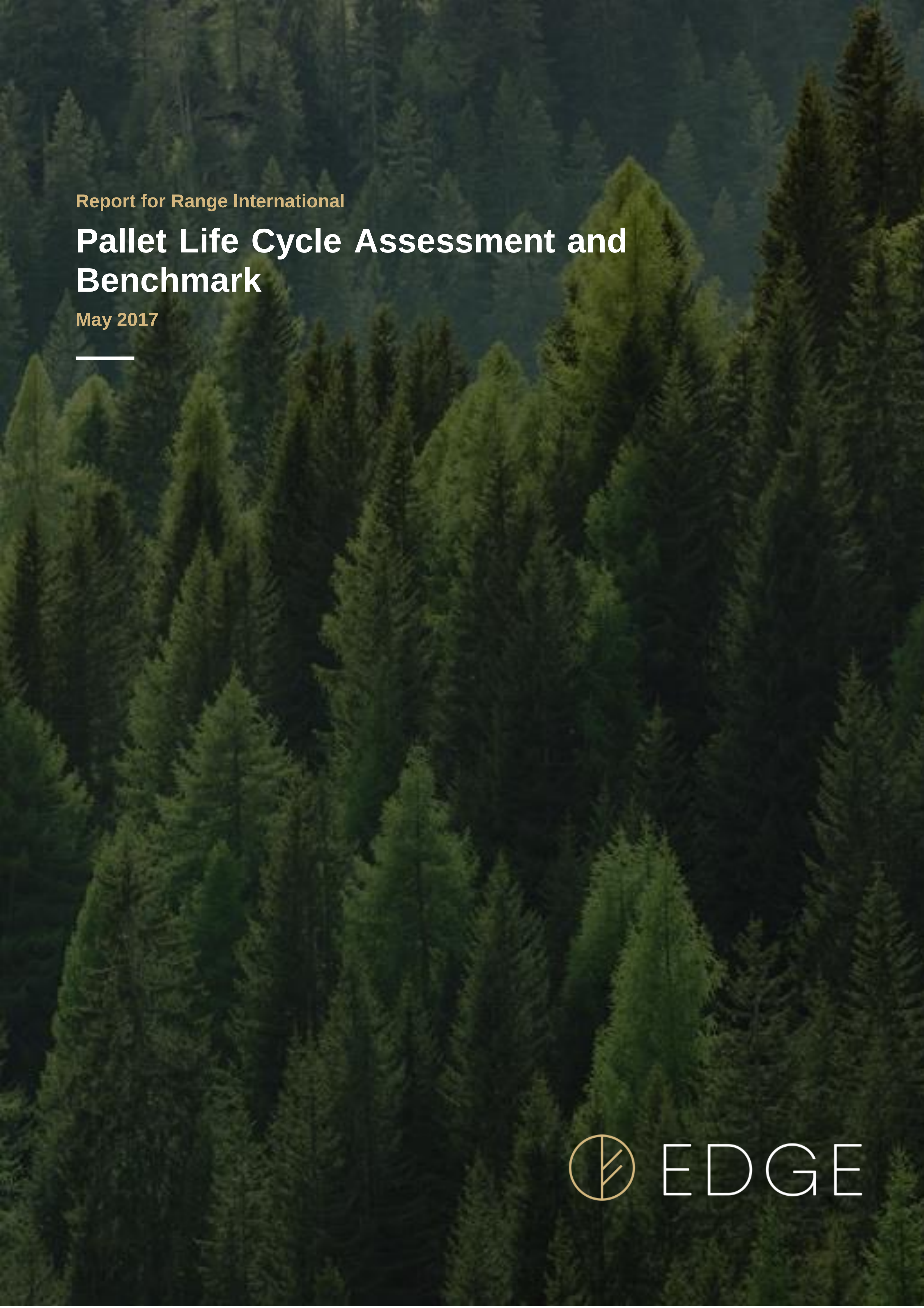
Report for Range International

Pallet Life Cycle Assessment and Benchmark

May 2017



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Revision	Revision Details	Author	Reviewed by	Approved by
Draft 1	2 March 2017	Dr Joana Almeida, Jonas Bengtsson	Jonas Bengtsson, Dr Joely Taylor	Jonas Bengtsson
Draft 2	3 April 2017	Dr Joana Almeida, Jonas Bengtsson	Kendall Reid, Lars Amstrup	Jonas Bengtsson
Draft 3	12 May 2017	Dr Joana Almeida, Jonas Bengtsson	Prof. Wouter Achten	Jonas Bengtsson

Executive Summary

Range International (RI) is a company that manufactures plastic products from waste plastic sources, using a unique production technology, ThermoFusionTM. Range International's product range includes Re>Pal pallets made from 100% recycled plastic waste.

Pallets can be manufactured from a variety of materials, including wood, metal, plastic (including from both virgin and recycled polymers) and cardboard. Each material has its advantages and disadvantages

Questions remain, however, over the environmental performance of Re>Pal, compared with conventional wood and plastic pallets that are used for the same applications as Re>Pal. Range International's major clients are sensitive to the issue, and often have sustainability strategies and targets where logistics and pallets play a part.

Range International commissioned Edge Environment (Edge) to compare the environmental credentials of various pallet options using ISO 14040 and 14044 compliant life cycle assessment (LCA). The study quantifies and compares the cradle-to-grave impacts (raw materials, transport, manufacture, customer use and end of life disposal) for Re>Pal and for comparable conventional wood and plastic pallets. The study was conducted for pallet manufacturing in Indonesia or Australia.

To compare the environmental impacts of different pallet systems, we needed a single reference unit. In this study, the reference unit is 1 trip.

An in-depth analysis of the environmental impact was conducted using key indicators: carbon emissions, energy use, waste output and timber resource use. Additional indicators reported on are acidification, eutrophication, fossil fuel depletion, land occupation, human health and ecosystem damage.

Environmental impact results

- At the factory gate, Re>Pal pallets have a lower carbon footprint than timber and plastic pallets, with the exception of softwood pallets from certified timber (typical for Australia).
- Re>Pal uses less energy for manufacture than other pallet types, and has the lowest embodied impact raw material feedstock.
- When use and durability are taken into account, Re>Pal surpasses conventional pallets in all assessed environmental indicators due to their lower replacement requirements, lighter weight and lower emission intensity of production (see Figure 1 for carbon footprint specifically).
- Re>Pal pallets are almost waste neutral; they use almost as much waste during manufacture as the waste that is produced throughout their life cycle, including transport and end of life (EOL) disposal.
- Although the results are sensitive to the nature of the supply chain, Re>Pal pallets will have a lower environmental impact than other pallets under equal circumstances. The figure below shows the default/typical carbon footprint per trip for the pallets assessed in this study for three supply chain depth scenarios.

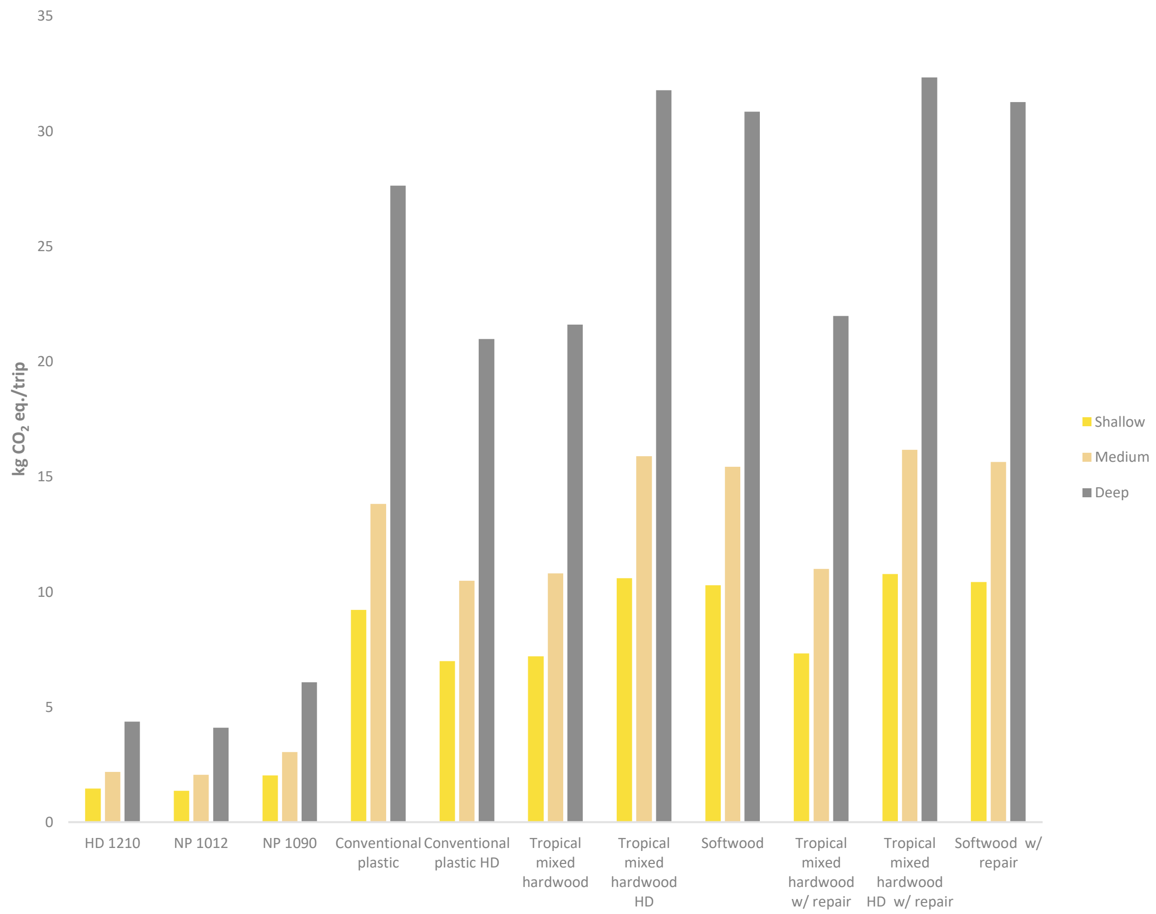

Figure 1 – Global warming potential of 1 trip per pallet type in each supply chain depth and for average handling intensity.

Monte Carlo simulations of the uncertainty showed, over 10,000 simulation runs, for the medium supply chain depth scenarios above:

- The typical /default carbon footprint is not the median or average carbon footprint of the assessment;
- There is 5% of less probability that timber or conventional plastic pallets have a lower carbon footprint than 10.8kgCO2eq per trip. There is less than 5% probability that the NP1210 pallet has more than 10.8kgCO2eq per trip.
- Within 95% confidence:
    - NP1210 have a footprint between 1.3 – 11.8 kgCO2eq per trip
    - Tropical mix hardwood pallets with repair have a footprint between 9.2 – 50.3 kgCO2eq per trip.
    - Conventional plastic pallets have a footprint between 9.3 – 34.8 kgCO2eq per trip.
    - Softwood pallets with repair have a footprint between 12.8 - 83.2 kgCO2eq per trip.

In addition to the standard LCA indicators, well researched and established, Re>Pal and alternative pallet life cycle solutions offer additional positive and negative impacts such as the following:

- Conventional plastic pallets are produced from homogenous plastic feedstocks (virgin or recycled, both valuable global commodities).
- Range International's Re>Pal business model is founded on using mixed plastic waste with low economic value that often poses environmental, social and economic problems.
- Most pallets used for comparable services to Re>Pal are produced using timber (ideally sustainably managed) without land clearance and associated carbon emissions, but are more likely produced from tropical hardwood, resulting in land clearance, biodiversity loss and carbon emissions.

Quantifying the impacts/benefits of using a problem waste compared with sustainably or unsustainably harvested timber or produced using scarce non-renewable resources poses a challenge for the traditional LCA method.

Accounting for plastic waste – what is the benefit?

Re>Pal pallets are almost "waste neutral" because the waste output throughout their life cycle, from cradle-to-grave, is nearly offset by the waste used as feedstock. Re>Pal uses large quantities of low-value, hard to recycle plastic waste, which has been diverted from landfills and from becoming litter. The benefit of doing so is that, contrary to plastic and timber pallets, Re>Pal consumes a burden free feedstock.

Do Re>Pal save trees? And if so why does this matter/help?

If the question is whether fewer trees are cut because of Re>Pal, the answer is we don't know for sure that one more Re>Pal pallet supplied to the market means one less timber pallet is produced. The factual benefit that Re>Pal can communicate is this: Re>Pal offers a timber alternative, produced using plastic waste, with a low environmental footprint, and with no risk of illegal logging and deforestation.

Recommendations and next steps

Steps to lowering impacts:

- **Lowering the carbon footprint:** Using renewable electricity, making the most of Indonesia's natural resources or photovoltaic installations, would significantly lower the carbon footprint. Photovoltaic panels would reduce the footprint by 67%. This would make Re>Pal more climate friendly than certified pine pallets.
- **Waste neutral manufacture:** Re>Pal rejects 15% of the waste that comes into the factory. If this fraction could be reduced, manufacture could be waste neutral. The footprint would also be lower. If using waste more efficiently implied the selection of better quality waste, this could have a trade-off in the value of absorbing low-quality, unrecyclable plastic.
- **Waste neutral life cycle:** Re>Pal can be criticised for marketing a product that can only be landfilled at its EOL. In this sense, giving a new life to a waste product can be perceived as displacing the problem. Re>Pal could counter this criticism with a take-back initiative, where retired pallets from a catchment area could be brought back to the factory and turned into new pallets. The impact of backhauling of pallets could replace the impact of transporting waste plastic from its source. In addition, retired pallets could be a more efficient feedstock in support of waste neutrality.

Communication:

Range International should consider third party expert critical reviews on the LCA study before the results are used to support a comparative assertion intended to be disclosed to the public. Edge recommend that Range International use statements such as:

- An independent life cycle assessment has demonstrated that Re>Pal has the lowest environmental impacts compared with functionally equivalent alternatives.
- Re>Pal offers an alternative, produced using plastic waste, with a low environmental footprint, and with no risk of illegal logging and deforestation.
- All pallets, from cradle-to-grave, use resources and energy, and have associated emissions. Re>Pal is arguably the most resource efficient and lowest emission alternative" or "Re>Pal pallets are almost "waste neutral", because the waste output throughout their life cycle, from cradle-to-grave, is nearly offset by the waste used as feedstock" and/or Re>Pal uses large quantities of low-value, hard to recycle plastic waste, which has been diverted from landfills and from becoming litter. The benefit of doing so is that, contrary to plastic and timber pallets, Re>Pal is produced from a burden free feedstock.

Closing knowledge gaps:

Re>Pal is invested in its mission to absorb waste plastic from streams where it would end up either in landfill or littering the environment. Aside from being granted a burden free feedstock, which is a benefit other pallet types do not have, the real savings and benefits from removing this waste to the planet, people and economy remain unclear.

