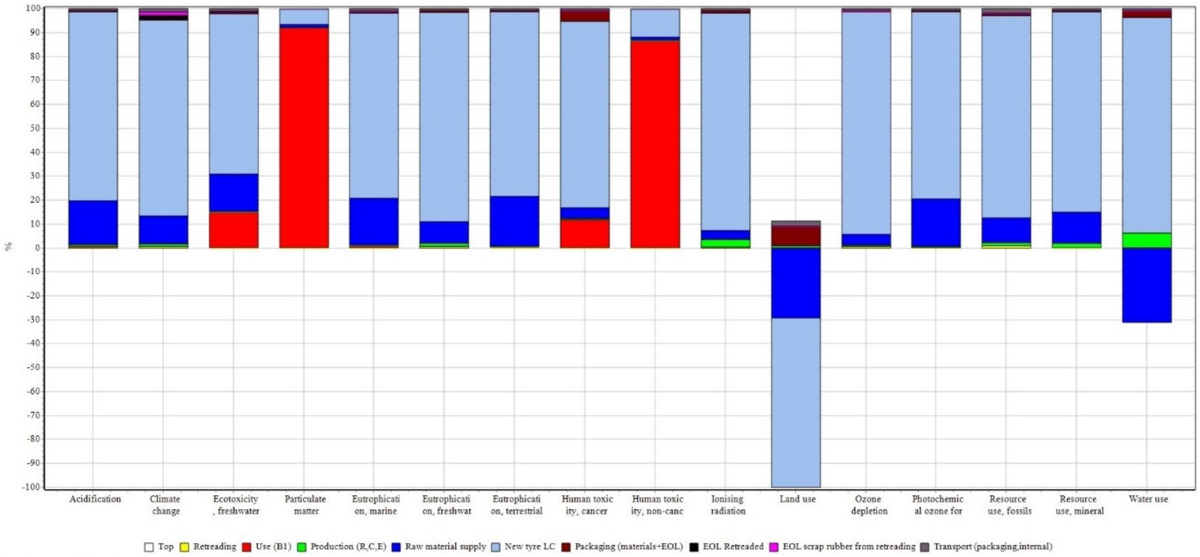

Figure 6.5: graphical representation of the impact assessment according to the groups created, covering the whole retreaded tyre life cycle.

It should be noted that, also in this case, the selected groups comprise all the processes, and therefore, the “Top” group is empty. Table 6.7 shows the quantitative results corresponding to the chosen groups, in absolute values, while Table 6.8 presents the corresponding contribution shares. From these results it can be asserted that: the new tyre, which is the greatest contributor to the climate change impact, is largely responsible also for the impacts over the other categories; the raw materials procurement phase implies significant impacts onto many of the categories; the manufacturing stage, in strict meaning (entailing the “production RCE” and the “retreading” groups) seems to holds very little influence on the final total burden, being the contribution in the category where it impacts the most (i.e., water use), only the 9 % of that category total; the packaging (materials and EOL), the transport of packaging and the internal transfers, the end of life of the production scraps and that of the whole retreaded tyre exhibit little contributions to the impact categories, and considered together are responsible, on average, for less than 3 % of the impacts among the categories. These results are consistent with the ones reported in [192].

Impact category	**Unit**	**Total**	**Retreading**	**Use (B1)**	**Production (R,C,E)**	**Raw material supply (A1-A2)**	**New tyre LC**	**Packaging (materials+EOL)**	**EOL Retreaded (C2-C3)**	**EOL scrap rubber from retreading**	**Transport (packaging,internal)**
Acidification	mol H+ eq	1.23E-02	3.89E-05	5.05E-05	7.67E-05	2.27E-03	9.73E-03	4.26E-05	8.06E-06	1.16E-05	8.88E-05
Climate change	kg CO^2 eq	1.93E+00	1.41E-02	0.00E+00	1.81E-02	2.25E-01	1.58E+00	7.99E-03	2.80E-02	2.81E-02	2.72E-02
Ecotoxicity, freshwater	CTUe	1.63E+01	3.15E-02	2.39E+00	5.22E-02	2.52E+00	1.09E+01	4.39E-02	4.72E-02	5.01E-02	1.92E-01
Particulate matter	disease inc.	1.12E-06	4.02E-10	1.03E-06	3.80E-10	1.42E-08	7.09E-08	6.85E-10	1.17E-10	2.10E-10	2.17E-09
Eutrophication, marine	kg N eq	2.94E-03	6.46E-06	1.90E-05	1.18E-05	5.76E-04	2.28E-03	1.19E-05	4.81E-06	6.45E-06	3.04E-05
Eutrophication, freshwater	kg P eq	2.76E-04	1.59E-06	0.00E+00	3.86E-06	2.49E-05	2.41E-04	2.42E-06	1.54E-07	1.63E-07	1.90E-06
Eutrophication, terrestrial	mol N eq	4.40E-02	6.67E-05	8.31E-05	1.35E-04	9.24E-03	3.40E-02	1.30E-04	3.48E-05	5.29E-05	3.21E-04
Human toxicity, cancer	CTUh	1.44E-09	3.45E-12	1.65E-10	7.57E-12	6.59E-11	1.12E-09	5.96E-11	1.17E-12	1.26E-12	1.23E-11
Human toxicity, non-cancer	CTUh	9.68E-08	4.66E-11	8.37E-08	2.59E-10	1.40E-09	1.11E-08	8.67E-11	8.37E-12	1.01E-11	2.71E-10
Ionising radiation	kBq U-235 eq	7.48E-02	3.47E-04	0.00E+00	2.28E-03	2.76E-03	6.80E-02	8.21E-04	2.12E-05	2.50E-05	5.15E-04
Land use	Pt	-9.63E+00	1.33E-02	0.00E+00	8.78E-02	-3.16E+00	-7.68E+00	8.65E-01	5.97E-03	6.90E-03	2.28E-01
Ozone depletion	kg CFC11 eq	6.68E-08	4.45E-10	0.00E+00	4.29E-10	2.95E-09	6.21E-08	1.72E-10	4.27E-11	5.58E-11	5.94E-10
Photochemical ozone formation	kg NMVOC eq	1.65E-02	3.28E-05	3.13E-06	5.62E-05	3.31E-03	1.29E-02	5.34E-05	1.18E-05	1.98E-05	1.32E-04
Resource use, fossils	MJ	2.03E+01	1.91E-01	0.00E+00	2.79E-01	2.10E+00	1.71E+01	1.56E-01	1.39E-02	2.29E-02	3.89E-01
Resource use, minerals and metals	kg Sb eq	9.99E-06	4.57E-09	0.00E+00	2.05E-07	1.29E-06	8.35E-06	4.29E-08	1.63E-09	2.04E-09	8.73E-08
Water use	m^3 depriv.	1.29E-01	3.78E-04	0.00E+00	1.14E-02	-5.80E-02	1.68E-01	4.81E-03	3.02E-04	3.12E-04	1.57E-03

Table 6.7: impact assessment according to the groups created, for the retreaded tyre life cycle.

Impact category	Retreading	Use (B1)	Production (R,C,E)	Raw material supply	New tyre LC	Packaging (materials+EOL)	EOL Retreaded	EOL scrap rubber from retreading	Transport (packaging,internal)
Acidification	0.3	0.4	0.6	18.4	79.0	0.3	0.1	0.1	0.7
Climate change	0.7	0.0	0.9	11.6	82.0	0.4	1.4	1.5	1.4
Ecotoxicity, freshwater	0.2	14.7	0.3	15.5	67.2	0.3	0.3	0.3	1.2
Particulate matter	0.0	92.0	0.0	1.3	6.3	0.1	0.0	0.0	0.2
Eutrophication, marine	0.2	0.6	0.4	19.6	77.4	0.4	0.2	0.2	1.0
Eutrophication, freshwater	0.6	0.0	1.4	9.0	87.3	0.9	0.1	0.1	0.7
Eutrophication, terrestrial	0.2	0.2	0.3	21.0	77.2	0.3	0.1	0.1	0.7
Human toxicity, cancer	0.2	11.5	0.5	4.6	78.0	4.2	0.1	0.1	0.9
Human toxicity, non-cancer	0.0	86.4	0.3	1.4	11.5	0.1	0.0	0.0	0.3
Ionising radiation	0.5	0.0	3.0	3.7	90.9	1.1	0.0	0.0	0.7
Land use	0.1	0.0	0.9	-32.8	-79.7	9.0	0.1	0.1	2.4
Ozone depletion	0.7	0.0	0.6	4.4	93.0	0.3	0.1	0.1	0.9
Photochemical ozone formation	0.2	0.0	0.3	20.1	78.1	0.3	0.1	0.1	0.8
Resource use, fossils	0.9	0.0	1.4	10.4	84.5	0.8	0.1	0.1	1.9
Resource use, minerals and metals	0.0	0.0	2.1	12.9	83.6	0.4	0.0	0.0	0.9
Water use	0.3	0.0	8.8	-45.1	130.5	3.7	0.2	0.2	1.2

Table 6.8: contribution analysis according to the groups created, covering the whole retreaded tyre life cycle; all the figures are expressed as percentages.