This lack of clarity arises from data gaps in science: we do not know how and in what magnitude plastics at their EOL cause damage to the environment and to society. Research points towards a problem of significant and concerning magnitude, but well accepted impact assessment methodologies like LCA do not have methods to account for the problem because its exact pathways and fates are unknown.

Re>Pal could aim for the clarification of what its contribution to "the plastic problem" is by aligning with research initiatives and procuring knowledge build upon the topic of the environmental impact of plastics in the environment.

Third-party peer-review report

Final Summary Review report
By Wouter Achten (ULB), on
Report for Range International - Pallet Life Cycle Assessment and Benchmark
By Edge Environment

Aim

The main aim of performing an external review on the report 'Pallet Life Cycle Assessment and Benchmark' is to verify the compliance of the life cycle assessment study and its reporting with the International standard on Life cycle assessment (LCA) ISO 14044. Additional the review checked if the executive summary is coherent with the content of the main report.

Procedure

The first draft of the report (which was already subject to some internal review rounds) was received on 14/4/2017. A first review report was send to Edge Environment Pty Ltd on May 2nd. Some of the elements of the review report were further discussed in a skype discussion between Joana Almeida (Edge Environment) and Wouter Achten (ULB) on May 12th, and a second version of the report, and the executive summary for external communication, was made available for a second review on May 15 and 16. For both documents a second review was made on May 16th. The final version of the report was received on May 22nd, and the final version of the executive summary was received on May 29th. This final summary review report aims to give a synthesis of the issues raised and discussed during this external review process.

Review content

Regarding compliance to the ISO 14044 international standard the following points were raised and further discussed:
- Several clarifications were requested regarding the 'reference unit' of the study (which apply both to the report and the executive summary). Clarifications were made to make clear that the function of the pallets (carrying a certain load) was excluded from the assessment. The use phase "*does not reflect the transport of a load but the transport and handling of a pallet*". After review and revision, also the executive summary makes this issue clear by mentioning: *"[…] reference unit is 1 trip made by the pallet, not considering the load […]*". Further clarifications were made regarding the difference in reference unit for the cradle-to-gate part of the study and for the cradle-to-grave part of the study, and on what was exactly meant by 1 trip.

- Clarification were also requested regarding the justification for the selection of impact categories studied. In the final version of the report the justification of including and excluding impact categories, coherent with the goal and scope definition, was strengthened.
- The allocation procedure was also subject to review and revision. Both the explanation of the allocation procedure used in the foreground and background system and the justification for this choice were further clarified in the final report based on the review interactions.

- The initial report lacked an explicit description of the cut-off rules applied in the study. In the final version the description is clear and sufficiently explicit. A link with exclusion of processes from the system boundaries was equally made to make the difference between these two sets of methodological decisions more clear.

- Regarding the executive summary the review showed that the summary is coherent with the content of the main study report. The review mainly made some textual suggestions which were generally followed and integrated. As mentioned above more clarity on the reference unit was requested in this summary, which was offered in the final revised version.

Next to these main comments related to compliance to ISO 14044, some other revisions were made e.g. on the descriptive comparison between pallets and on some editorial remarks. The bulk of them were addressed in the revisions of the report.

Conclusion

Based on the above described procedure and content of the review process, and based on the revisions integrated in the final report and executive summary, it can be concluded that the study and study reporting under evaluation are compliant to the ISO 14044 international standard on Life cycle assessment. Further, the executive summary is considered coherent with the content of the main report.

Annexes:

- First review report on the study report (May 2nd) (Report_001.docx)
- Second review report on the study report (May 16th) (Report_002.docx)
- Track comments integrated in the executive summary report (May 16th) (Pallet Life Cycle Assessment and Benchmark - Executive Summary for Range International - Draft_WA.docx)

Wouter Achten
Associate Professor Environmental Management, ULB
29/5/2017, Brussels

Disclaimer

The results presented in this study are based on a number of realistic models of typical pallet life cycles. As with any model, different assumptions will lead to different outcomes. It is important to understand the working of the model, the scope and the limitations before applying these results to other situations.

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1. Assessing and comparing pallet impacts

Pallets are devices that are used for moving and storing freight. A pallet is used as a base for assembling, storing, stacking, handling, and transporting goods of all sectors as a unit load. Pallets are available in a wide variety of sizes and designs, based on the region that they are used in and the application in which they are needed.

Pallets can be manufactured from a range of materials, including wood, metal, plastic (including from both virgin and recycled polymers) and cardboard. Each material has its advantages and disadvantages as outlined below in Table 1.

Table 1 – Advantages and disadvantages of pallet materials (Frost & Sullivan, 2015).

	Advantages	Disadvantages
Wood	• Low cost • Easy to repair • Can be recycled • Easy to manufacture	• Wood pallets used in international logistics need to be treated to ensure that they are not carrying pests[1] • Easily damaged in use – limited durability • Can cause handling injuries (wood splinters, raised nails, etc.) • Difficult to clean and, if wet, can encourage growth of bacteria/fungi • Relatively heavy
Virgin plastic	• Low weight • Highly durable • Does not require treatment and marking for international transport • Easy to clean • More hygienic than wood pallets • Can be recycled	• Significantly more expensive than wood • More complex/difficult to manufacture than wood • Harder to repair than wood • Manufactured from non-renewable resource
Recycled plastic	• As with virgin plastic, plus: • Manufactured from waste products, reduces landfill volume • Can be recycled • Averts landfill costs • As cheap as wood pallets	• Harder to repair than wood
Cardboard	• Very light weight • Low cost • Fully recyclable • Can be manufactured in customised sizes	• Easily damaged • Suitable for only one journey • Cannot handle heavy loads • Cannot withstand inclement weather conditions

[1] According to ISPM 15, wood for pallets must be heat treated by reaching a core temperature of 56°C for 30 minutes, or fumigated with methyl bromide (chemical treatment) for a certain amount of time (FAO, 2013).

	Advantages	Disadvantages
Metal	• Highly durable • Does not require treatment and marking for international transport • Easy to clean • Can be recycled	• High cost • More complex/difficult to manufacture than wood • Harder to repair than wood • From non-renewable resource • Generally heavier than other materials

Waste plastic is a major global environmental issue. Over 300 million tonnes of plastic were produced in 2014 and this is projected to reach well over 600 million tonnes per annum by 2034. Only 14% of this is being captured by recycling systems. The rest is going to landfills, being incinerated or otherwise escaping into natural ecosystems (Ellen MacArthur Foundation, 2016) There are clear environmental benefits to producing plastic products from recovered plastics, compared with using virgin polymers and disposing of the product post-use via incineration or landfill (WRAP, 2016).

Timber consumption is a serious issue facing the pallet industry. The market is dominated by timber pallets, with 93% of the five billion new pallets forecasted to be produced in 2017 to made from wood (Freedonia, 2014) .The pallet industry consumes 40% of hardwood produced in the USA, 20% of the sawnwood produced in Europe (Frost & Sullivan, 2015).

Questions remain, however, over the environmental performance of plastic pallets made from recycled waste plastic compared with pallets from other materials carrying out an equivalent service, when assessed across the full life cycle.

Range International commissioned Edge Environment (Edge) to undertake a comparative study of the environmental credentials of various pallet options using life cycle assessment (LCA). The purpose of the study is to:

- Profile the key environmental impacts of Re>Pal pallets;
- Assess the environmental implications of using waste plastic as a resource, rather than virgin plastic or timber;
- Benchmark conventional pallet types against Re>Pal with consideration of their properties and functions;
- Provide Range International with a critical assessment of the environmental performance of their products; and
- Establish the methodology and background dataset for the development of LCA tools for Range International.

The target audience for this study includes key clients, Asia Pacific governments and broader community stakeholders.

This report describes:

- The pallets studied;
- The LCA methodology used;
- The data on raw materials, manufacturing inputs, distribution and use of the pallets;
- Comparative results for each pallet type, showing their environmental impact during their assumed lifespan;
- Sensitivity analyses exploring key parameters and methodological choices; and
- Interpretation of the results and recommendations for further actions and communication of the results.

- A key objective is to present the study and results on two distinct levels:
- Practical and plainly explained for use in external communications, sales and marketing. Backed up by simple to use tools and collateral.
- Rigorous and transparent in terms of method, data and interpretation, for satisfying the most demanding scientific scrutiny if required.

2. Range International

Range International is a company that manufactures plastic products from waste plastic sources, using a unique production technology, ThermoFusion™. Range International's product range includes Re>Pal pallets made from 100% recycled plastic waste.

The manufacturing process allows waste plastic products of almost any type or source to be used, without the need for sorting, or any other form of pre-preparation. Range International's process uses waste plastic as its only raw material. This makes the technology different to other production processes using recycled plastics, where plastic needs to be sorted and prepared before use, and where virgin polymers often need to be used to supplement waste polymers.

Range International's manufacturing process allows plastic pallets to be manufactured at a price comparable with the costs of wooden pallets. Although plastic pallets manufactured from virgin and/or waste plastic polymers are currently widely available, these are significantly more expensive than wooden pallets, and consequently have only a minor share of the global pallet market, as price is the main purchasing criterion for buyers of pallets.

3. Our approach to the study

3.1. Study methodology

3.1.1. Life cycle assessment

LCA is an internationally standardised analytical framework for identifying and quantifying the impact of resource use and emissions (e.g. greenhouse gases) from the “cradle” to the “grave” of a system. The general impacts to be considered include resource depletion, human health and ecological consequences. For example:

- Emissions of greenhouse gases affecting human health and causing loss of ecosystem quality through the effects of global warming and climate change;
- Depletion or pollution of scarce freshwater resources necessary for human consumption, food production systems and to sustain ecosystems; and
- Use of finite resources such as fossil fuels limiting the available pool for future generations.

The study followed the ISO 14040 and ISO 14044 guidelines, that is, it:

- Identified the goal and scope of the pallets and life cycle to be reviewed;
- Identified the energy, water and materials used, pollution emitted and waste generated through the life cycle, by life cycle stage;
- Assessed the potential resource use, human and ecological impacts of those uses and emissions, acknowledging the uncertainties and assumptions used;
- Compared those impacts for the selected pallets; and
- Highlighted any significant results and implications.

To complete compliance, the study must be critically reviewed before public disclosure.

Details on the methodology and on the LCA standards that inform it are provided in “APPENDIX A: LCA standards and references”.

3.1.2. Footprint or market effect – Attributional and consequential LCA

LCA can be applied to answer one of the following questions at a time:

- What is the footprint of my product based on the current life cycle; or
- What is the effect on the additional offer/demand of a certain product in the market?

Our analysis is based on attributional perspective of LCA – this is an accounting based method looking at the here and now. This is a standardised modelling approach that assesses a product against its interaction with the environment, based mainly in physical exchanges.

An alternative pathway to LCA modelling is the consequential approach, which is best suited to answer questions such as “what is the effect on the additional offer/demand of a certain product in the market?” In consequential LCA, market models are employed to establish displacement and substation sequences in the market.

See Table 2 for a summary of the four main differences between the two approaches.

Table 2 – Difference between attributional and consequential LCA (Brander, et al., 2009).

	Attributional	Consequential
Application	Understanding the total emissions directly associated with a life cycle	Understanding the change in emissions resulting from a purchasing or policy decision that leads to a change in output of a product
System boundary	Processes and flows directly involved in the life cycle	Processes and flows directly and indirectly affected by the marginal output of the life cycle
Data and uncertainty	Balanced relationships between flows, low uncertainty	Modelling of market effects, high uncertainty

3.1.3. Software platforms

The life cycle model was created in a leading international LCA software tool SimaPro® (PRé, The Netherlands). SimaPro® is a platform that links LCA background databases with environmental impact assessment methods, making it possible to calculate impacts from an inventory model (see Figure 2).

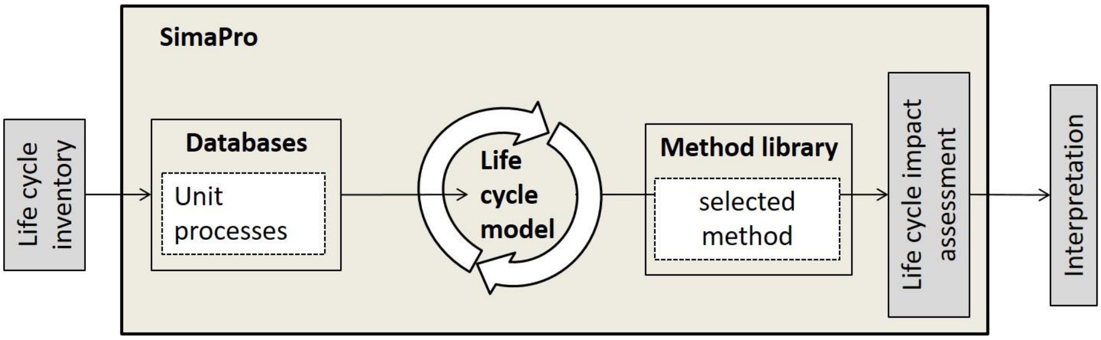

Figure 2 – Use of SimaPro in LCA.

3.2. Communication and use of study in public domain

Although the results are robust and defensible, they are complex, and care needs to be taken when placing them in the public domain.

If these results are to be used for any comparative assertion in the public domain (e.g. that plastic pallets are better than wood pallets), they require critical peer review. We have therefore taken care to prepare this report for peer review, including compliance with ISO 14044, the international benchmark for this type of assessment.

This study provides detailed communication guidelines in section 8.2.

3.3. Scope of study

3.3.1. System boundaries

We performed two assessment scopes on all pallets (see Figure 3 and Figure 4):

- Cradle-to-gate, which includes raw material provision and manufacture. For Re>Pal, this represents present manufacture conditions at the Tabanan factory.

- Cradle-to-grave, which extends the life cycle onto use and end of life (EOL). For all pallets, this is scenario-based (see Section 4.3).

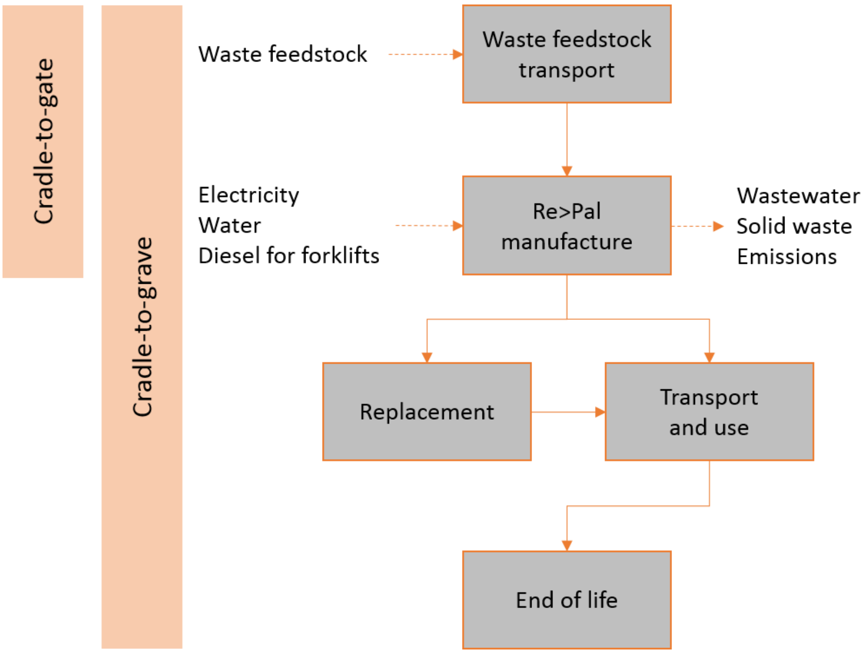

Figure 3 – System diagram of Re>Pal pallet production and use, and corresponding LCA scopes.

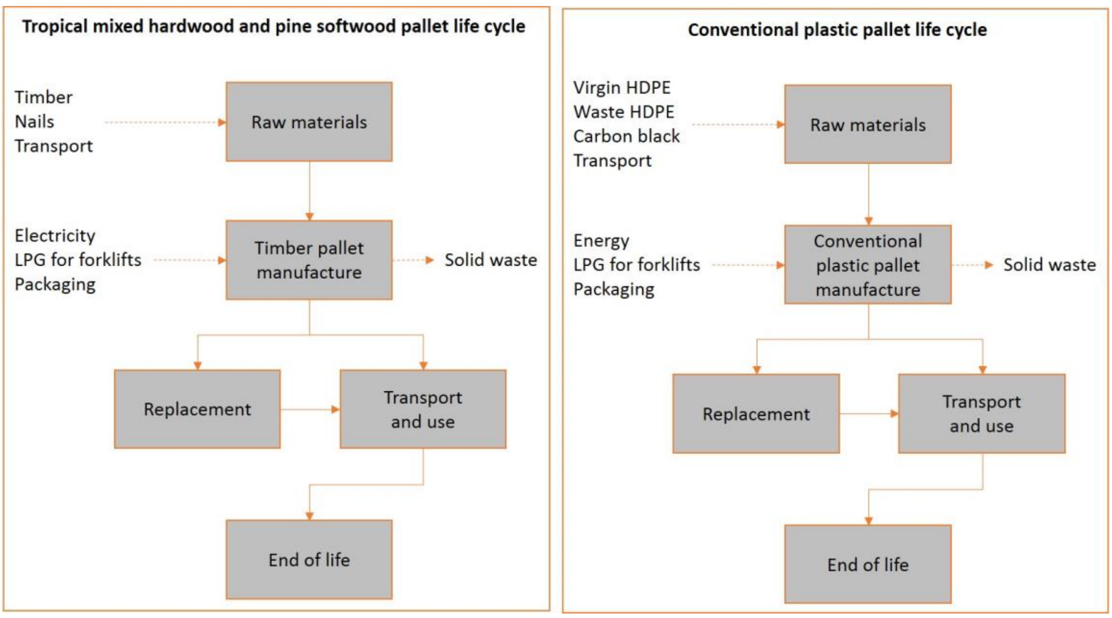

Figure 4 – Life cycle diagrams of timber and conventional plastic pallets, benchmarks to Re>Pal pallets.

3.3.2. Re>Pal pallets

Range International manufactures nestable and heavy duty pallets, and a rackable pallet is in development (not modelled due to lack of production data). Two nestable and one heavy duty pallets were assessed (see Table 3).

Table 3 – Products assessed (as specified by Range International).

Pallet	Name	Dimensions (length × width) (mm)	Mass (kg)
Nestable	NP 1210	1,200 × 1,000	13.75
	NP 1090	1,090 × 1,090	15.50
Heavy duty	HD 1210	1,200 × 1,000	35.00
Rackable	Not included	-	-

3.3.3. Benchmark pallets

Edge and Range International scoped the market for Re>Pal's main competing pallets. Competing pallets included in this study are timber and plastic and are detailed in Table 4.

Data requirements and inventory for benchmark pallets are given in Section 4.1.2.

Table 4 – Benchmark pallet types.

Material	Types	Included in the study
Wood	• Certified/uncertified hardwood • Certified/uncertified softwood • Heavy duty/light duty	• Uncertified tropical mixed hardwood, light duty • Uncertified tropical mixed hardwood, heavy duty • Certified softwood, light duty
Virgin plastic	• Heavy duty/light duty • 100% virgin • Virgin/scrap mix	• Virgin/scrap mix, light duty (conventional plastic) • Virgin/scrap mix, heavy duty (conventional plastic)
Cardboard	Not included	Not included
Metal	Not included	Not included

3.3.4. Reference unit (1 trip)

To compare the environmental impacts of different pallet systems, we needed a single reference unit. In this study, the reference unit is 1 trip.

To that end, we have sourced the available data, then normalised it to determine the number of pallets needed to provide the logistic movements required, the material inputs and outputs for that number of pallets, and their total impacts. This includes the durability of timber pallets, which varies for each kind of pallet and is a function of the intensity and complexity of the supply chain.

A reference unit was used rather than a functional unit because the assessed excluded the load carried by the pallet, which reflects its function. Because the load is typically much higher than the pallet weight it would shift the burden of the results to the transport of the load and away from manufacture, use and end of life performances, which are the aspects under study.

3.3.5. Geographical scope

The geographical scope of the study is pallet production and dispatch from South East Asia and Australia.

3.3.6. Time boundary

The data sourced from Range International was generally for the year 2016 under optimal operational conditions. It is not assumed that this data will be representative of Range International operations beyond this period due to the factory upgrade due to happen in 2017.

3.3.7. Environmental impact assessments

According to ISO 14044, the selection of impact categories, category indicators and characterisation models used in the life cycle impact assessment methodology shall be consistent with the goal of the study.

The methodology for the environmental impact assessment was based on leading international assessment methods. With a well-established and recognised set of methods, we reported on a set of key indicators:

- 100-year global warming potential[2] (rather than a more short-term "individualistic" 20-year perspective or a more generation-neutral 500-year perspective);
- Cumulative energy demand; and
- Net waste balance[3].

In addition, we touched upon impacts of:

- Terrestrial acidification, freshwater eutrophication, fossil fuel depletion, land occupation and land transformation[2]; and
- Damage to human health and damage to ecosystems[4].

Several midpoint indicators were excluded due to the degree of scientific uncertainty (e.g. toxicity), deemed relevance to the goal and audience of the study (e.g. ionising radiation) and since they would to some extent be covered in the endpoint indicators (damage to human health and damage to ecosystems).

Finally, outside of the current LCA framework, we:

- Explored the implications of avoidance of littering and landfilling plastics; and
- Estimated the timber requirement of timber pallets as number of trees.

3.3.8. Co-product allocation

Co-product allocation is an approach to allocate the environmental impacts of a single process to multiple products or services.

The pallet life cycle produces several co-products that could have economic value, including:

- Retired pallets or pallet parts; and

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[2] Hierarchist ReCiPe (v1.12) midpoint method.

[3] The calculation was based on the waste output categories bulk waste, slag/ashes, hazardous waste, and radioactive waste from EDIP 2003, which we compound in a sole waste output indicator.

[4] Hierarchist ReCiPe (v1.12) endpoint method.

- Waste packaging.

Each of these co-products can be inputs into other product life cycles depending on their EOL, e.g. new pallets, secondary pallets and timber-based products. The co-product approach allocates environmental impacts to both the pallet and the co-product life cycle, in proportion to their economic value.

Equally, the inherited burden from previous life cycles is also recognised in the products used for pallets, such as recycled plastic, recycled steel for nails, recycled cardboard, recycled high-density polyethylene (HDPE) for plastic pallets, etc. Details on the allocation procedure for recycled HDPE are given in Section 4.1.2.

The choice of economic allocation is underpinned by the Australian building products and construction sector's level-playing field LCA method development project. The ISO 14044 compliant allocation approach is described in the document Methodology Guidelines for the Construction Materials and Building Products Life Cycle Inventory Database. The method development involved industry, government, LCA experts & academia, and peak industry bodies in Australia.

That said, in this study, we did not allocate/share any of the environmental impacts to the co-products because (i) co-products are recycled internally (allocation not necessary), or (ii) the value of co-products, including salvaging used pallets at the end of use, has been assumed to be highly uncertain and small relative to the value of the original pallets. This is a conservative approach that otherwise would have reduced the impact of the pallets overall.

Allocation in background data is as per ecoinvent's allocation to the point of substitution mode.

The pallet life cycle will, however, include the negative impacts associated with waste generated, including recycling operations and used timber disposed in landfill.

3.3.9. Biogenic carbon in benchmark timber pallets

Forests are an important sink for carbon in this cycle because they help to offset carbon dioxide emissions and other greenhouse gases that would otherwise contribute to climate change.

In the LCA of land-based products, the use of land and its attributes is part of the life cycle. Hence, LCA can include, and in some cases shall include, shifts in carbon stocks in soil and biomass that are the responsibility of the product being analysed. Losses or gains in carbon stocks due to land-use change (LUC) imply the emission or sequestration of CO_2, respectively.

Trees have a natural ability to concentrate and store carbon. Through photosynthesis, trees absorb CO_2 from the atmosphere. Carbon accounts for around 50% the dry weight of a tree. When trees are harvested, and manufactured into products, this carbon remains stored for the life of the wood product, and can continue to reside in the wood for a considerable time once the product's service life ends, depending on how it is disposed. Only when a tree or wood product decays or is burned does the carbon return to the atmosphere. When timber goes to landfill, it takes hundreds of years to break down into both carbon dioxide (CO_2) and methane (CH_4), resulting in a temporary carbon sink, removing CO_2 from the atmosphere. This temporary removal of carbon dioxide from the atmosphere results in a delay of climate warming impact.

The effect of delayed emissions due to temporary carbon storage was not considered in this study. This is due to uncertainty in the methodology, which is acknowledged in LCA guidelines, as well as to the fact that non-pooling pallets are, in principle, short-lived goods.

The inventory included the sequestration of carbon and its release at the end of the life cycle in accordance to the end of life pathway.

3.3.10. Deforestation emissions

When timber is harvested outside a sustainable forestry scheme (e.g. compliant with the Forest Stewardship Council (FSC) certification requirements), it can be assumed that deforestation occurred and that the biomass stock in the forest will not be replenished. This is due to a land use (e.g. forest to cropland) or due to poorly managed land use (e.g. forest can regrow but not fully). In either case, there is a change in the carbon stock of that area and the lost carbon is accounted for as a CO_2 emission (see Figure 5).

The carbon that is lost is the carbon stock of the removed biomass. Part of that carbon stock is preserved in the wood product during its lifetime. A share of that stock, however, is assumed to be immediately lost through biomass burning and degradation.

If, on the other hand, timber is harvested sustainably, it can be assumed that there is a cycle with carbon neutrality, the carbon lost through harvest is re-absorbed through re-growth. Only the emissions from biomass that is immediately burned/degraded are considered.

Burdening a wood product with an emission from land clearing or LUC is not a linear attribution. Besides quantifying the carbon stock that is lost, it is necessary to gauge the strength of the cause–effect relationship between the product and the LUC.

In this study, we considered both the amount of carbon that is lost and the causality between pallets and deforestation. This is explained in Section 4.1.1, and in more detail in "APPENDIX A: LCA standards and references".

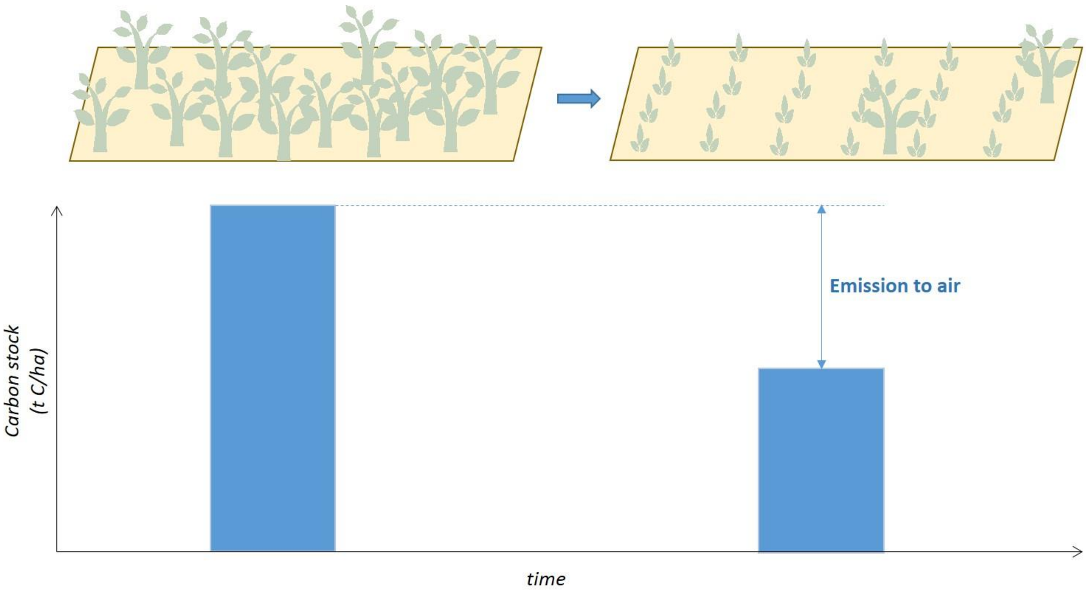

Figure 5 – Loss of carbon stocks in land due to LUC/deforestation.

3.3.11. Background data sources

We used **ecoinvent v3.2,** the world's leading database with several thousands of life cycle inventory (LCI) datasets. ecoinvent is developed and provided by the Swiss Centre for Life Cycle Inventories.

Data used for the purposes of modelling was selected based on the following criteria:

- **Relevance:** Information from appropriate sources, data and methods in relation to the primary product data was used.
- **Completeness:** Data was used if it provided a significant contribution to the products' life cycle impacts.

- **Consistency:** Only data that enabled meaningful comparisons in life cycle impact assessment (LCIA) information was used.
- **Accuracy:** Only accurate data was used to reduce bias and uncertainty as far as is practical.
- **Transparency:** Published data was used as far as practical to disclose information to allow third party scrutiny.

These data sources are further detailed in Section 4 and “APPENDIX B. Background data”.

3.3.12. Exclusion of small amounts

This study has been conducted with the attempt to capture and include all inputs and outputs. It is however common practice in LCA/LCI protocols to propose exclusion limits for inputs and outputs that fall below a threshold percentage of the total impact. These impacts can be smaller than the error range associated with the inventory data itself.