6.2.3.1 Retreading process

In the following, the results concerning one tyre retreaded from the old virgin carcass are presented (thus, not referred to the functional unit), focusing on the processes under the operational management of the Metalepsi Proteron, with the addition of the treatments required for the scrap rubber (residues) produced in its processes. The group analysis conducted, exhibited Figure 6.6 and in Table 6.9, is based on the groups selected as:

- "Raw materials" group: entails the raw materials used for the ring compound, the substrate (or cushion) compound, the solution compound, and the envelopes, all considered net of transports:
- "Packaging (materials)" group: includes the materials employed for the packaging, net of related transports. Note that this group also includes the pallet production in order to take into account all the related impacts, since the Ecoinvent process used for modelling the pallet lacks the required energy consumption, see e.g. Table 5.29;
- "Production (retreading + productions)" group: covers, in terms of energy consumption, the manufacturing of the ring and of the substrate, the retreading process (strict sense), and the manufacturing of the envelopes;
- "Transport" group: concerns the transport required for the raw material supply and for the packaging supply, and also the internal transport of the production phase;
- "EOL scrap rubber from retreading" group: regards the treatments required for managing the manufacturing scrap.

Note that, the "Top" group correctly results as zero (indeed, does not appear in the diagram, nor it is reported in the Table 6.9), which means that this analysis covers all the related flows, and that these are arranged into the indicated groups. The importance of the raw material production (net of transports) is evident, being the main impact contributor to each of the category, except for the ionising radiation category. Furthermore, the relevant contributions on the environmental burden of all the considered transport ("transport" group) and of the manufacturing and retreading processes ("production (retreading + productions)" group) should be noticed.

The total emissions of carbon dioxide equivalents accounts to 102 kg CO_2-eq, as reported in Table 6.9. From a (semi-finished) product perspective, it can be deduced that the manufactured ring tread product (used for the retreading), involving all the required raw materials, transports, processing and internal transports (thus, ready to be applied on the carcass in the Ofir plant), represents the 77 % of the climate change impact, while the substrate, with all the required raw materials, transports, processing and internal transports (thus, ready to be used for the retreading process in the Ofir plant), accounts for the 7 % of the climate change impact. It may be also pointed out that the impacts caused by the ring compound, the substrate compound, and the solution compound, all obtained at the Ofir plant (before the transfer to Bitinia, for the ring and substrate compounds) are approximately the 64 %, the 6 %, and the 0.2 % of the total impact on the climate change category, respectively.

Specifically, considering a material approach, the TSR (natural rubber) is finally responsible for the emissions of 53.7 kg CO_2-eq (per one retreading process, in general sense), representing nearly the 53 % of the overall climate change impact. Carbon black supply contributes for the 13 % of the total climate change impact, mainly due to its production (which corresponds to the 11 % with respect to the total carbon dioxide equivalents emissions).

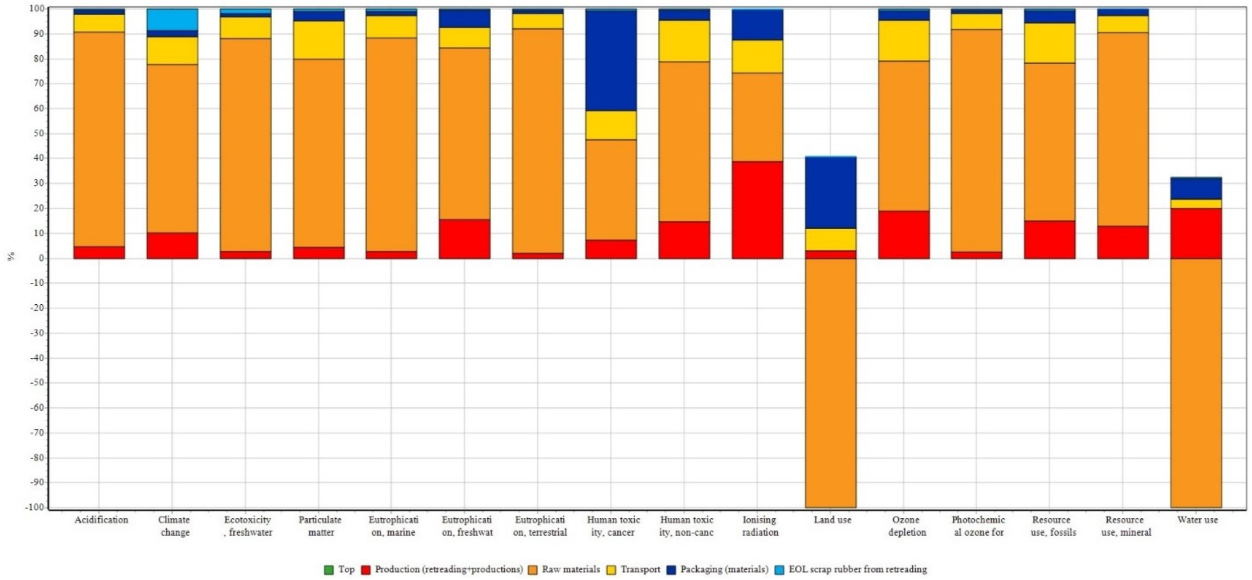

Figure 6.6: graphical representation of the impact assessment according to the groups created, regarding the raw materials, the packaging, the manufacturing processes, the required transports, and the EOL of the manufacturing scraps of one retreaded tyre.

Impact category	Unit	Total	Production (retreading+productions)	Raw materials	Transport	Packaging (materials)	EOL scrap rubber from retreading
Acidification	mol H+ eq	8.09E-01	3.70E-02	6.96E-01	5.93E-02	1.31E-02	3.63E-03
Climate change	kg CO_2 eq	1.02E+02	1.03E+01	6.90E+01	1.16E+01	2.25E+00	8.99E+00
Ecotoxicity, freshwater	CTUe	9.25E+02	2.68E+01	7.89E+02	7.97E+01	1.36E+01	1.60E+01
Particulate matter	disease inc.	5.75E-06	2.50E-07	4.34E-06	8.85E-07	2.09E-07	6.63E-08
Eutrophication, marine	kg N eq	2.05E-01	5.83E-03	1.75E-01	1.85E-02	3.52E-03	2.05E-03
Eutrophication, freshwater	kg P eq	1.11E-02	1.74E-03	7.65E-03	9.22E-04	7.78E-04	4.68E-05
Eutrophication, terrestrial	mol N eq	3.18E+00	6.44E-02	2.86E+00	1.98E-01	3.90E-02	1.68E-02

Human toxicity, cancer	CTUh	4.82E-08	3.53E-09	1.95E-08	5.55E-09	1.93E-08	3.96E-10
Human toxicity, non-cancer	CTUh	6.63E-07	9.79E-08	4.24E-07	1.10E-07	2.75E-08	3.01E-09
Ionising radiation	kBq U-235 eq	2.16E+00	8.40E-01	7.64E-01	2.86E-01	2.64E-01	6.48E-03
Land use	Pt	-6.08E+02	3.23E+01	-1.03E+03	9.23E+01	2.95E+02	2.15E+00
Ozone depletion	kg CFC11 eq	1.49E-06	2.80E-07	8.98E-07	2.44E-07	5.43E-08	1.13E-08
Photochemical ozone formation	kg NMVOC eq	1.15E+00	2.85E-02	1.03E+00	7.12E-02	1.62E-02	6.28E-03
Resource use, fossils	MJ	1.00E+03	1.51E+02	6.33E+02	1.63E+02	4.86E+01	7.16E+00
Resource use, minerals and metals	kg Sb eq	5.22E-04	6.71E-05	4.05E-04	3.53E-05	1.38E-05	5.43E-07
Water use	m^3 depriv.	-1.27E+01	3.77E+00	-1.88E+01	6.80E-01	1.54E+00	8.92E-02

Table 6.9: impact assessment according to the defined groups, for one retreaded tyre (including the corresponding: raw materials, packaging, manufacturing processes, required transports, and EOL of the manufacturing scraps).

6.2.4 Natural rubber

From the previous discussion, notably Sections 6.2.2 and 6.2.3.1, the pivotal contributions of the raw materials production to the potential environmental impacts have been detected, with natural rubber production emerging as the main driver for these contributions. The results of natural rubber presented in the following sections are expressed referring to 1 kg.

6.2.4.1 Technically specified rubber

In particular, natural rubber tremendously represents over one fifth of the potential impacts for ten out of sixteen categories and over the 60 % for six out of sixteen categories, as far as the life cycle of new tyre is considered (see Table 6.5). It carries more than 60 % of the environmental burden for the acidification, the eutrophication marine and terrestrial, and the photochemical ozone formation categories, while it holds environmental benefit considering the land use and water use categories (again, referring to Table 6.5). In the case of the virgin tyre life cycle, the land use benefit (negative impact – positive effect) caused by natural rubber offsets the positive impacts (negative effect) of all the other contributors, while the water use benefit brought by natural rubber is not sufficient for counterbalancing the positive impacts of the other contributors, resulting in a total water withdrawal. The same occurs for the retreaded tyre life cycle (see Table 6.7). Since the retreading system implies the use of less water with respect to the amount used in the new tyre system, the impact on the water use category considering the retreading process of one tyre (as done in Section 6.2.3.1) is clearly negative, that means beneficial from the environmental point of view. The environmental benefit concerning the water use category stem from the wastewater treatment in the TSR manufacturing, as shown in Table 6.10, which outweighs the positive impacts (water deprived) due to the raw materials production (unsmoked sheets, field coagula). Instead, the land use benefit requires a deeper analysis, since it is not feasible to figure out the ultimate reason(s) from that Table, but it is possible to guess the cause keeping in mind the model adopted in the inventory.

The results attained for 1 kg of natural rubber, as STR 20, are exhibited in Figure 6.7 and Table 6.10.

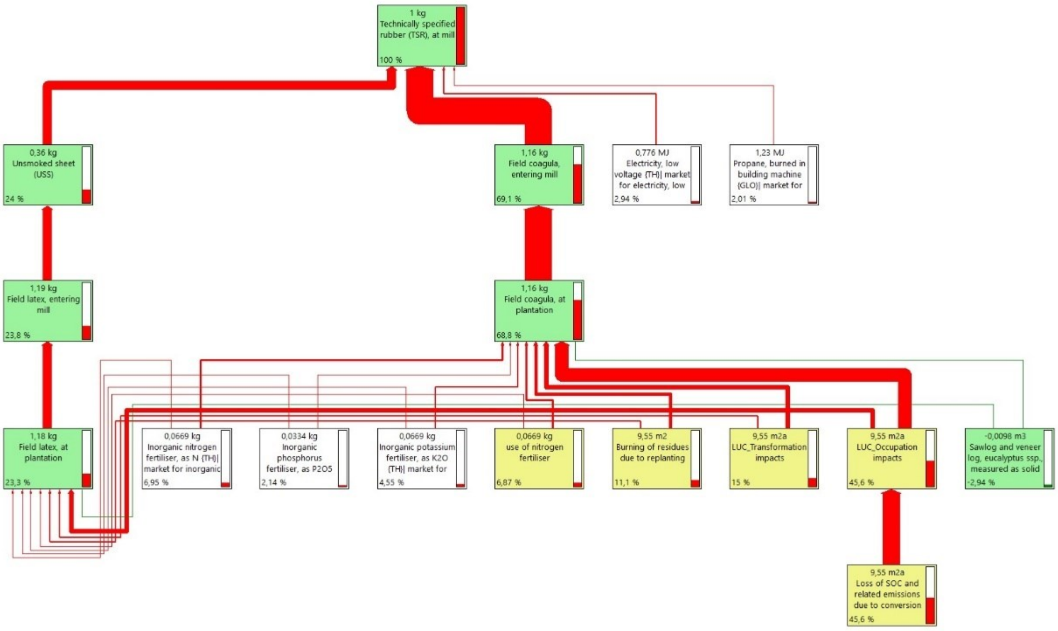

Figure 6.7: network flow chart of technically specified rubber at mill gate (1 kg), impact category climate change, cut-off of 2 %.

From Figure 6.7, where the results only on the climate change impact category are shown, it can be observed that land use change emissions represent the greatest contributor to the total emitted carbon dioxide equivalents, followed by the field emissions (mainly by the burning of residues after harvesting). The impacts on all the categories are shown in Table 6.10, as absolute values.

Impact category	**Unit**	**Total**	**Unsmoked sheet (USS)**	**Field coagula, entering mill**	**Electricity**	**Diesel, burned**	**Propane, burned**	**Wastewater treatment**
Acidification	mol H+ eq	6.63E-02	1.63E-02	4.79E-02	6.04E-04	1.25E-03	2.43E-04	5.21E-05
Climate change	kg CO_2 eq	5.74E+00	1.37E+00	3.97E+00	1.69E-01	1.02E-01	1.15E-01	1.02E-02
Ecotoxicity, freshwater	CTUe	4.79E+01	1.17E+01	3.41E+01	4.96E-01	6.46E-01	1.38E-01	8.33E-01
Particulate matter	disease inc.	2.86E-07	7.17E-08	2.07E-07	1.47E-09	2.36E-09	3.58E-09	6.87E-10
Eutrophication, marine	kg N eq	1.75E-02	4.15E-03	1.22E-02	1.22E-04	5.57E-04	7.90E-05	4.24E-04
Eutrophication, freshwater	kg P eq	6.35E-04	1.22E-04	3.48E-04	1.09E-04	5.54E-06	8.26E-06	4.08E-05
Eutrophication, terrestrial	mol N eq	2.93E-01	7.23E-02	2.13E-01	1.11E-03	6.06E-03	8.55E-04	1.61E-04
Human	CTUh	7.41E-10	1.65E-10	4.45E-10	4.24E-11	3.00E-11	4.62E-11	1.26E-11

toxicity, cancer								
Human toxicity, non-cancer	CTUh	2.62E-08	5.81E-09	1.63E-08	1.72E-09	4.91E-10	4.12E-10	1.48E-09
Ionising radiation	kBq U-235 eq	3.83E-02	9.41E-03	2.56E-02	6.24E-04	7.23E-04	1.44E-03	5.23E-04
Land use	Pt	-1.14E+02	-2.87E+01	-8.54E+01	1.31E-01	1.02E-01	1.05E-01	4.02E-02
Ozone depletion	kg CFC11 eq	3.43E-08	7.22E-09	1.95E-08	3.60E-09	1.59E-09	2.30E-09	6.32E-11
Photochemical ozone formation	kg NMVOC eq	1.02E-01	2.52E-02	7.42E-02	4.03E-04	1.69E-03	3.85E-04	3.24E-05
Resource use, fossils	MJ	1.60E+01	3.14E+00	7.83E+00	2.07E+00	1.30E+00	1.57E+00	8.99E-02
Resource use, minerals and metals	kg Sb eq	1.84E-05	4.36E-06	1.25E-05	9.39E-07	3.55E-07	2.56E-07	3.25E-08
Water use	m^3 depriv.	-2.31E+00	2.07E-01	5.32E-01	2.30E-02	2.98E-03	3.95E-03	-3.08E+00

Table 6.10: impact assessment results regarding 1 kg of TSR, at mill.

It must be detected that the impacts stemming from the manufacturing of the TSR (as energy consumption of electricity, diesel, propane) represent small contributions (< 17 %) to each of the categories, except for the eutrophication fresh water (19 %), the ozone depletion (22 %), and the resource use fossils (31 %) categories. Indeed, the main contributor corresponds to the raw materials production, being responsible for over the 74 % of the total impacts, for fifteen out of sixteen categories. As a consequence, the following Section aim at understanding the raw materials impacts.

6.2.4.2 Unsmoked Sheets, field latex and field coagula

Regarding unsmoked sheets (USS), an average of 98 % of the impacts for all the categories is due to the use of field latex (which enters the mill). Thus, it is important to focus on the field latex, along with the other TSR raw material, i.e., the field coagula. The impact assessment results for 1 kg of field latex are here reported. Since field latex and field coagula have been obtained as non-wood products from the *Hevea brasiliensis* plantation model with the appropriate partitioning factors, it is here deemed necessary and sufficient to exhibit the outcomes for one of the two products, in order to avoid redundancy. Table 6.11 shows the related results, with reference to one kg of the fresh latex at plantation exit.

Impact category	Unit	Total
Acidification	mol H+ eq	1.36E-02
Climate change	kg CO_2 eq	1.13E+00
Ecotoxicity, freshwater	CTUe	9.69E+00
Particulate matter	disease inc.	5.86E-08
Eutrophication, marine	kg N eq	3.46E-03
Eutrophication, freshwater	kg P eq	9.90E-05

Eutrophication, terrestrial	mol N eq	6.06E-02
Human toxicity, cancer	CTUh	1.23E-10
Human toxicity, non-cancer	CTUh	4.59E-09
Ionising radiation	kBq U-235 eq	7.23E-03
Land use	Pt	-2.44E+01
Ozone depletion	kg CFC11 eq	5.48E-09
Photochemical ozone formation	kg NMVOC eq	2.12E-02
Resource use, fossils	MJ	2.16E+00
Resource use, minerals and metals	kg Sb eq	3.55E-06
Water use	m^3 depriv.	1.52E-01

Table 6.11: impact results of 1 kg of field latex from *Hevea b.* plantation.