The cut-off of small amounts in background is as per standard in ecoinvent and AusLCI. In the foreground data, no cut-off was applied. The only exclusions pertain to items left outside the system boundaries, such as impacts associated with capital equipment and buildings that are typically insignificant in LCIs. For this project, capital equipment and buildings were excluded from the assessment scope, as previous studies (Frischknecht, et al., 2007) have demonstrated their immateriality.

The impacts of employees are also excluded from inventory impacts on the basis that if they were not employed for this production or service function, they would be employed for another. It is also difficult to accurately determine the proportion of overall employee impacts to allocate to their work at Range International.

3.3.13. Data requirements and quality

The data quality requirements for the study were set to include a number of sources:

- The data sourced from Range International shall be representative of the year 2016 and be assumed to reasonably represent the typical operations of the Tabanan factory in the foreseeable future beyond this period.
- The foreground data shall be sourced from Range International’s manufacturing.
- The background data shall be sourced from nationally relevant databases or adapted to regional conditions as far as practical.
- The background data shall be representative of contemporary technology and practices.

The data requirements for the LCA are summarised in Table 5.

Table 5 – Data requirements.

Component	Data related to pallets	Data source	Data quality
Raw materials	Source and quantities used for manufacturing and repairing pallets	Range International staff; Bengtsson & Logie (2015)	Re>Pal: Good (primary data) Benchmarks: Good
Transport to manufacturing site	Transport mode and distance (fuel consumption)	Range International staff ecoinvent 3.2 standard market mix distances	Good

Component	Data related to pallets	Data source	Data quality
Manufacturing of pallets	Material use, energy, emissions, waste and recycling	Range International staff; Bengtsson & Logie (2015); ecoinvent 3.2 standard processes	Re>Pal: Good (primary data) Benchmarks: Good
Pallet relocation	Transport modes and distance	Scenario developed by Edge	Low
Distribution and use	Fuel consumption	ecoinvent 3.2. standard fuel consumptions	Good
Maintenance and repair	Material use, energy, emissions, waste and recycling	Scenarios developed by Edge and Range International staff	Low
End of life	Secondary use and waste disposal	Scenarios developed by Edge and Range International staff	Low

3.3.14. Uncertainty analysis

Most of the background and foreground data used in this study includes a degree of variability (see Table 6). This variation was included in the LCA model and is handled with a Monte Carlo analysis. The aim of this step is to capture:

- the variation in the environmental impact of Re>Pal pallets; and
- the probability of overlap between Re>Pal and its benchmarks.

Table 6 – Uncertainty data in the LCA[5].

Data	Source of uncertainty	Distribution of uncertainty
Generic background data	Averaging of multiple data sources	Various types of distribution, mostly normal with averages and standard deviation
Re>Pal manufacture	Inputs ranges, for example energy and its feedstock transport distance	Assumed uniform, average and range
Pallet durability	Pallet handling model, in which pallet durability varies along a range of stress	Assumed uniform, average and range

We tested the uncertainty of the data with Monte Carlo analysis of the climate change impacts. A Monte Carlo analysis in SimaPro essentially runs the LCIA *n* times, and for each time it randomly samples values within the distributions defined in the inventory. By doing so, it yields the possible and the probable distribution of results. By possible we mean all the results the

[5] By uniform distribution we mean there is a minimum, typical and maximum value defined, and the probability is uniform between the min and max.

Monte Carlo calculated with the random sampling. By probable we imply the fitting in a probability distribution.

3.4. "Trees saved" calculation

It can be claimed that the production of timber pallets relies on timber supply and therefore is related to the felling of trees. Manufacturing a stock of timber pallets is responsible for felling a certain number of trees, while manufacturing a stock of Re>Pal pallets does not. We cannot conclusively say that for each Re>Pal pallet supplied to the market, one less timber pallet will be produced. Without the backup of a consequential LCA, looking at the marginal supply of pallets by type, we need to make these statements with caution.

In addition, felling trees is not necessarily a bad outcome to the environment if the trees are harvested in a sustainably managed forestry scheme.

That said, in some worlds regions pallets consume 20-40% of timber production (Frost & Sullivan, 2015). The supply for pallets to the market is plenty, price and quality drive demand. If Re>Pal can provide pallets at a lower or better price than timber pallets, it may replace the marginal product (timber one-way pallets), driving down the demand for timber.

Re>Pal can also inform its clients of the timber requirements of conventional timber pallets and its effects concerning carbon sequestration and deforestation, which are not carried into the supply chain when Re>Pal pallets are used.

This study estimates:

- How many trees are required to satisfy the timber demand of the different use profiles of timber pallets; and
- How much CO_2 would have been sequestered in those trees.

3.4.1. Modelling assumptions

The following assumptions were used to estimate the number of trees associated with the timber requirement of pallets:

- 82% of the wood in a tree is extractable (see Figure A1).
- 51% of the extracted wood is used (De Schryver, et al., 2012).
- 1 tree has 10.65 m^3 of wood (UNECE, 2009).

3.5. Diversion of waste plastic

A Re>Pal pallet both consumes waste and produces waste during its life cycle. We analysed the waste balance of Re>Pal, comparing the net generated waste with the net uptake of waste.

LCA standards and method do not foresee that a product can be credited with the avoided impacts of the waste when using waste-streams as a feedstock. The main benefit lies in starting from zero, that is with no embodied impact of resources and emissions from oil refining and polymerisation of monomers.

The benefits of using Re-Pal pallets are in the use of a zero-impact feedstock, rather than timber or virgin plastic.

4. Life cycle inventory

This section describes the sources and quality of the data used in the LCA, for both the raw materials and the processes used at each stage of the pallet life cycle. This section also lays out the assumptions used to calculate impacts for the primary direct processes of a pallet's life cycle, and the materials used in those processes. The assumptions used for processes and data outside Re>Pal's direct influence and control are listed as background data in "APPENDIX B. Background data".

4.1. Raw materials and manufacture

Primary pallet materials considered in the analysis are shown in Table 7. The assumptions for calculating the impacts of these materials are discussed below.

Table 7 – Primary pallet materials considered in analysis.

Material	Use	Pallet weight (kg)
Re>Pal		
Waste plastic	Nestable, simple/one-way, light duty	15.5[6]
Waste plastic	Nestable, simple/one-way, light duty	13.75[6]
Waste plastic	Heavy duty	35[6]
Benchmarks		
Softwood (radiata pine)	Simple/one-way, light duty	13[7]
Mixed tropical hardwood	Simple/one-way, light duty	17[6]
Mixed tropical hardwood	Heavy duty	37.5[6,7]
Conventional plastic	Nestable, simple/one-way, light duty	6.5[8]
Conventional plastic	Heavy duty	34[7]

4.1.1. Re>Pal

Re>Pal pallets are manufactured from 100% mixed waste plastic. The waste plastic is transformed by ThermoFusion™ processing (melt and mix) and moulds mixed soft plastic waste with minimal pre-treatment into pallets.

The incoming plastic waste is sorted for visible contaminants such organic residues and aluminium foil. The raw material is washed with water, hot air-dried, molten, weighed, moulded and left to cool.

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[6] Re>Pal measurements.

[7] Bengtsson et al. (2015).

[8] Common model in the SE Asian market, product ID X4840K4-1A.

For LCA, the plastic waste it is free of embodied burden, as opposed to mined and manufactured feedstocks. Transport of the waste to the Re>Pal manufacturing site is accounted for as part of its life cycle.

Currently, all waste is sourced domestically from Bali. This is included in the cradle-to-gate assessment, of present manufacturing conditions. In the use scenarios, looking forward after scaling up production, we considered a split of international and domestic sources.

Table 8 below summarises the manufacturing data for the Range International pallets.

Table 9 shows the sources of feedstock waste.

Table 8 – LCI of one production line of the Re>Pal factory operations during 1 year.

Inputs		
Waste plastic (t)	12,774	
Electricity (MWh)	133.190	
Water (l)	269,280	
Diesel (forklifts, l)	2,805–4,208	
Outputs		
	# pallets	**t**
NP 1210	235,620	3,240
NP109	215,160	3,335
HD1210	121,440	4,250
Wastewater (l)	180–300[9]	
Mixed solid waste (t)	1,949	

Table 9 – Transport distances of plastic waste from source to the Tabanan factory in the present situation (cradle-to-grave, when all the plastic waste is sourced domestically, and in future potential scenarios, where a domestic and international mix of sources was simulated.

[9] Corresponds to wastewater that is channelled to wastewater disposal. Excludes run-off and evaporative water. The impacts of the latter were not accounted for due to lack of measurements on emission and fate.

Source	Distance (km)	Vehicle	Split (current)	Split (scenarios)
Indonesia (Bali/East Java)	50-380	Various road vehicles	100%	20%
	10	Ship		
International	50–100	Various road vehicles	0%	80%
	150–6,654	Ship		

Modelling assumptions

- The factory operates 330 days per year at 85% capacity. This was used to convert daily and monthly records, provided in the raw data by Range International, to annual.
- Direct emissions from the production line, arising from the heating and processing of plastic materials, correspond to plastic thermoforming (see Table A 1 in Appendix B for background processes used).
- The solid waste mix leaving the factory (consisting of mud, aluminium foil, contaminated waste plastic) is treated as municipal solid waste in landfill.
- Forklift requires 0.02 kg diesel to generate 1 MJ energy.
- Waste plastic is a waste stream and is free of burden.
- Electricity supply to the factory corresponds to the Indonesian average energy mix (see Figure 6).

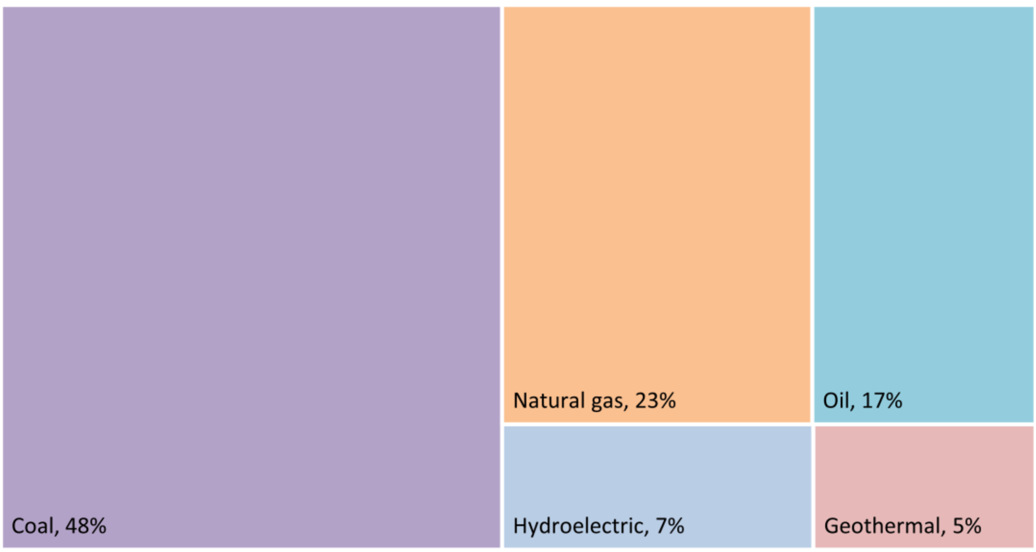

Figure 6 – Fuel mix of grid electricity in Indonesia as per ecoinvent v3 data (ecoinvent Centre, 2016).

4.1.2. Benchmarks

The main data source for benchmark pallets is a study conducted by Edge Environment consisting of an industry LCA for Loscam (Bengtsson & Logie, 2015). Data was retrieved from pallet manufacturers in Australia and China, as well as a literature review (including CHEP's LCA).

Transport of materials is included in their background data. ecoinvent data contains average transport distances of products in the market. For instance, ecoinvent data for HDPE will include an average sampled distance for HDPE pallets between the points of manufacture and transformation.

Pallets from the following raw materials were considered:

- Mixed tropical hardwood, harvested informally in the region, non-certified;
- Softwood (pine), commercial and certified; and
- Conventional plastic (virgin and recycled mix).

Modelling assumptions and data – Conventional plastic pallets

Table 10 contains the manufacturing data of conventional plastic pallets.

Table 10 – LCI of the manufacture of one conventional plastic pallet (all units per pallet).

	Heavy duty	Light duty
Inputs		
Virgin HDPE (kg)	28.88	5.52
Recycled HDPE (kg)	5.50	0.98
Electricity (kWh)	48.32	8.38
Carbon black (kg)	0.39	0.07
Outputs		
HDPE waste (kg)[10]	0.35	0.07

Economic allocation of plastic scrap

We assumed that the feedstock mix of conventional plastic pallets is 15% HDPE scrap and 85% virgin HDPE. The HDPE scrap has commercial value and is from a controlled recycling stream (e.g. recycled milk bottles). For this reason, the recycled plastic earns a share of the environmental burden of producing the plastic commodity in the first place.

We allocated this burden economically, following losses from the plastic recycling stream (not all plastic is recycled, there is a loss in each life cycle the plastic is recycled) and the decrease in value (recycled plastic is worth less than virgin plastic/resin). This resulted in an allocation of 79% of the burden to virgin plastic and 21% of the burden to the scrap.

Modelling assumptions and data – Timber pallets

[10] Assumed to be internally recycled.

The following table contains the manufacturing data of timber pallets.

Table 11 – LCI of the manufacture of wood pallets (all units per pallet).

	Hardwood, heavy duty	Hardwood, light duty	Softwood, light duty
Inputs			
Timber (kg)	35–40	17	13
Electricity (kWh)	0.61–1.40	0.27–0.55	0.29–0.58
Nails (kg)	0.69	0.29	0.31
LPG (forklifts, MJ)	0.85–1.45	0.57–0.81	0.60–0.90
Cardboard packaging (kg)	0.03	0.02	0.02
Outputs			
Wood waste (kg)	2.18	1.37	1.44
Cardboard waste to recycling (kg)	0.03	0.02	0.02

Fumigation

Timber pallets meant for export are subject to chemical or thermal treatments for sanitary reasons. In this study, we made the conservative approach to exclude fumigation. This is because the LCA does not model export versus import scenarios, but a level-playing field setting where all pallets are compared under the same use chain, regardless of their design being meant for export of domestic use.

Biogenic carbon in timber pallets

We assumed that mixed tropical hardwood is harvested non-sustainably. Overall, tropical hardwood pallets contribute to net deforestation.
Because this study models generic, non-case specific timber pallets, we did not use a specific case to estimate a deforestation emission of timber sourced in Indonesia. Alternatively, we modelled an average emission associated with harvesting 1m^3 of non-sustainable mixed tropical hardwood. To estimate this emission, we:

a) Calculated the carbon loss caused by deforestation based on the amount of timber used in the pallets (see “APPENDIX C. Emissions of deforestation”); and
b) Assumed the timber would be, in 70% of the instances, the cause of deforestation (see Section 3.3.10 and “APPENDIX C. Emissions of deforestation”).

The emission of deforestation associated with 1 m^3 of timber was thus calculated as:

$$emission\ deforestation = kg\ GHG\ emitted \times 70\%$$

4.2. Use

Pallets can be used in a myriad of options, including:

A. Single-use pallets typically transport goods for one trip between a product manufacturer and a warehouse/distribution facility;

B. Pooled pallets are used in a loop system and make multiple trips between trading partners; and

C. Pooled pallets are the shared use of high quality standard pallets and containers by multiple customers who collectively benefit from the network scale of the pool.

Our comparative assessment is not for the entire pallet market, as the different pallet options are not used interchangeably for different tasks and different products. Specifically, we focused on case A and excluded pooling altogether (cases B and C).

As explained in 3.3.4, the usage does not reflect the transport of a load but the transport and handling of a pallet. Load-bearing capacity is reflected in the pallet's weight and performance. See section 4.2.1 for details.

4.2.1. Pallet performance

Range International estimated the number of trips done by a pallet under a range of logistic profiles. These data were formulated for Re>Pal and its benchmarks, based on general industry knowledge compiled by Range International.

The logistic profiles were based on supply chain depth and handling intensity and represents merely a few of the possible, innumerous cases.

Supply chain depth

Supply chain depth characterises the extension of use of pallets. Range International defined shallow, medium and deep supply chains, in order of impact on pallet durability (see Figure 7).

The depth level was defined by unit load weight; type of packaging; number and types of handling equipment; and number, types and duration of storage and transport (e.g. edge racking long term or not).

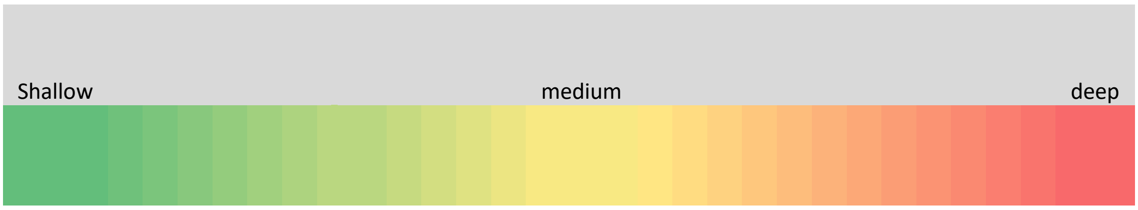

Figure 7 – Supply chain depth levels and its impact on pallet durability.

Handling intensity

Handling intensity refers to the stress pallets are subject to during handling. It varies from gentle to severe (see Figure 8), in order of impact on pallet durability, and correlates directly to number of touch-points.

Handling intensity includes aggressiveness and frequency of handling, severity of handling stress due to many factors including fork-lift driver behavior and storage temperatures.

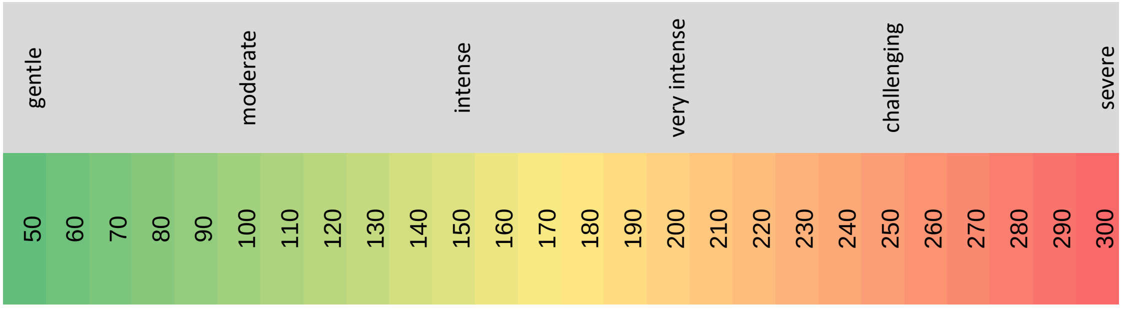

Figure 8 – Handling intensity level scale in function of number of touch-points per trip.

4.2.2. Maintenance and replacement scenarios

In this section, we isolate some use cases for each pallet and supply chain to reflect pallet performance, based on the modelling by Range International.

We performed an LCA of each pallet under each supply chain depth for 1 trip, with or without repair of timber pallets (plastic pallets are not repaired), as shown in Figure 9.

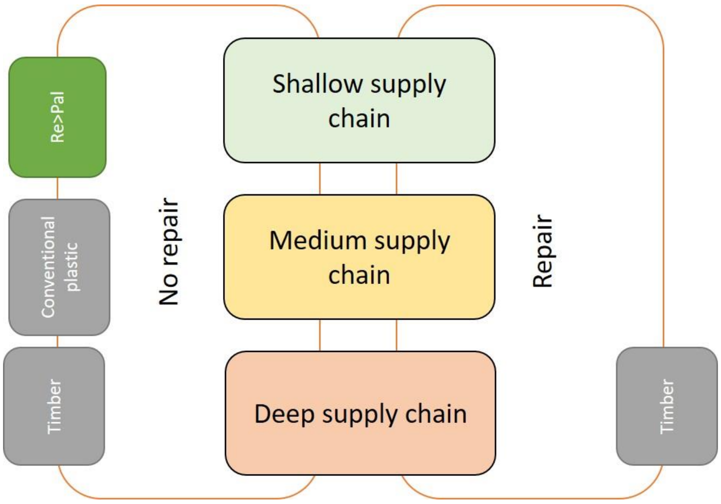

Figure 9 – Scope of scenarios in relation to supply chain depths.

Each 1 trip done by a pallet in one scenario requires the replacement and/or repair defined by its durability. The basis for this calculation was the fraction of pallets required to perform 1 trip, considering their durability and the stress they are subject to (see Table 12).

Table 12 – Typical number of pallets per trip per pallet type and supply chain depth.

Use profile		*No repair*								*Repair*		
Supply chain depth	**Handling intensity**	*Re>Pal, HD1210*	*Re>Pal, NP1210*	*Re>Pal, NP1090*	*Conventional plastic*	*HD Conventional plastic*	*Tropical mixed hardwood*	*HD Tropical mixed hardwood*	*Softwood*	*Tropical mixed hardwood*	*HD Tropical mixed hardwood*	*Softwood*
Shallow	**Gentle**	0.019	0.035	0.029	0.024	0.015	0.097	0.064	0.222	0.097	0.065	0.223
	Average	0.065	0.118	0.098	0.083	0.052	0.331	0.221	0.761	0.340	0.227	0.782

	Severe	0.152	0.277	0.231	0.194	0.121	0.777	0.518	1.787	0.816	0.544	1.876
Medium	**Gentle**	0.028	0.052	0.043	0.036	0.023	0.145	0.097	0.333	0.146	0.098	0.335
	Average	0.097	0.177	0.148	0.124	0.078	0.496	0.331	1.141	0.511	0.341	1.172
	Severe	0.228	0.416	0.347	0.291	0.182	1.165	0.777	2.680	1.224	0.816	2.814
Deep	**Gentle**	0.057	0.104	0.086	0.072	0.045	0.290	0.193	0.667	0.292	0.195	0.670
	Average	0.194	0.354	0.295	0.248	0.155	0.992	0.662	2.282	1.021	0.681	2.345
	Severe	0.455	0.832	0.694	0.583	0.364	2.331	1.554	5.361	2.447	1.631	5.629

In this scenario analysis, the handling intensity defined pallet durability, replacement and repair needs. There is a range between the minimum and the maximum number of trips one pallet can do depending on how roughly it is handled:

- gentle = maximum number of trips
- severe = minimum number of trips.

When we convert this to the reference unit of the study, which is 1 trip, we can say that:

- gentle = minimum number of pallets
- severe = maximum number of pallets.

Damaged Re>Pal and conventional plastic pallets are rarely repaired, they are replaced, requiring the manufacture of a whole new pallet. Damaged timber pallets are typically repaired, which requires the supply of the same amount of timber that is damaged.

4.2.3. Pallet use

Transport of pallets in the use model was assumed as:

- 2,000 km international shipping, done 80% of the time by freight ship and 20% by air freight; and
- 6 legs of 50 km overland transport by truck (total before and after international dispatch).

The inclusion of transport is relevant to capture the impact of hauling pallets with different weights, because heavier loads lead to higher impacts and vice versa. The use of an arbitrary transport scenario does not influence the relative impacts between pallets because all of the pallets are transported in the same way.

4.3. End of life: Recycling and disposal

Different EOL options were modelled for Re>Pal pallets and its benchmarks (see Table 13). Each EOL process includes the energy and material inputs needed to dispose of or recycle the pallet waste, as well as any direct emissions arising from the waste processing.

The release of biogenic carbon of timber pallets in landfill and municipal incineration was included as per the corresponding ecoinvent process. The emissions of burning are defined by the Intergovernmental Panel on Climate Change (IPCC) (see Table A 2

We applied different EOL scenarios based on the assumed likelihood of the pallets ending up in landfill, incinerated, recycled, etc. Two EOL scenarios were deemed unlikely, and were excluded from the analysis:

- Municipal incineration, as pallets are unlikely to enter that waste stream; and
- Recycling of Re>Pal pallets, because the material can only be reprocessed by Re>Pal itself, and a product stewardship scheme is not in place.

There is little evidence in terms of the EOL scenarios for each pallet, and it was also removed from the influence of the pallet manufacturer (since we are not looking at pooling). Therefore, we assumed that the used pallets are processed using different pathways, based on deemed probability.

Table 13 – EOL options for Re>Pal and benchmark pallets.

End of life	Pallets	Process	Included processes	Probable
Municipal incineration	Re>Pal Timber, conventional plastic	Waste disposal services dispose of pallets in municipal incineration facilities	Operation of incinerator and emissions	No
Dumping and burning	Timber	Pallets are burned outside appropriate facilities	Direct emissions	Yes
Recycling	Re>Pal Timber, conventional plastic	Pallets are recycled by waste disposal services or in the factory (Re>Pal)	Preparation of materials for reprocessing, excluding inputs to reprocess materials	Yes for timber and plastic No for Re>Pal[11]
Landfill	Re>Pal Timber, conventional plastic	Waste disposal services dispose of pallets in landfill	Operation of landfill and direct emissions	Yes
Mulching	Timber	Pallets are mulched up for animal bedding or landscaping	Shredding	Yes

In the scenario model, we assumed an average EOL impact, i.e. that equal shares of waste are distributed among probable EOLs.

In the bespoke logistics tool, the user can select an EOL and the corresponding impact is calculated.

The environmental impact of each EOL option varies for each pallet, as it depends on the type of material of the pallet (see emission factors in Table 14).

[11] This case was considered in a sensitivity analysis in Section 7.3.2.

Sending Re>Pal pallets to landfill has a lower carbon footprint than landfilling timber pallets, since the timber pallet will decompose and emit methane (a potent greenhouse gas), while Re>Pal will remain largely inert in landfill. The same is true for conventional plastic pallets.

Table 14 – Climate change impact of EOL options for main pallet materials.

Pallet	End of life	kg CO_2 eq./kg material	kg CO_2 eq./average pallet
Re>Pal	Landfill	0.088	2.222
Timber	Recycling	0.333	7.496
	Landfill	0.415	9.326
	Burning, hardwood	0.230	5.166
	Burning, softwood	0.230	5.166
	Mulching	0.016	0.351
Conventional plastic	Recycling[12]	-	-
	Landfill	0.088	2.725

[12] No pre-processing considered.

5. Bespoke Re>Pal tools

Two tools were built for Re>Pal for posterior use (see Figure 10).

One tool articulates the manufacture process and has been designed to update the cradle-to-gate LCA of Re>Pal upon adjustments in production (see Figure 11).

The second tool articulates the possible logistic scenarios based on a set of parameters and compares a Re>Pal pallet stock with another pallet stock (see Figure 12).

Both tools are connected to the same background datasets and impact calculation algorithms. This logistics LCA tool compares like for like applications and use scenarios for Re>Pal and alternative pallet solutions (i.e. functionally equivalent). It will also process different scenarios and combinations for pallet uses, durability and EOL fates.

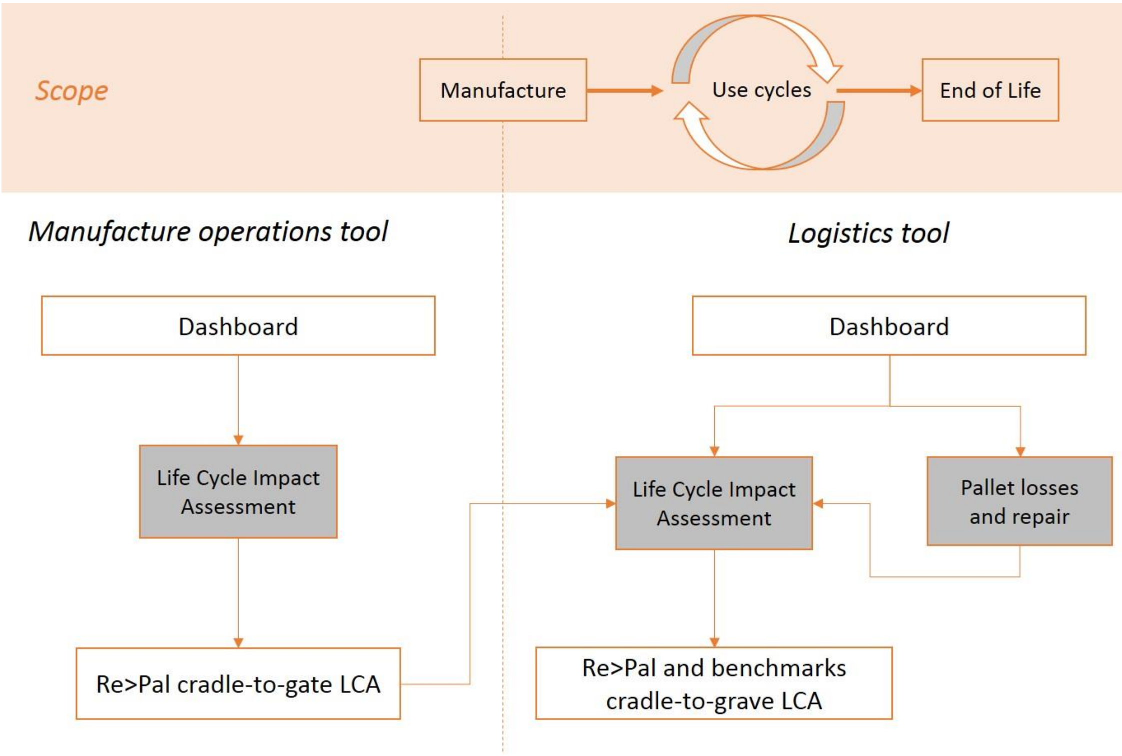

Figure 10 – Articulation and scope of manufacture and logistics tools.