The Table 6.12 lists the outcomes, as contribution shares to the impacts, of a group analysis conducted, where the group "production of fertilisers" entails the production of the nitrogen, phosphorus, and potassium fertilisers, the group "use of fertilisers" covers the field emissions derived from their application, the group "burning of residues" involves the field emissions due to the burning of the *Hevea b.* residues for subsequent replanting, the group "LUC impacts" includes the transformation and occupation impacts, the group "*Eucalyptus* ssp. logs" considers the avoided production of timber from these species, and the group "other" denotes the contributions of the energy carriers consumption (for tillage, thinning, harvesting operations).

Impact category	**Production of fertilisers**	**Use of fertilisers**	**Glyphosate production**	**Burning of residues**	**LUC impacts**	***Eucalyptus* ssp. logs**	**Other**
Acidification	8.0	32.8	0.8	25.1	33.7	-1.0	0.6
Climate change	14.8	7.5	1.9	12.1	65.7	-3.2	1.2
Ecotoxicity, freshwater	82.5	1.0	11.1	1.1	1.5	-2.2	1.5
Particulate matter	18.1	33.5	1.9	27.6	37.1	-18.9	0.8
Eutrophication, marine	5.3	38.4	0.7	24.1	32.4	-1.9	1.1
Eutrophication, freshwater	49.3	33.5	28.4	0.0	0.0	-13.1	1.9
Eutrophication, terrestrial	4.7	38.1	0.4	24.5	32.9	-1.1	0.6
Human toxicity, cancer	74.8	0.0	39.7	0.0	0.0	-23.0	8.5
Human toxicity, non-cancer	59.8	0.3	6.6	11.5	15.6	-2.2	8.0
Ionising radiation	67.3	0.0	32.0	0.0	0.0	-2.4	3.1
Land use	3.8	0.0	0.4	0.0	0.0	-105.0	0.7
Ozone depletion	44.1	0.0	58.4	0.0	0.0	-5.9	3.4
Photochemical ozone formation	2.7	15.4	0.4	35.4	47.6	-2.1	0.7
Resource use, fossils	90.6	0.0	14.6	0.0	0.0	-12.3	7.1
Resource use, minerals and metals	93.0	0.0	5.0	0.0	0.0	-0.5	2.5
Water use	87.0	0.0	13.1	0.0	0.0	-0.9	0.8

Table 6.12: assessment results for 1 kg field latex at plantation, according to the defined groups, expressed as percentages.

Among the several observations that can be made, these results draw attention to the quite high contributions of the agrochemicals (production and application thereof), to the impacts stemmed from the land use change, which are relevant for different categories, first of all for the climate change one, and to the negative impacts (benefits) obtained from the avoided forest production of logs (modelled in this study as *Eucalyptus* ssp. wood), specifically to the benefit concerning the land use impact category. Therefore, in light of these findings, it is clear that this avoided product is responsible for the great benefit regarding the land use category for the unsmoked sheets and field coagula, and thus for the TSR as a whole, offsetting the other contributors (which carry positive impacts) to that category for the new tyre and retreaded tyre life cycles. It must be stated that the individual assessment results of the avoided production of *Eucalyptus* ssp. wood, and its effects on the analysed systems, are based on the assumptions made in this study (Section 5.1.1.14), in particular to the supported observation that this genus represents the most important industrial wood source in the specific geography considered, i.e., Thailand (Section 3.3.3.3). Moreover, it is worthwhile stressing that the impacts caused by the fertilisation practices (production and use of fertilisers), shown in Table 6.12, may represent underestimates, due to the underlying conservative assumptions about the quantities of fertilisers used (exhaustively discussed in Section 3.3.4). Of note, the assumptions and estimations performed in this study concerning the changes in land use occurred in the specific context analysed (Section 3.5), are also clearly determinant of their corresponding environmental potential impacts.

Chapter 7
Conclusions and future perspectives

This work aims at claiming comparative statements about the environmental performance of two product systems, namely a retreaded truck tyre and a virgin truck tyre, not intended for public disclosure. This is accomplished conducting a comparative Life Cycle Assessment of those two systems, based on primary data, when available, and on secondary data or estimations, as necessary. Both the analysed tyres are primarily made of natural rubber, a critical raw material for the European Union, which is mostly obtained as a non-wood product from *Hevea brasiliensis* plantations located in Southeast Asia. For modelling both the tyres systems, a specific and original Life Cycle Inventory results dataset of natural rubber is developed and used, since the lack of systematic natural rubber models in the literature and in the existing LCA databases. This is the rationale for the thorough literature review conducted concerning the cultivation of *Hevea b.* tree species and the subsequent primary rubber production, specifically focusing on the Thailand context. The model of natural rubber created, which represents a cradle to gate assessment itself, is representative of the technically specified rubber, a peculiar intermediate rubber product used for tyre applications (tyre-grade rubber), and it is based upon several sub-models including all the upstream supply network. The base sub-model being characteristic of the natural rubber (*Hevea b.*) plantation, entailing all the relevant inflows and outflows. In particular, the corresponding field emissions stemming from the on-field application of nitrogen and phosphorus fertilisers are here estimated, along with the emissions due to the burning of *Hevea b.* harvested residual biomass before the subsequent replanting of the plantation. The developed *Hevea b.* plantation model, moreover, covers the direct Land Use Change emissions, estimated according to the related internationally-adopted methodologies and to the latest improvements, as these are found to be relevant for the latex product, and therefore, their impacts must be assessed.

As far as the analysed tyres systems are concerned, the corresponding Product Category Rule (PCR) is employed in this study and the choices and assumptions made on the scope system boundaries of these two systems are selected in order to enhance their comparability, which is of paramount importance when desiring to reach definite comparative claims. These findings can be here summarised stating that the retreaded system (number of retreads considered equal to one) demonstrates environmental benefits accounting for an average of 33 % across all the chosen impact categories. In other words, retreading a worn truck tyre (specifically the type considered in this study), which avoids the use of a new virgin tyre, prevents approximately, and on average, one third of the total environmental impact for each of the impact categories, in a life cycle perspective.

The raw material supply phase, along with a secondary contribution from the manufacturing phase, emerges as the most significant contributor to the impacts associated with the new truck tyre life cycle. The primary factors affecting the impacts of the retreaded system are found to be the life cycle of the virgin tyre and, secondarily, the procurement of raw materials. Of all the required materials, natural rubber proved to be the main source of environmental impacts in both the systems analysed, primarily owing to the plantation establishment and management. It would be interesting to research and comprehend the effects of the main impact sources (agrochemicals and land use change emissions) to the total impact of the natural rubber plantation. In other words, sensitivity analyses will certainly endorse further robustness. In particular, it is in relation to the estimation of the changes in land use (e.g., deforestation), performed in this study, that the development of methods specifically based on different possible scenarios could be of great interest and beneficial for improvements. In the context of this work, the availability of supported and clear data specifically regarding the yields of latex and coagula from Thai plantations, the extent, temporal evolution and characteristics of forests in Thailand (e.g., details on primary forests, corresponding above-ground biomass, dead organic matter etc.), the composition and dynamics of the other land use classes, the dynamics of natural ecosystems, the carbon stocks of specific land use types, and the organic chemicals and energy inputs involved in virgin tyre production, could also enhance the data quality. This, in turn, would provide a basis for improving the estimations here made, or, in some cases, prevent from performing them, and therefore, having access to that information will lead to more accurate final outcomes, since an LCA study is as significant as its inventory. Although this work and its results are deemed as representative and robust, it should be always recognised that, echoing Korzybski’s famous metaphor, the map is not the territory.

Chapter 8
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APPENDIX A

The evaluation of the productivity of *Hevea brasiliensis* plantations in Thailand, in terms of field latex and field coagula outputs, is presented. Impacts derived from the land use change (transformation and occupation impacts) and the emissions linked to the plantation activities (field emissions) are here concisely reported.

A.1 Estimation of fresh latex and field coagulum yields

The average yield of fresh latex for the year 2011 was 1.6 tons per hectare, according to Jawjit et al. (2015) [46]. The yield for the year 2008 accounted for 5.64 tons per hectare [93]. Both the results were obtained from the Office of Agricultural Economics (OAE) of the Thai Ministry of Agriculture and Cooperatives, specifically from the 2012 report and the 2007 report, respectively. Notwithstanding the reliability and the geospatial focus, these data sources have not been completely accessible (partial unavailability), making it arduous to validate the data. It may be important to remark, moreover, that in the OAE report of the year 2017, the only that was accessible, the quantities shown regard the export, not the production. In the other literature examined, the yield value from Jawjit et al. (2015) [46] is used, as the most recent. For these reasons, estimation has been performed and preferred, trying to obtain a recent information. The most recent official statistics regarding the plantation and the harvested areas and the production, are presented by the OAE and related to 2021 [89], while no plantation nor harvested areas for the year 2022 are offered. Thus, the year 2021 is here considered, for which full data availability is ensured.