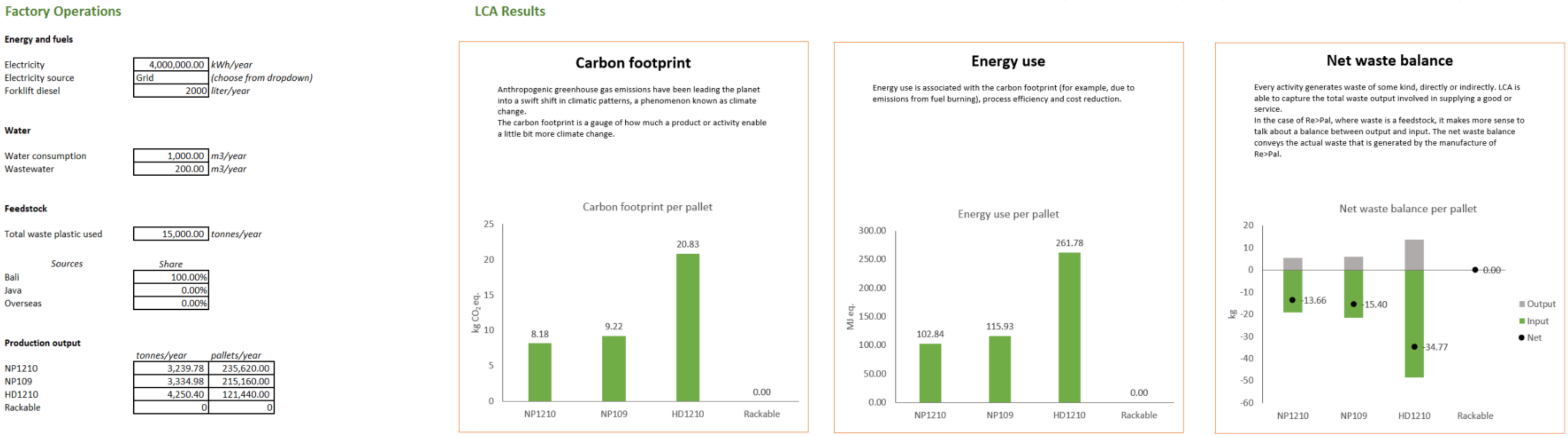

Figure 11 – Screenshot of tool to calculate cradle-to-gate LCA of Re>Pal pallets based on annual production data. The figures in the dashboard can be updated to match ongoing conditions at Range International's factory, which automatically updates the LCA results.

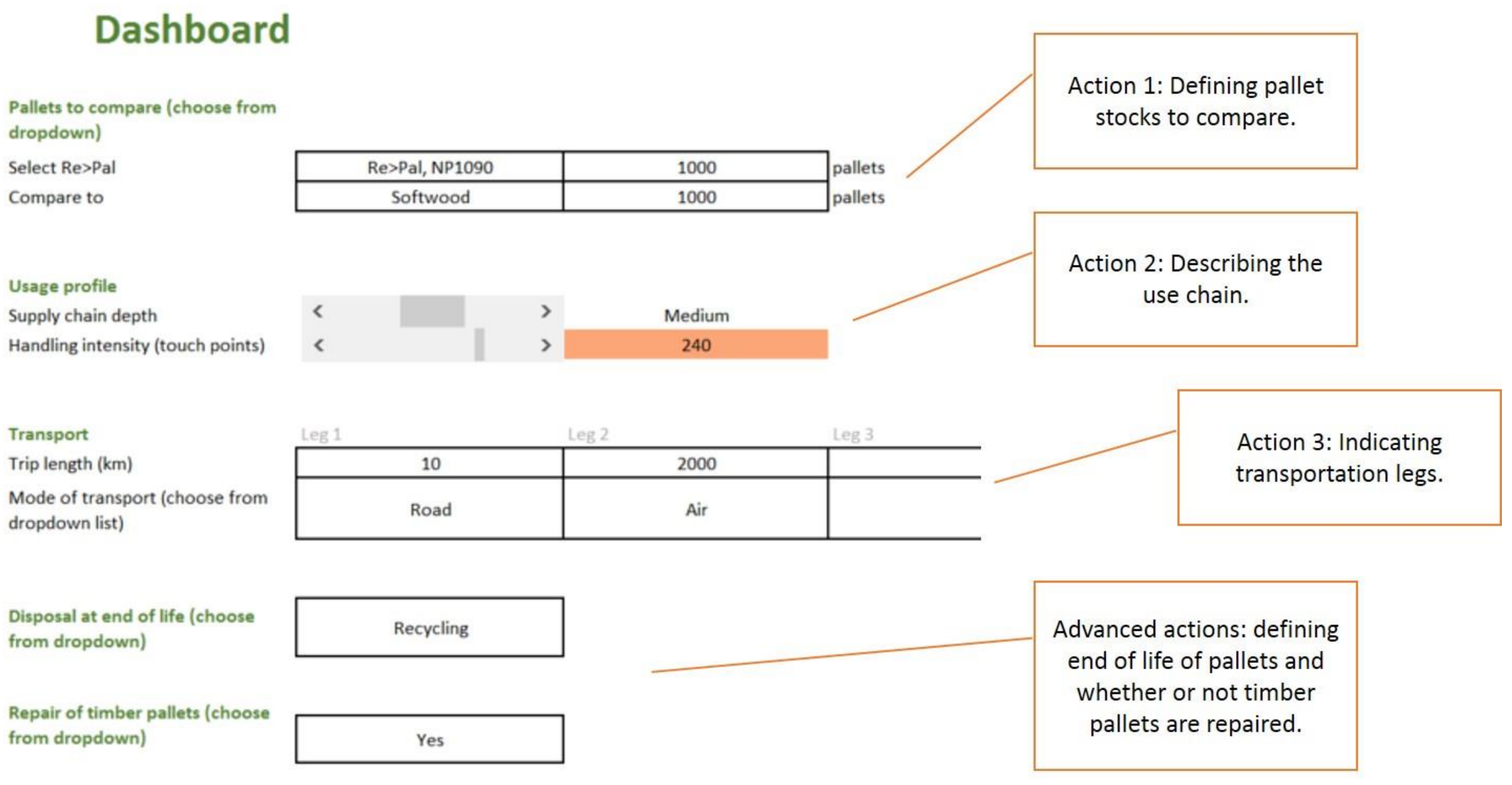

Figure 12 – Draft dashboard of the logistics LCA tool. Based on the intended used defined in the dashboard, this tool calculates the comparative environmental impacts of two pallet stocks.

6. Results

The results from the LCA are set out in this section as impacts on:

- 100-year climate change (kg CO_2 eq.), also known as the carbon footprint or global warming potential;
- the cumulative energy demand (MJ eq.), which measures the total energy use by the life cycle;
- fossil fuel depletion (kg oil eq.), which measures the rate of depletion of finite energy resources;
- terrestrial acidification (kg SO_2 eq.), which impacts on soil quality, the built environment and forests;
- freshwater eutrophication (kg P eq.), which is the excessive nutrient enrichment of freshwater bodies, causing algal bloom and oxygen depletion for aquatic life;
- land occupation (m^2a), encompassing urban and agricultural land;
- land transformation (m^2), reflecting land use change; and
- the waste output and net waste balance (kg).

In addition, we explore:

- the implications of timber requirements of timber pallets (in terms of trees used); and
- the implications of plastic waste diversion by Re>Pal.

We report on the cradle-to-gate impact of each pallet type, as well as on the cradle-to-grave impact per trip for each pallet type and different supply chain depth.

In summary, and the details are in the following sections, the study found that:

- At the factory gate, Re>Pal pallets have a lower carbon footprint than conventional plastic and tropical mixed hardwood pallets, but slightly higher than softwood pallets from sustainably managed timber sources.
- The main driver of the carbon footprint of Re>Pal manufacture is electricity used in the factory. If the whole life cycle is considered, transport and EOL are also important factors.
- Re>Pal pallets have lower environmental impacts than its counterparts along the use and disposal stages under present assumptions on pallet durability and replacement needs.
- Re>Pal pallets are nearly waste neutral because they use nearly as much waste plastic as the total waste produced through its life cycle.
- The carbon footprint may change if Re>Pal sources waste plastic from a different source mix and also depending on the EOL of the pallet.

Detailed results tables are provided in Appendix D.

6.1. Cradle-to-gate LCA

Cradle-to-gate LCA impacts include the sourcing and transport of raw materials and pallet manufacture. The assessment stops at the factory gate, which means that use and distribution are not accounted for. This is an incomplete comparison, since the service or function of the different pallets are not equal. These results are shown per pallet, rather than per trip, for that same reason.

Figure 13 and Figure 14 show that Re>Pal pallets have a lower impact than conventional plastic and tropical mixed wood pallets, but a higher impact than softwood pallets.

Comparing Re>Pal and timber at the factory gate shows the following:

- A heavy duty Re>Pal has 37% lower global warming potential and has 109% less energy than a heavy duty tropical mixed hardwood pallet.
- Nestable Re>Pal have 114% to 141%% lower global warming potential and over 1000% less energy demand than a light duty tropical mixed hardwood pallet.
- Nestable Re>Pal have 2% to 13% higher global warming potential and 10-11% less energy demand than a softwood pallet.

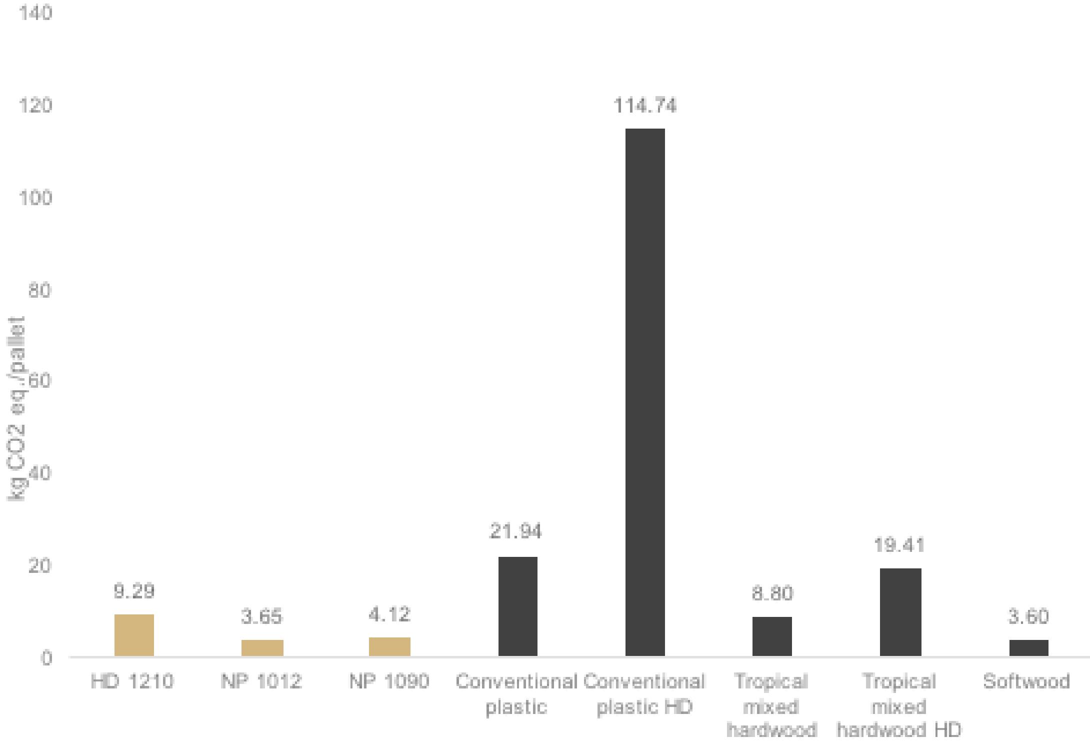

Figure 13 – Global warming potential from the manufacture of Re>Pal pallets (orange) and its benchmarks (blue).

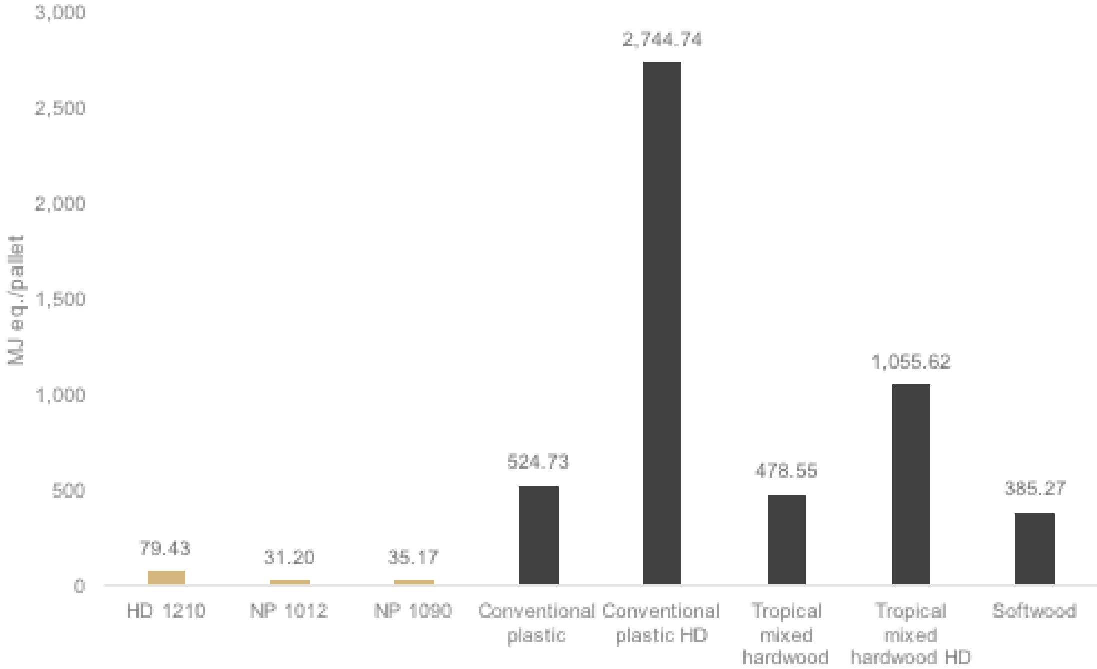

Figure 14 –Cumulative energy demand from the manufacture of Re>Pal pallets (orange) and its benchmarks (blue).

Timber pallets require more energy due to electricity use at manufacturing and due to machinery use in forestry operations and wood processing.

Conventional plastic pallets have the highest enviromental impact due to electricity use during manufacture, as well as due to the provision of HDPE. The fact that 15% of the HDPE is scrap does not attenuate impacts because of the energy invested in recovering and reprocessing the waste plastic.

The impact of climate change is related to energy demand (see Figure 15).

The main driver of impact of Re>Pal pallets are:

- electricity use in the factory - 70% of the global warming potential and 86% of the energy demand;
- followed by the treatment of manufacturing waste – 26% of the global warming potential and 3% of the energy demand;
- and transport of the plastic waste to the factory – 4% if the global warming potential and 11% of the energy demand.