For estimating the rubber yield(s) the Equation A1 is considered:

$$yield\ [ton/ha] = \frac{total\ upstream\ production\ [ton]}{total\ plantation\ area\ of\ H.brasiliensis\ [ha]} \tag{A1}$$

As denominator of the fraction, the total plantation area has been selected, instead of the total harvested area, since it seems more correct to divide by the plantation area in order to consider the whole area dedicated to rubber trees. It is deduced from Warren-Thomas et al. [44, supplementary material] that the calculation of the yield per hectare in case of steady state management (i.e., when the extent of plantations in the establishment phase is lower than the total amount of plantations) should be based on the total plantation area. Considering the Thailand specific case and the information about the extents of plantation and harvested areas reported in Tables 3.5, 3.8, and 3.9

(that is, productive/harvested area is lower than the planted one), it is correct to assume a steady state management situation as the status quo, therefore validating the fact that the yield calculation is based on the plantation area, not the harvested nor an adjusted harvested area.

Hevea b. plantation area in 2021

In 2021, the overall Thai rubber plantation area was 24,466,804 million rai, while the harvested area was 21,975,567 million rai [89]. Therefore, since 1 rai = 1600 m^2 = 0.16 ha, conversion from rai to hectare gives: plantation area of 3,914,689 ha and harvested area of 3,516,091 ha. Note that the overall Thai land area is 51,089,000 ha [122]. The result concerning the plantation area (i.e., 3,914,689 ha) has been used in the following estimation. As we can appreciate, the two areas are not the same, this is due to the specific agriculture of the *Hevea b.* rubber tree: young trees do not give latex (are not tapped) and thus, it is reasonable that the harvested area is lower than the plantation area.

To further validate the figure related to the year 2021, it is possible to note that:

- according to Jawjit et al. (2010) [93] the total plantation area was 2.46 million ha, but no direct reference to the year is reported, while the word “current” is used in the text; it is here supposed that it was related to 2009;
- following Petsri et al. (2013) [79] the total plantation area in the year 2010 was 2.87 million ha;
- according to Musikavong and Gheewala (article available online 26/07/2016) the plantation area was 2.95 million ha in the year 2011, and 3.55 million ha in the year 2013.
- the FAO FRA 2020 [122] reports a rubber plantation area of 3,537,000 ha in the year 2020.

Hence, considering the increasing trend occurred, the plantation area value for the year 2021 of 3.914 million ha is highly reasonable and valid (after all, it represents an official statistic from the OAE, so it should be reliable as it is).

Upstream production in 2021

Few data precisely about the (Thai) fresh latex production are found in literature, and none related to a year as recent as the 2021. Information on the field coagulum yield is even more scarce. Considering the annual variability of the plantation area and especially that of the harvested area (trees reaching maturity, ready for tapping – productive stage), it was decided here not to use proxies. Furthermore, since the denominator pertains to 2021, it was decided to estimate the numerator, which represents the raw material for rubber, bio-synthesised and collected in 2021, and this was attained by leveraging information sourced from a Thai-official report (i.e., [48]), thus promoting consistency. In particular, an estimation can be obtained starting from the information about the primary rubber products and going backwards, exploiting the raw materials to primary rubber products' ratios considered in the Section 3.4.2, some of which are themselves estimates. Note that the expression "upstream production" (UP) is used to denote the harvested material, whether in the form of fresh latex and/or coagulum, depending on the cases.

The assumptions performed for the estimation are:

i. in 2021, the Thai intermediate rubber production accounted for: 1,150,222 metric tons of concentrated latex (DRC); 1,907,781 metric tons of block rubber; 678,288 metric tons of RSS; 1,252,423 metric tons of compound rubber and 180,138 metric tons of 'other types' (mainly air dried rubber, skim rubber, crepe rubber, USS) [48]. Note that concentrated latex is given in dry rubber content (DRC);
ii. the mass ratios between the upstream production (UP) necessary to manufacture those intermediate rubber products and the intermediate products themselves, are depicted by the ratios specified in Section 3.4.2 (recall that compound rubber is assumed as TSR, and also that, since the block rubber export is mainly as STR 20, block rubber type is assumed all as this grade);
iii. the contribution to the overall intermediate rubber production due to 'other types' of primary rubber products, which accounts for 3.5% of the total, is neglected;
iv. for the year 2021, the quantity of co-product field coagulum collected amounts to the 8 wt.% of the total UP, in Thailand [117] (note that this cited value is from the RRIT, according to the quoted source, so it is highly reliable).

Therefore, from the first and second assumptions, it is possible to obtain:

- 1,150,222 tons concentrated latex (in DRC) *(2/0.6) = 3,834,073 tons of UP (i.e., fresh latex in this case);
- 1,907,781 tons TSR *2 = 3,815,562 tons of UP (i.e., fresh latex + cup lump in this case);
- 678,288 tons RSS *3.3 = 2,238,350 tons of UP (i.e., fresh latex in this case);
- 1,252,423 tons compound rubber * 0.8 = 1,001,938 tons of NR as TSR → 1,001,938 tons TSR *2 = 2,003,877 tons of UP (i.e., fresh latex + cup lump in this case).

Then, summing these contributions (and according to the third assumption), the total UP (fresh latex and cup lump) for the year 2021 results: 11,891,863 tons of UP.

Considering the fourth assumption, the 92 % of the total UP will be in the form of fresh latex, while the remainder as field coagulum:

- 11,891,863 tons UP – (11,891,863 tons *0.08) = 11,891,863 tons UP – 951,349 tons field coagulum = 10,940,514 tons fresh latex.

Finally, this means that the two yields per hectare can be identified as:

- fresh latex yield per hectare (year 2021) = 10,940,514 tons fresh latex / 3,914,689 ha of plantation area = 2.795 tons/ha;
- field coagulum yield per hectare (year 2021) = 951,349 tons field coagulum/ 3,914,689 ha of plantation area = 0.243 tons/ha.

Equivalently, it is possible to divide the total production by the total plantation area obtaining 3,038 kg/ha and then obtaining its 92% representing fresh latex yield and its 8% that of cup lump.

A.2 Hevea *b.* biomass output (co-product)

Considering the dry mass of a 25 year old *Hevea brasiliensis* tree as equal to 612.9 kg, that can be deduced from [79], the plantation density of 440 trees per hectare assumed in this study, and the organs mass fractions directly sourced from [80] (shown in Table A1), it is possible to derive the corresponding mass values for the 25 year old tree, as shown in Table A2, then, the mass values for one hectare of plantation at the end of its cycle, in Table A3, and finally the total mass of rubber wood for the wood industry along with the total mass of residues destined to be burnt. All values are expressed in dry matter.

Components	Share of total mass
stumps+roots	14.38 %
branches	10.41 %
leaves	1.25 %
stem	73.97 %

Table A1: mass ratios of tree organs, deduced from [80].

Mass of components	
0.0881	ton (stumps+roots)/tree 25y
0.0638	ton (branches)/tree 25y
0.0076	ton (leaves)/tree 25y
0.4533	ton (stem)/tree 25y

Table A2: mass of the components for a 25 year old rubber tree in Thailand.

Mass per hectare (considering density of 440 trees/ha)	
269.677	ton dry matter/ha
of which	
38.7785	ton (stumps+roots)/ha
28.072	ton (branches)/ha
3.36174	ton (leaves)/ha
199.473	ton (stem)/ha

Table A3: mass values for one hectare of Thai rubber plantation at its end of life, considering 440 trees per ha as tree density.

Therefore, the total mass of *Hevea b.* wood is about 199.47 ton per hectare (the mass of the stems per hectare). The total mass of residues (stumps, roots, branches, and foliage) for burning is obtained equal to approximately 70.21 ton per hectare.

A.3 Transformation impacts

A.3.1 Burning of the 20 % of the Above-ground biomass

This section refers to the first assumption of Section 3.5.3.6, i.e., the incineration of the twenty percent of the above-ground biomass in the transformed forest land. With reference to Sections 3.5.3.1 and 3.5.3.6, the naturally regenerating forest area converted amounts to 32,151 ha/y and the carbon contained in 20 % of the AGB results to be 47 ton/ha. Tables A4 and A5 exhibit the results of the estimation performed in this study.

Emission	**Quantity**	**Unit**
Mass C emitted	4.23E+01	ton C/ha
total CO_2 emitted	1.55E+02	ton CO_2/ha
of which		
Input CO_2 from CH_4	1.74E+00	ton CO_2/ha
Input CO_2 from CO	1.53E+01	ton CO_2/ha
Input CO_2 from NMVOC	2.77E+00	ton CO_2/ha
that finally oxidize to CO_2*; hence, the* CO_2 *direct emission is*		
CO_2 'immediately released' (i.e., directly)	1.35E+02	ton CO_2/ha

Table A4: carbon emissions due to the burning of 20 % of the forest AGB, considering the previously calculated forest area converted.

Pollutant	**Emission ratio**	**Unit of emiss. ratio**	**Emission**	**Unit**
CO *	230	g/kg C emitted as CO_2	9.73E+00	ton CO/ha
CH_4 *	15	g/kg C emitted as CO_2	6.35E-01	ton CH_4/ha
NMVOC *	21	g/kg C emitted as CO_2	8.88E-01	ton NMVOC/ha
NO_X [a]	8	g/kg C emitted as CO_2	3.35E-01	ton NO_X/ha
NH_3 [a]	1.8	g/kg C emitted as CO_2	7.54E-02	ton NH_3/ha

N_2O d	0.4	g/kg C emitted as CO_2	1.69E-02	ton N_2O/ha
SO_X	1.6	g/kg C emitted as CO_2	6.77E-02	ton SO_X/ha

Table A5: '*' means that the quantity reported is the total quantity emitted, before the final oxidation of CO, CH_4, and NMVOC emissions (these inputs to CO_2 emissions are reported in Table A4; 'a' denotes emissions of ammonia and nitrogen oxides net of atmospheric deposition; 'd' indicates direct emissions.

A fraction of the emitted NO_X and a fraction of the emitted NH_3, namely the 1 % (i.e., the emission factor EF4, that takes into account the atmospheric deposition of N from NO_X and NH_3 emissions) lead to indirect emissions of nitrous oxide, as exhibited in Table A6.

	Quantity	Unit
EF4	0.01	kg N_2O-N/kg NH_3-N or NO_X-N emitted
NO_X-N	1.03E-01	ton NO_X-N/ha
NH_3-N	6.27E-02	ton NH_3-N/ha
N_2O (indirect)	2.60E-03	ton N_2O/ha

Table A6: indirect nitrous oxide emissions due to burning of 20 % of the forest AGB.

Therefore, the total N_2O emissions (direct and indirect) result to be 1.95E-02 ton per hectare. It should be noted that all the emitted values here reported refer to that precise naturally regenerating forest land area converted each year of the considered period 2000 – 2020.

A.4 Occupation impacts

A.4.1 Change in carbon in mineral soils

This section refers to the point (**a**) of Section 3.5.3.7, i.e., the change of organic carbon in mineral soils. Following the tier 2 approach proposed in [104], the change in soil carbon stock amounts to -17 ton soil C per hectare, which, considering the annual naturally regenerating forest area converted of 32,151 ha/y, leads to the result that $5.466 \cdot 10^5$ ton of soil carbon were lost for each year in the reference timespan. Equivalently, the loss of SOC accounts to $8.097 \cdot 10^2$ kg C per hectare of forest land converted and per year (in the time period analysed); which means $2.969 \cdot 10^3$ kg CO_2/(ha*y).

The nitrous oxide emissions due to mineralised nitrogen as a result of soil carbon loss caused by land use change are estimated with IPCC tier 1 method [104], considering the updates in the 2019 Refinement [146] when present. The annual nitrogen mineralised results to be 53.98 kg N/(ha*y) and the corresponding N_2O emissions stem from a direct route and two indirect routes (volatilisation and leaching/run-off). The direct N_2O emissions (due to N mineralised only) results to be 0.85 kg N_2O/(ha*y); the fraction of leached N that remains (mainly) in the form of NO_3^- into soil and water is equal to 56.73 kg NO_3^-/(ha*y); the indirect N_2O emissions derived from the N leaching/runoff are 0.22 kg N_2O/(ha*y).

Note that all these emissions are here reported per hectare of forest land converted and per year of the selected time period (i.e., 2000 – 2020). Moreover, it is important to state that calculations regarding this source of nitrogen-related emissions, i.e., the nitrogen mineralisation correlated to the soil organic carbon loss, are performed separately to the ones concerning the nitrogen fertilisation, and double counting is avoided.

A.4.2 Accumulation of carbon in Above-ground biomass

This section refers to the point (**c**) of Section 3.5.3.7, i.e., the increase of carbon in living biomass on the new land use that is not harvested. The accumulation of biomass C following the transformation of cropland area into rubber plantation area equals 86.89 ton carbon per hectare. As a result, this gain (of carbon from the atmosphere), leads to obtain 4.14 ton C/(ha*y), which considers the cropland area converted per year (i.e., 41,666 ha per y; Section 3.5.3.1).

A.5 Field emissions

A.5.1 Application of nitrogen fertiliser

The use of nitrogen fertiliser leads to nitrous oxide direct emissions into air, presented in Table A7, nitrous oxide indirect emissions into air, shown in Table A8, ammonia emissions into air, nitrogen oxides emissions into air, and nitrate emissions into the ground and/or water surfaces. In those Tables: EF_1 refers to the nitrous oxide emission factor considering nitrogen additions; FSN stands for the quantity of inorganic fertiliser used; EF_4 denotes the nitrous oxide emission factor from the nitrogen atmospheric deposition; $Frac_{GASF}$ refers to the volatilised fraction of N fertiliser; EF_5 represents the nitrous oxide emission factor from the leached/runoff nitrogen; and $Frac_{LEACH}$ indicates the part of the provided nitrogen lost due to leaching/runoff.

Direct N_2O emissions		
EF_1	1.00E-02	kg N_2O–N / (kg N input)
FSN	7.00E+01	kg N/(ha*y)
N_2O_{direct} – N	7.00E-01	kg N_2O–N/(ha*y)
N_2O_{direct}	**1.10E+00**	**kg N_2O/(ha*y)**

Table A7: direct nitrous oxide emissions due to the application of N fertiliser.

Indirect N_2O					
EF_4	1.00E-02	kg N–N_2O / (kg NH_3–N + NO_X–N volatilised)	EF_5	1.10E-02	kg N_2O–N / (kg N leached and runoff)
$Frac_{GASF}$	1.10E-01	kg N volatilised / (kg of N applied)	$Frac_{LEACH}$	2.40E-01	kg N / (kg of N additions)
$N_2O_{(ATD)}$–N	7.70E-02	kg N_2O–N/(ha*y)	$N_2O_{(L)}$–N	1.85E-01	kg N_2O–N/(ha*y)
$N_2O_{(ATD)}$	**1.21E-01**	kg N_2O/(ha*y)	**$N_2O_{(L)}$**	**2.90E-01**	kg N_2O/(ha*y)

Table A8: indirect nitrous oxide emissions through the atmospheric deposition (ATD) of volatilised N and through the leaching/runoff (L) of added nitrogen, stemming from the application of N fertiliser.

Therefore, the total nitrous oxide emissions result to be 1.51 kg N_2O/(ha*y).

The fraction of volatilised NH_3 not converted into N_2O (99 %) remains as NH_3 and thus, the ammonia emitted (net of atmospheric deposition) amounts to 3.37 kg NH_3/(ha*y). The fraction of volatilised NO_X not converted into N_2O (99 %) remains as NO_X and thus, the nitrogen oxides emitted (net of atmospheric deposition) amount to 15.9 kg NO_X/(ha*y).

The leached fraction of N in several forms (mainly NO_3^-), which does not convert into N_2O (98.9 %), is therefore assumed to remain into the ground/water surfaces, and accounts to 73.6 kg NO_3^- /(ha*y).

A.5.2 Application of phosphorus fertiliser

The application of phosphorus fertiliser implies the leaching of phosphate to groundwater (Table A9), the runoff of phosphate to surface water (Table A10), and the emissions of phosphorus to surface water due to erosion (Table A11). The input data required for the calculation are sourced from the cited methodology (Section 3.6.1.1; which is Swiss-focused), except where otherwise specified. The rationale for these (few) exceptions lies in the availability of country-specific information or in its ease of estimation, in order to improve the overall accuracy and representativeness of the results.

In Table A9: P_{gwl} is the average P leached to groundwater for a specific land use type and among the default values available in the model used, the value for “forest unproductive vegetation” is selected as the most suitable; P_{gw} indicates the amount of phosphorus leached to groundwater, obtained correcting the average quantity by a specific factor, which in the analysed case resulted to be unitary.

Soluble phosphate leaching to ground water		
P_{gwl}	5.00E-02	kg P/(ha*y)
P_{gw}	5.00E-02	kg P/(ha*y)
Phosphate leached	1.53E-01	kg PO_4^{3-}/(ha*y)

Table A9: phosphate leached to ground water.

In Table A10: P_{rol} refers to the mean phosphorus loss to surface waters due to runoff for a specific land use type and its value is here taken as the one referring to “forest unproductive vegetation”, among the other alternatives; $P_2O_{5,min\text{-}fert}$ stands for the P_2O_5 content in the mineral fertilisers used; F_{ro} is a correction factor that in the analysed situation resulted to be as reported; P_{ro} represents the phosphorus loss to surface waters due to runoff.

Soluble phosphate runoff to surface water		
P_{rol}	1.00E-01	kg P/(ha*y)
$P_2O_{5,min\text{-}fert}$	3.50E+01	kg P_2O_5/(ha*y)
F_{ro}	1.09E+00	kg/(ha*y)
P_{ro}	1.09E-01	kg P/(ha*y)
Phosphate runoff	3.33E-01	kg PO_4^{3-}/(ha*y)

Table A10: phosphate lost due to runoff, towards surface waters.