The waste leaving the Re>Pal factory is a mix of mud from the washing line and rejected feedstock waste that is landfilled (e.g. contaminants, aluminium foil). Emissions and energy use to process and landfill the waste are included.

The transport of feedstock contributes to 4% of emissions, which is due to change if Range International starts sourcing waste plastic feedstock from other locations (see sensitivity analysis in Section 7.3.1).

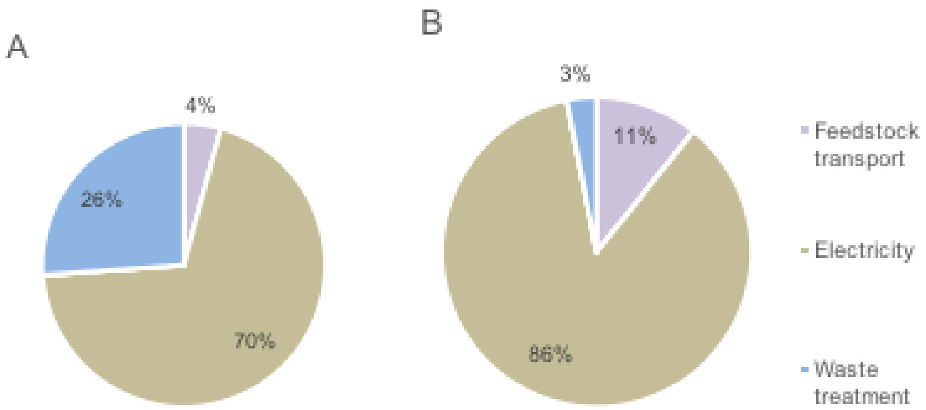

Figure 15 – Contribution to the climate change impact (A) and to embodied and onsite energy use (B) of inputs of Re>Pal pallet manufacture in the Tabanan factory.

6.2. Cradle-to-grave LCA

The main changes in inputs to the supply chain driven by an increase in use intensity are the replacement pallets or repair materials, the disposal of waste (of the pallet and the portion that has been repaired/replaced) and transport distances.

The deeper the supply chain, the more pallets are required to fulfil one trip. Hence, there is a common trend for higher demand for raw materials and manufacture. Accordingly, there is the need to displace more pallets and an increased need to dispose of retired pallets. Because emissions across all these life cycle stages are proportional to the weight of material being produced, transported and disposed of, emissions increase with the depth of the supply chain. This applies to all pallets.

6.2.1. Midpoint indicators

Re>Pal

- The main contributor to the climate change impact of the Re>Pal life cycle is transport (57%), followed by manufacture (28%), EOL (10%) and raw material provision (5%) (see Figure 16).
- Transport requires 73% of the life cycle energy, manufacture 18%, raw materials 6% and EOL 3% (see Figure 17).

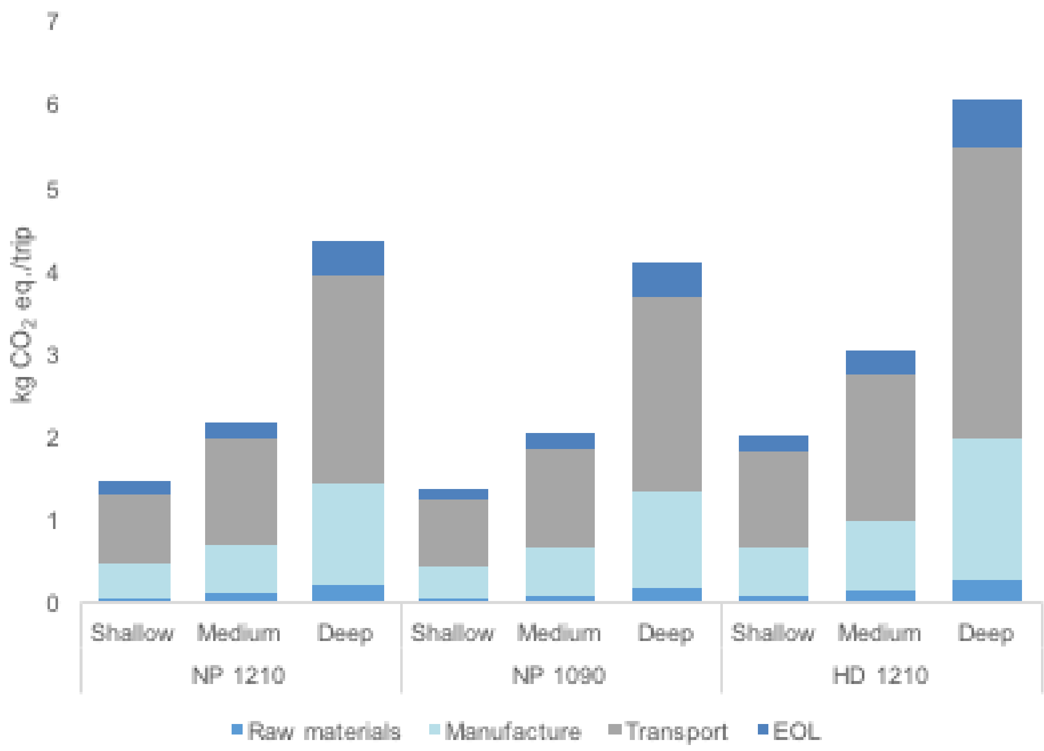

Figure 16 – Global warming potential of 1 trip by Re>Pal pallet at an average handling intensity.

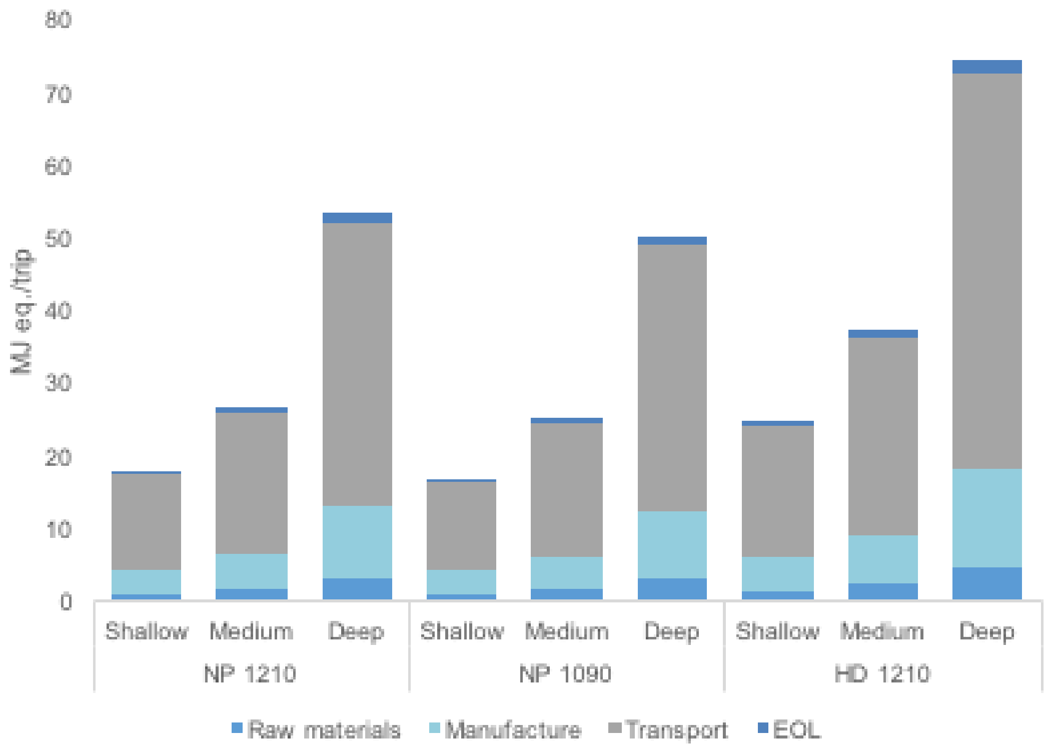

Figure 17 – Cumulative energy demand of 1 trip by Re>Pal pallet at an average handling intensity.

Comparative assessment

Carbon footprint and energy use

As it would be expected, the climate change impact and energy demand increase with use intensity (see Figure 18 and Figure 19). The main driver behind this increase is the replacement of pallets or their repair, and the disposal of retired pallets and waste pallet materials.

When logistics requirements are considered:

- Re>Pal pallets have lower emissions and lower energy requirement than their conventional plastic and timber counterparts. This is due to their higher average expected durability, that means that Re>Pal can handle more trips.
- Despite having the highest emissions per pallet, heavy duty conventional plastic pallets fare on average better than timber pallets per trip. This is due to higher durability as well.
- Repairing timber pallets does not give them a significant advantage because replenishing damaged materials and disposing of them negates the durability potential.
- Repair and replacement of timber and conventional plastic pallets, respectively, is the main differentiator of logistic impacts.

Other midpoint indicators

The same trend of impact aggravation with use intensity is observed in the remaining indicators. Re>Pal has lower impact than all other pallets across all indicators.

- Terrestrial acidification (see Figure 20) and freshwater acidification (see Figure 21): Re>Pal pallets have a consistently lower impact, while other pallets fall within the same impact range among each other.
    - Fossil fuel depletion (see Figure 22):
    - Fossil fuel use observes the same pattern of cumulative energy demand, with Re>Pal pallets having a lower impact.
    - Conventional plastic pallets require markedly more fossil fuels, due to plastic production.
    - Among timber pallets, softwood uses more fossil fuels because of high material requirements due to breakage linked with energy use in forestry operations.
- Land occupation and transformation (see Figure 23 and Figure 24):
    - Non-timber pallets have negligible impacts.
    - Softwood pallets take up more land across the life cycle than hardwood pallets due to higher timber requirements.
    - Tropical hardwood causes more land use change due to deforestation. Land transformation is negligible in softwood because the timber hails from sustainable forestry.

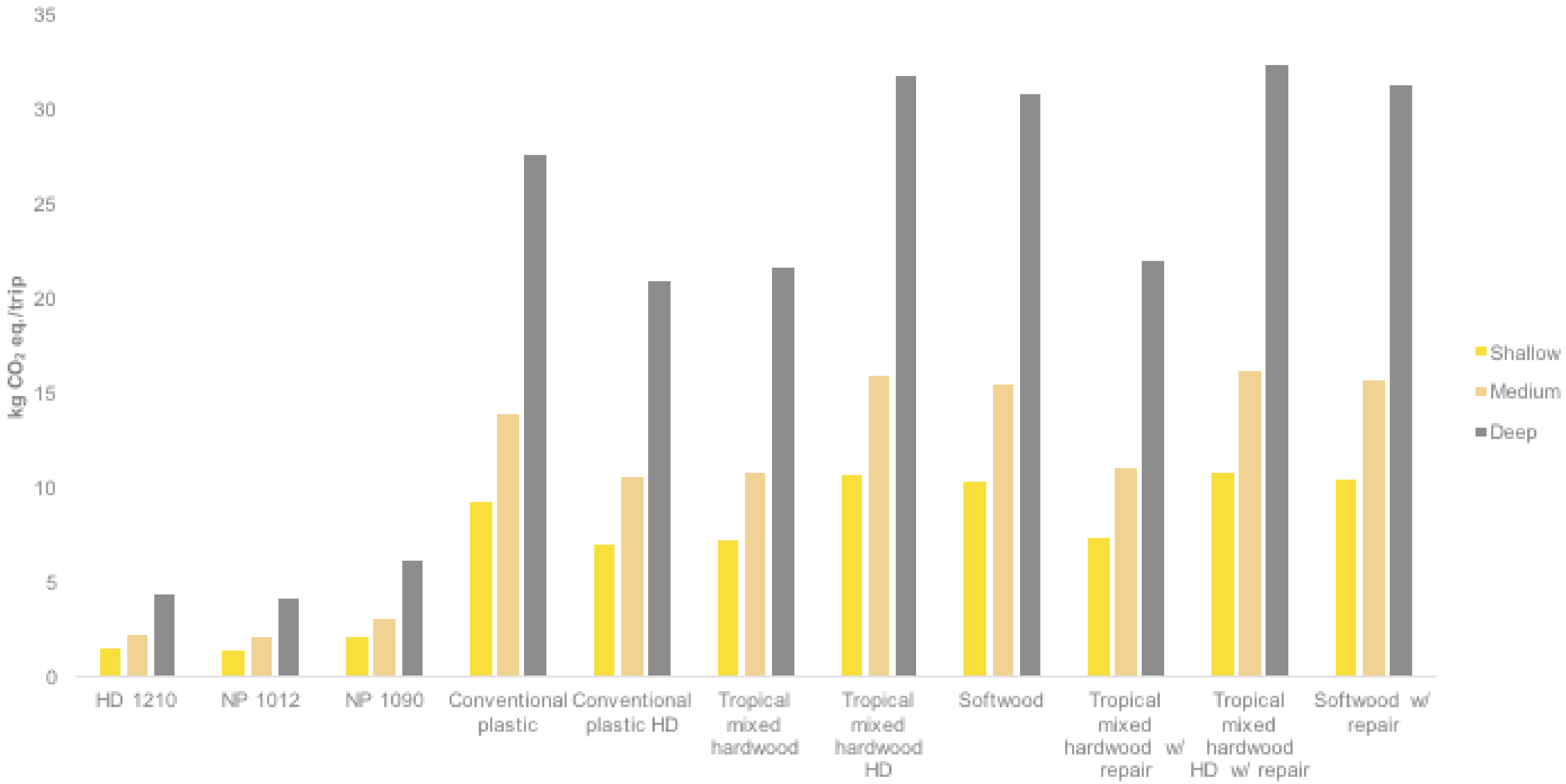

Figure 18 – Global warming potential of 1 trip per pallet type in each supply chain depth, at average handling intensity.