In Table A11: S_{er} indicates the mass of eroded soil and, since the availability (scarce but sufficient) of Thai-specific data about rubber plantation soil erosion at a general-regional scale, it is taken from [193]; P_{cs} represents the concentration of phosphorus in the soil, and it is taken from the Thai-specific literature, as later clarified; F_r is the enrichment factor (dimensionless); F_{erw} considers the part of eroded soil reaching the surface waters (dimensionless); P_{er} stands for the resulting emitted P to surface waters.

P loss via erosion to surface water		
S_{er}	1.00E+03	kg soil/(ha*y)
P_{cs}	5.00E-06	kg P/kg soil
F_r	1.86E+00	-
F_{erw}	2.00E-01	-
P_{er}	1.86E-03	kg P/(ha*y)

Table A11: phosphorus loss to surface waters caused by soil erosion.

Note that to consider the P content in Thai rubber plantation soils is required due to the far dissimilar conditions of Thai soils with respect to the soils for which the methodology was developed (Swiss soils).

Soil available P

Mainly, soils of the Ultisol and Oxisol orders (U.S. Soil Taxonomy classification) spread onto Thailand area, which are acid soils characterised by low available phosphorus, high exchangeable Al and Mn, low pH, low organic substance, and other constraints to crop productivity [194]. Indeed, fertilisation is necessary due to the low available P, since phosphorus is fixed in complex mineral phosphates [195]. According to FAO – UNESCO [196] Thailand is covered generally by soils belonging to the Acrisol soil group (FAO nomenclature), that are acid (and taxonomically related to the Oxisol type). A rough estimate of the soil phosphorus status in Thai soils is here attained on the basis of the reliable information retrieved from the FAO “Soil map of the world” [196], from the International Atomic Energy Agency (IAEA) [194, 195], and from the country-specific study of [111]. Figure A1 shows the soil regions for Thailand with the FAO classification/nomeclature [196].

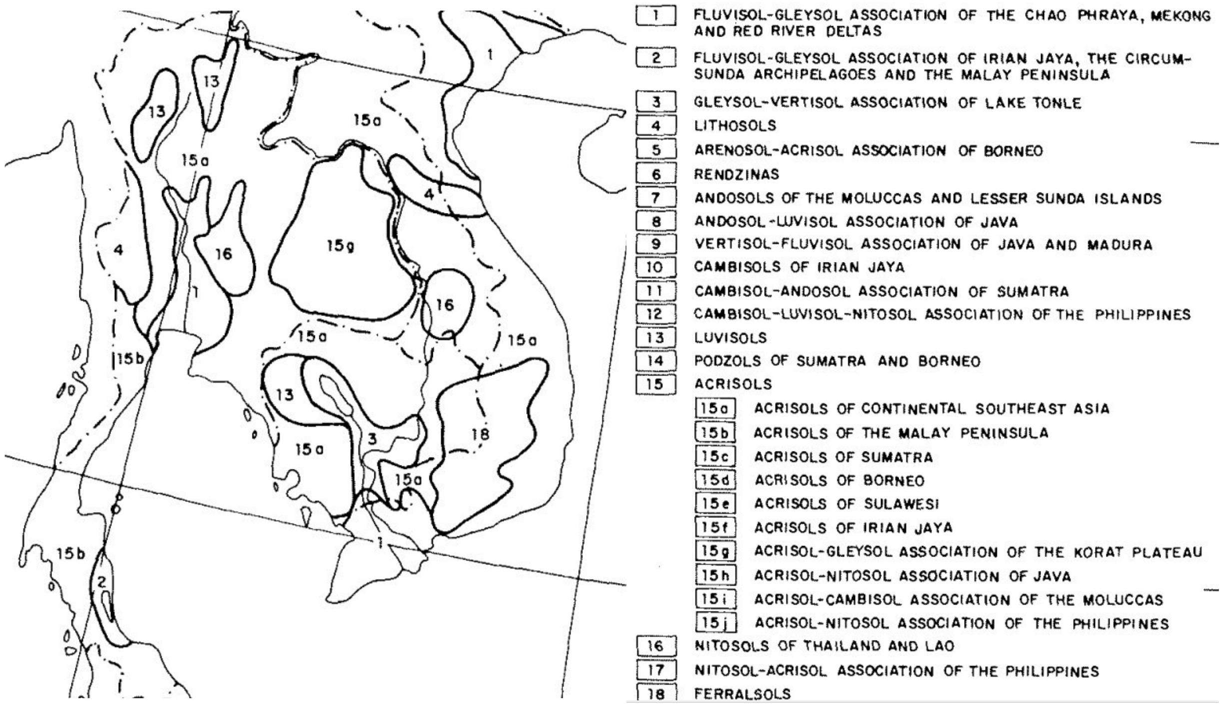

Figure A1: Thai soil map and soil legend, from [196].

Data analysed in [196] were obtained with Bray I or II methods, of which: P content in Acrisol sites (orthic Acrisol and gleyic Acrisol) is near 17 ppm P for a depth of 0 – 30 cm; data for four sites exhibiting other kinds of soil type (cambic Arenosol, dystric Nitosol, thionic Fluvisol, eutric Cambisol) are in line with the previous content; while four sites (of the groups orthic Luvisol, calcic Luvisol, calcaric Fluvisol, calcic Cambisol) present slightly higher amounts of available P, in the range 20 – 80 ppm in the 0 – 50 cm layer. Notwithstanding the lack of quantitative shares of the total country land area or other useful information, from the Figure A1 it is possible to affirm that these soil groups represent a small percentage of the overall land. Similar soil P concentrations in the ranges 5 – 24 ppm and 12 – 46 ppm, are reported for Thailand [111]. The IAEA [194, 195], analysed four reference sites located one in the north, two in the central region, and one in the south part of the country, for which an average of approximately 6 ppm can be obtained, but with no reference to the soils depths. Due to conservative reasons, in this study a first level estimate of 5 ppm of P available in the topsoil (0 – 30 cm) is deemed as sufficiently valid for the purpose and used, even if brings evident limitations. Therefore, the factor P_{cs} used in Table A11 is 5 ppm, equivalent to 5 mg P/kg soil and to $5 \cdot 10^{-6}$ kg P/kg soil.

As a check for the implications of the choice made about this single factor, it is enough to consider that the default average value suggested by the methodology, specific for Swiss soils, is 950 ppm (0.00095 kg P/kg soil) [160, 162]. Therefore, it is far higher than the one here used; this sounds reasonable since Thai soils exhibit less P content. Therefore, it is possible to state, as far as this specific factor is concerned (P_{cs}), that overestimation is avoided due to the use of country-specific estimate. It is important to mark, however, that this estimate represent the lower limit of the aforementioned literature ranges, for the conservative principle. Hence, a possible but slight underestimation of the P loss through erosion may have been made.

A.5.3 Burning biomass residues due to replanting

Tables A12 and A13 show the emissions of pollutants stemmed from the burning of above-ground residues and roots before the next replanting, considering the assumed annual average area burnt of 11,455 hectares per year (see Section 3.6.2). Calculations are performed in compliance with the EMEP/EEA Guidebook 2019 [156] and the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [159]. Double counting is correctly avoided.

Emission	**Quantity**	**Unit**
Mass C emitted	3.60E+05	ton C/y
total CO_2 emitted	1.32E+06	ton CO_2/y
of which		
input CO_2 from CH_4	1.49E+04	ton CO_2/y
input CO_2 from CO	1.30E+05	ton CO_2/y
inputCO_2 from NMVOC	2.36E+04	ton CO_2/y
that finally oxidize to CO_2*; hence, the* CO_2 *direct emission is*		
CO_2 'immediately released' (i.e., directly)	1.15E+06	ton CO_2/y

Table A12: carbon emissions due to the burning of residues for end-of-life/replanting.

Pollutant	**Emission ratio**	**Unit of emiss. ratio**	**Emission**	**Unit**
CO *	230	g/kg C emitted as CO_2	8.29E+04	ton CO/y
CH_4 *	15	g/kg C emitted as CO_2	5.41E+03	ton CH_4/y
NMVOC *	21	g/kg C emitted as CO_2	7.57E+03	ton NMVOC/y
NO_X *	8	g/kg C emitted as CO_2	2.88E+03	ton NO_X/y
NH_3 *	1.8	g/kg C emitted as CO_2	6.49E+02	ton NH_3/y
N_2O [d]	0.4	g/kg C emitted as CO_2	1.44E+02	ton N_2O/y
SO_X	1.6	g/kg C emitted as CO_2	5.77E+02	ton SO_X/y
Pollutant	**Emission factor**	**Unit of emiss. factor**	**Emissions**	**Unit**
TSP	17	g/kg wood burnt	1.37E+04	ton TSP/y
PM10	11	g/kg wood burnt	8.85E+03	ton PM10/y
PM2.5	9	g/kg wood burnt	7.24E+03	ton PM2.5/y
BC	9	% of PM2.5	6.51E+02	ton BC/y

Table A13: '*' indicates that the quantity reported is the total quantity emitted, before (i) the atmospheric deposition of nitrogen from the NO_X and NH_3 emissions, and before (ii) the final oxidation of CO, CH_4, and NMVOC emissions (these inputs to CO_2 emissions are reported in Table A12); 'd' means direct emissions.

A fraction of the emitted NO_X and a fraction of the emitted NH_3, namely the 1 % (i.e., the emission factor EF4, that takes into account the atmospheric deposition of N from NO_X and NH_3 emissions) lead to indirect emissions of nitrous oxide, as exhibited in Table A14.

	Quantity	**Unit**
EF4	0.01	kg N_2O-N/kg NH_3-N or NO_X-N emitted
NO_X-N	8.78E+02	ton NO_X-N/y
NH_3-N	5.34E+02	ton NH_3-N/y
N_2O (indirect)	2.22E+01	ton N_2O/y

Table A14: indirect nitrous oxide emissions due to biomass burning.

Therefore, the total N_2O emissions (direct and indirect) result to be 166 ton per year. It should be noted that the emitted values here reported refer to the annual burning of that precise amount of area, which is the area that must be replanted, since the related *Hevea b.* plantation is at its end of productive life (25 year old rubber trees).

A.6 Partitioning

A.6.1 Natural rubber plantation

With reference to Section 5.1 and to the NR plantation products, the economic partitioning is performed using the factors taken from the literature and shown in Table A15.

Product	Economic allocation factor
fresh latex	0.57
field coagulum	0.15
Hevea wood	0.26
Hevea seeds	0.02

Table A15: economic allocation factors, sourced from [97].

A.6.2 STR 20 manufacturing

With reference to Section 5.1, the economic allocation is made, estimating the required factors for the products STR 20 and scrap rubber, which represent the main product and the by-product of the STR 20 production, respectively.

Price statistics can be retrieved from Thai official sources, for instance from the latest Thailand Rubber Statistics (2023) [48], which shows information for the decade 2013 – 2023. In this document, the prices, specifically free on board (F.O.B) prices, of rubber by types are present, but while STR 20 prices are presented, no prices for scrap rubber (a low-value rubber, by-product of low importance) are reported. In particular, due to the characteristics of this by-product, there is a lack of information about its prices/market. In the following, thus, scrap rubber is assumed as equal to field coagulum (i.e., cup lump) in order to have statistics on prices; in other words, cup lump is here selected as proxy for scrap rubber. The Thai Rubber Association [197] is here employed as the source for the cup lump prices (in particular as local price of Thai market, i.e., daily rubber price in Baht), while information about STR 20 prices has been retrieved from the Rubber Research Institute of Thailand (RRIT, now RAOT) [198] (in the form of weekly average F.O.B prices for Bangkok port, already reported in US Dollar). Both sources are characterised by high reliability, nonetheless, it is worth noting that consistency could be further enhanced if it were feasible to access a single source for evaluating both STR 20 and scrap rubber prices. As far as allocation is concerned, it is judged fair to consider the prices related to the year 2021 only, for both the products for the sake of simplicity. A value averaged over several years, or over the reference period (clarified in Table 5.1 in Section 5.1), would adjust price fluctuations that occur over the time, solving problems which could potentially arise using this kind of allocation strategy; though, in this specific case no potential problems have been identified at a first glance. Moreover, the availability of data is pivotal. Concerning STR 20, prices for the period 2009 – 2021 are available, while for cup lump only prices covering the period 2017 – 2021 are accessible. The average price of STR 20 for the period 2009 – 2021 is approximately 1.83 EUR/kg, thus higher than the one here assumed. Regarding cup lump prices, from the accessed data it is possible to state that the mean over those years slightly differs from the mean here assumed. However, since allocation is performed, the calculated results (i.e., allocation factors) are not affected in praxis. For instance, even in the case where the cup lump average (for a long time period) price reaches a value lower than 1 EUR/kg, the related allocation factor would change by a relatively small amount, in the order of cents or thousandths of a unit. Additionally, it can be said that, in Musikavong and Gheewala [96, supplementary material] a scrap rubber price of 934 USD/ton for the year 2014 is reported and was taken from the Rubber Authority of Thailand (that, however, was not accessible for consultation).

Standard Thai Rubber grade 20 (STR 20)

The average price (Bangkok) STR 20 for 2021 is 1.679 USD/kg STR 20. For the conversion in Euro, the exchange reference rate derived from the European Central Bank [199] is used: average change of the year 2021 = 1.18; that means 1 EUR = 1.18 USD. Table A16 shows the weekly average F.O.B physical prices of STR 20 rubber type, for the whole year 2021.

Day/Weekend (WE)	**Bangkok STR20 [USD/100kg]**
Average for WE 8 Jan 2021	157.02
Average for WE 15 Jan 2021	158.00
Average for WE 22 Jan 2021	161.43
Average for WE 29 Jan 2021	157.21

Average for WE 5 Feb 2021	159.93
Average for WE 12 Feb 2021	162.92
Average for WE 19 Feb 2021	166.40
Average for WE 26 Feb 2021	175.87
Average for WE 5 Mar 2021	172.02
Average for WE 12 Mar 2021	175.68
Average for WE 19 Mar 2021	180.43
Average for WE 26 Mar 2021	176.11
Average for WE 2 Apr 2021	169.01
Average for WE 9 Apr 2021	169.48
Average for WE 16 Apr 2021	163.71
Average for WE 23 Apr 2021	163.04
Average for WE 30 April 2021	167.78
Average for WE 7 May 2021	172.76
Average for WE 14 May 2021	174.45
Average for WE 21 May 2021	167.87
Average for WE 28 May 2021	172.07
Average for WE 4 June 2021	168.55
Average for WE 11 June 2021	167.27
Average for WE 18 June 2021	162.11
Average for WE 25 June 2021	161.17
Average for WE 2 Jul 2021	161.33
Average for WE 9 Jul 2021	158.58
Average for WE 16 Jul 2021	160.14
Average for WE 23 Jul 2021	161.14
Average for WE 30 Jul 2021	166.50
Average for WE 6 Aug 2021	167.50
Average for WE 13 Aug 2021	171.88
Average for WE 20 Aug 2021	175.43
Average for WE 27 Aug 2021	172.85
Average for WE 3 Sep 2021	165.29
Average for WE 10 Sep 2021	163.48
Average for WE 17 Sep 2021	164.65
Average for WE 24 Sep 2021	161.12
Average for WE 1 Oct 2021	162.74
Average for WE 8 Oct 2021	166.30
Average for WE 15 Oct 2021	173.61
Average for WE 22 Oct 2021	174.23
Average for WE 29 Oct 2021	175.07
Average for WE 5 Nov 2021	172.7
Average for WE 12 Nov 2021	171.14
Average for WE 19 Nov 2021	176.37
Average for WE 26 Nov 2021	179.46
Average for WE 3 Dec 2021	175.35

Year Average	**167.90**

Table A16: average prices for STR 20, sourced from [198].

Therefore, as average price of one kg of STR 20, a value of 1.423 EUR is obtained, with regard to 2021.

Scrap rubber (by-product)

Field coagulum prices are used as proxy for scrap rubber prices. For the conversion of Thai Baht (THB) in Euro (EUR) the exchange reference rate derived from the European Central Bank [200] is used: average change of the year 2021 = 37.837 ; that means 1 EUR = 37.837 THB. Table A17 presents the Thai cup lump prices for the whole year 2021.

Date	Price cup lump Thailand	Unit	EURO/kg
15/01/2021	48	Baht/kg	1.2686
15/02/2021	41	Baht/kg	1.083595
15/03/2021	47	Baht/kg	1.24217
16/04/2021	43	Baht/kg	1.136454
14/05/2021	45	Baht/kg	1.189312
15/06/2021	43	Baht/kg	1.136454
15/07/2021	43	Baht/kg	1.136454
16/08/2021	49	Baht/kg	1.295029
15/09/2021	47	Baht/kg	1.24217
15/10/2021	48	Baht/kg	1.2686
15/11/2021	47.5	Baht/kg	1.255385
15/12/2021	46	Baht/kg	1.215741
Average	**45.625**	**Baht/kg**	**1.20583**

Table A17: cup lump prices in Thailand, data from [197].

Hence, as average price of one kg of scrap rubber, a value of 1.20583 EUR is considered, with regard to 2021.

Partitioning factors

In praxis, the economic partitioning factors (or allocation factors) are obtained employing the Equation A2 [201]:

$$EAF_i = \frac{Q_i \cdot P_i}{\sum_{i=1}^{n} Q_i \cdot P_i} \tag{A2}$$

in which, EAF_i represents the economic allocation factor of product i-th; Q_i is the quantity of the product i-th; P_i means the price of the product i-th.

Table A18 exhibit the resulting economic allocation factors for the two products.

Product	**Economic allocation factor**
STR 20	0.98
Scrap rubber	0.02

Table A18: economic allocation factors regarding STR 20 and scrap rubber, obtained and used in this study.

□