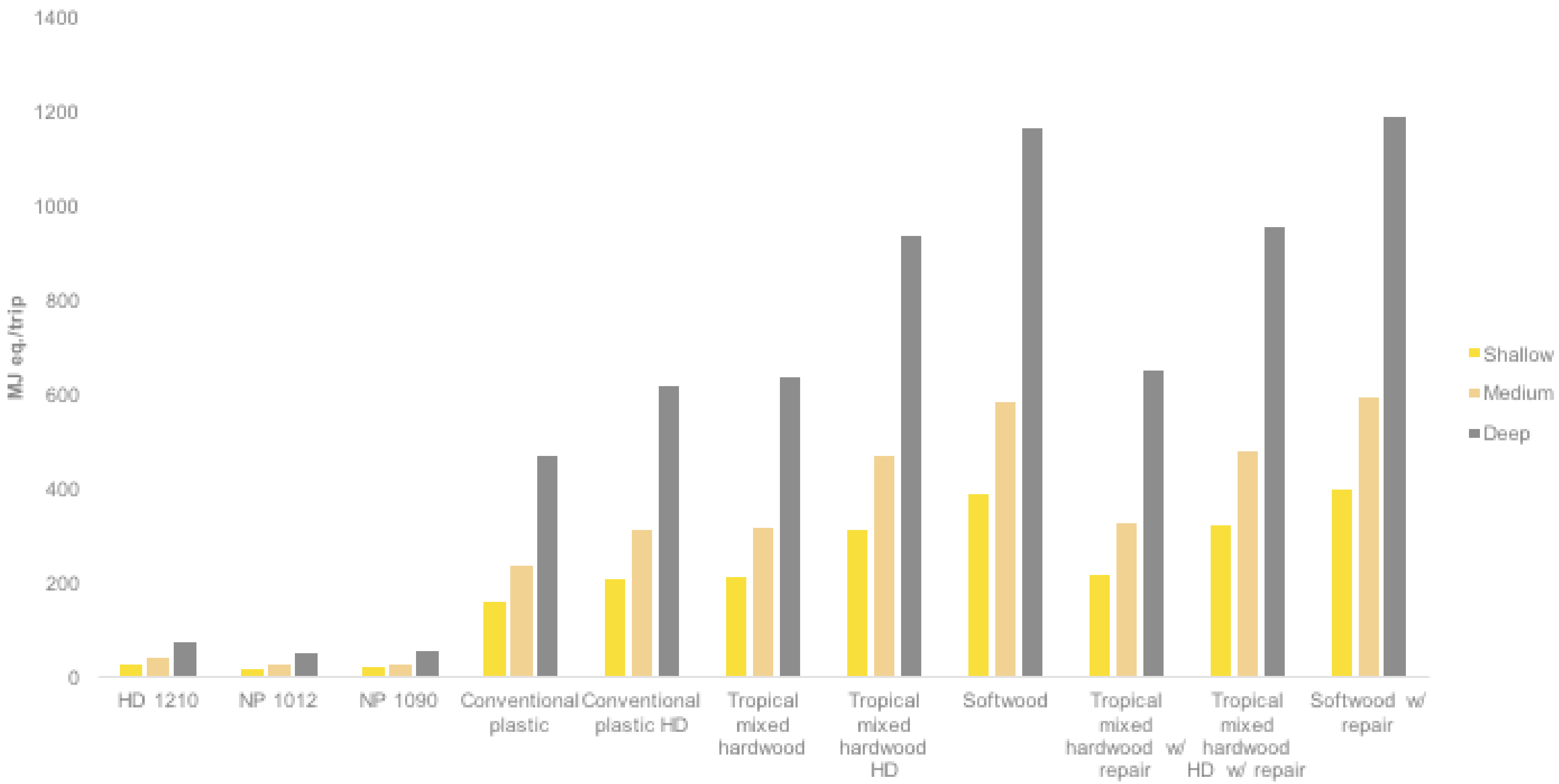

Figure 19 – Energy demand of 1 trip per pallet type in each supply chain depth, at average handling intensity.

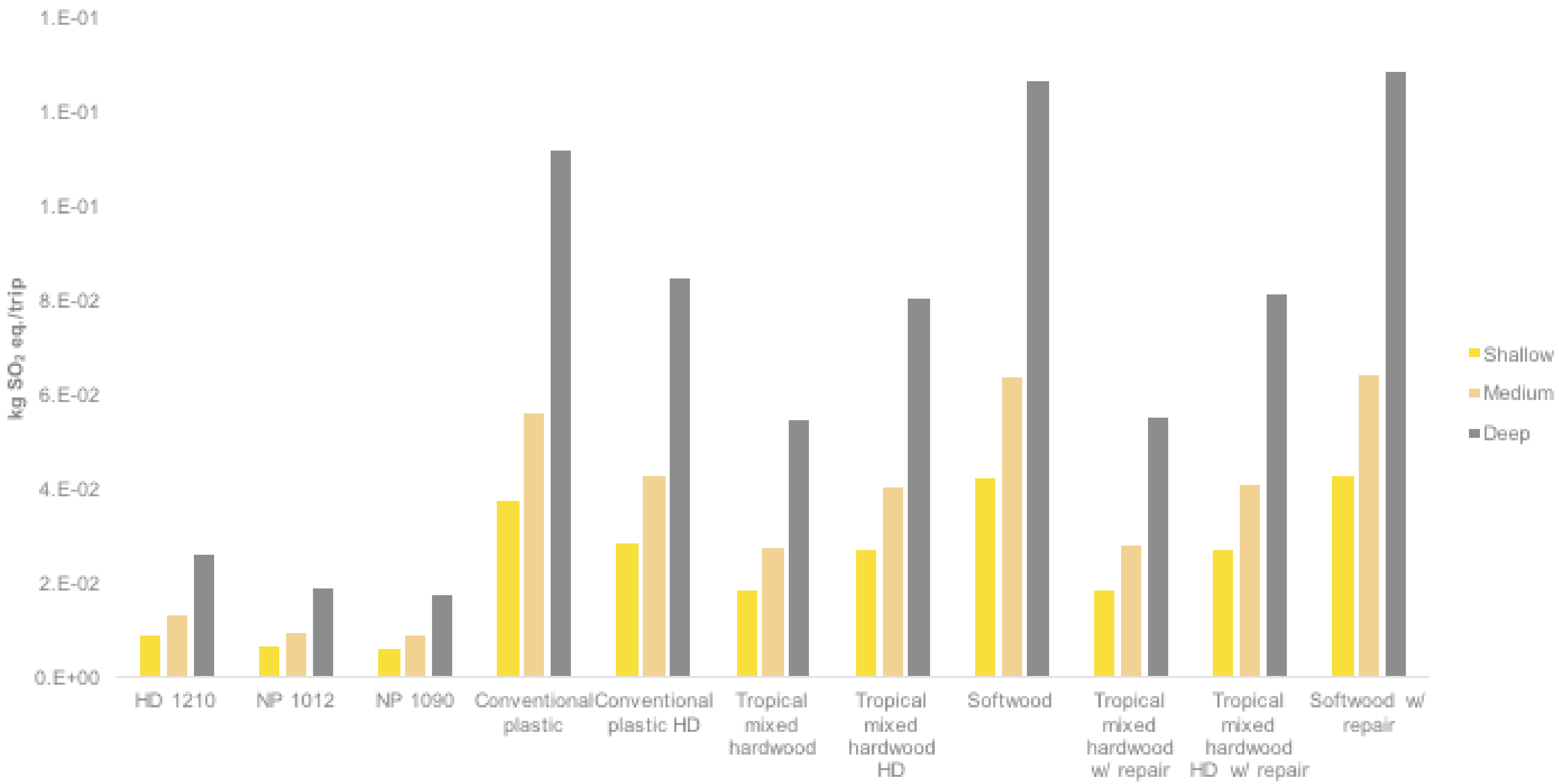

Figure 20 – Terrestrial acidification of 1 trip per pallet type in each supply chain depth, at average handling intensity.

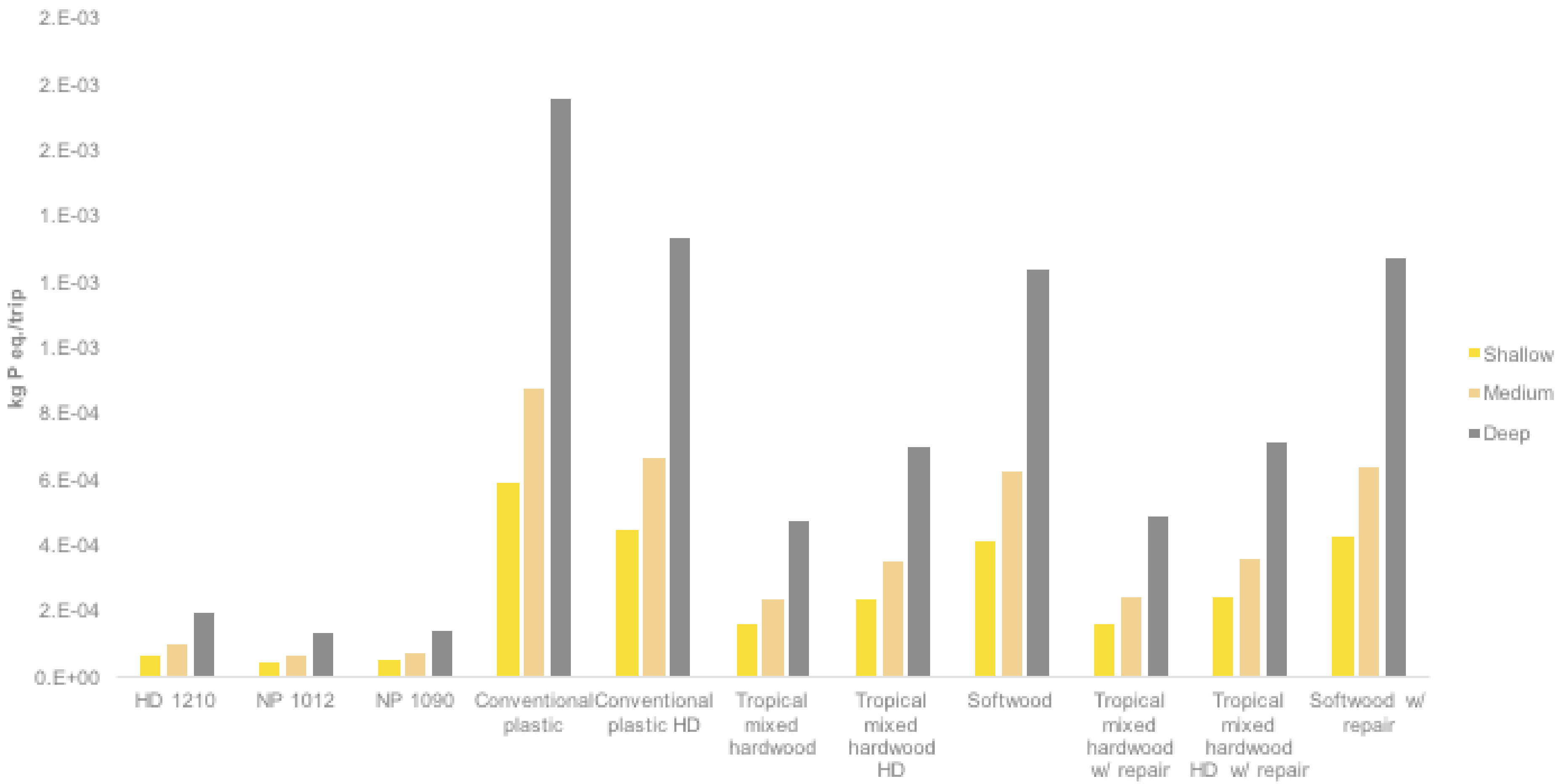

Figure 21 – Freshwater eutrophication of 1 trip per pallet type in each supply chain depth, at average handling intensity.

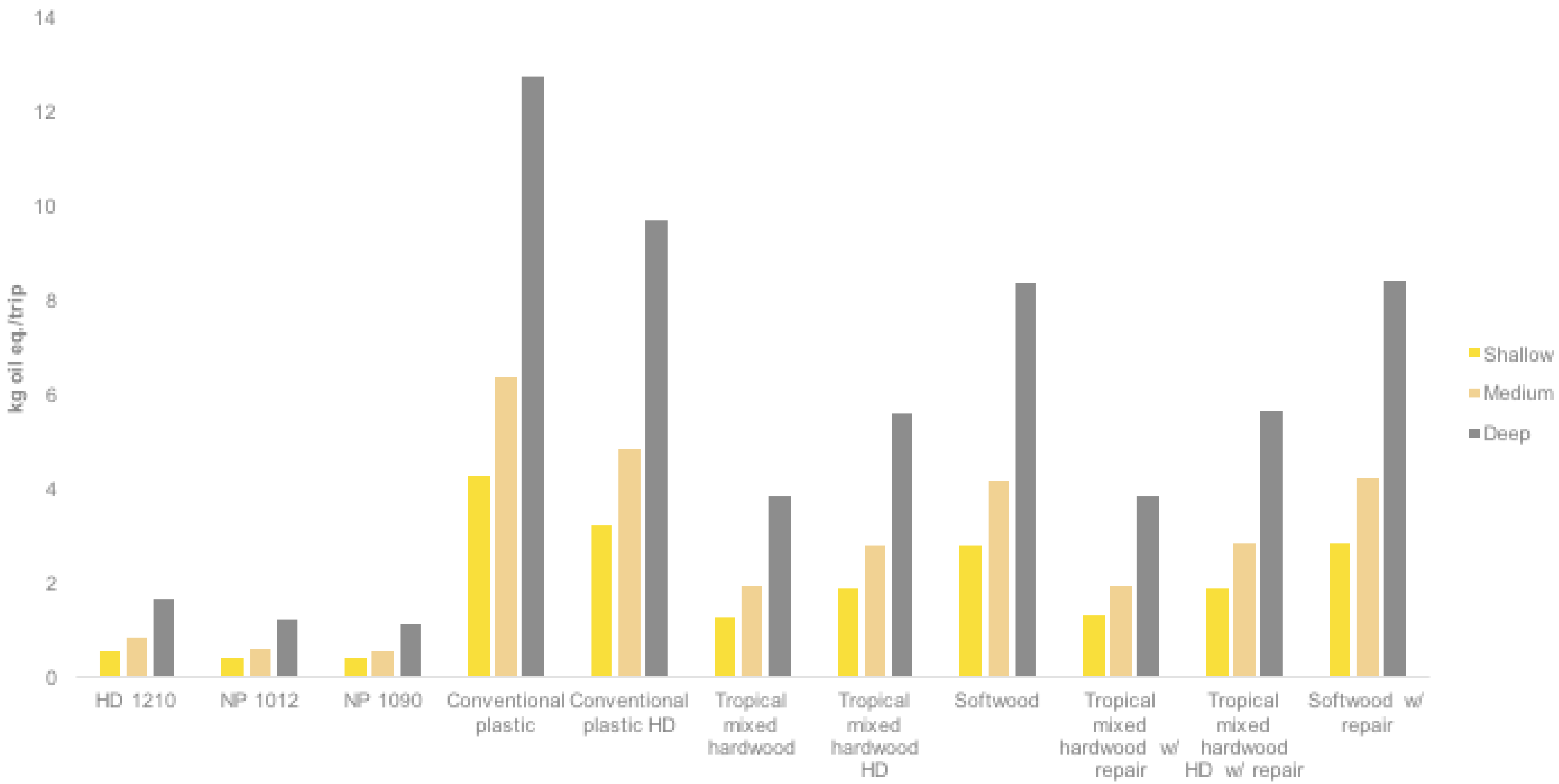

Figure 22 – Fossil fuel depletion of 1 trip per pallet type in each supply chain depth, at average handling intensity.

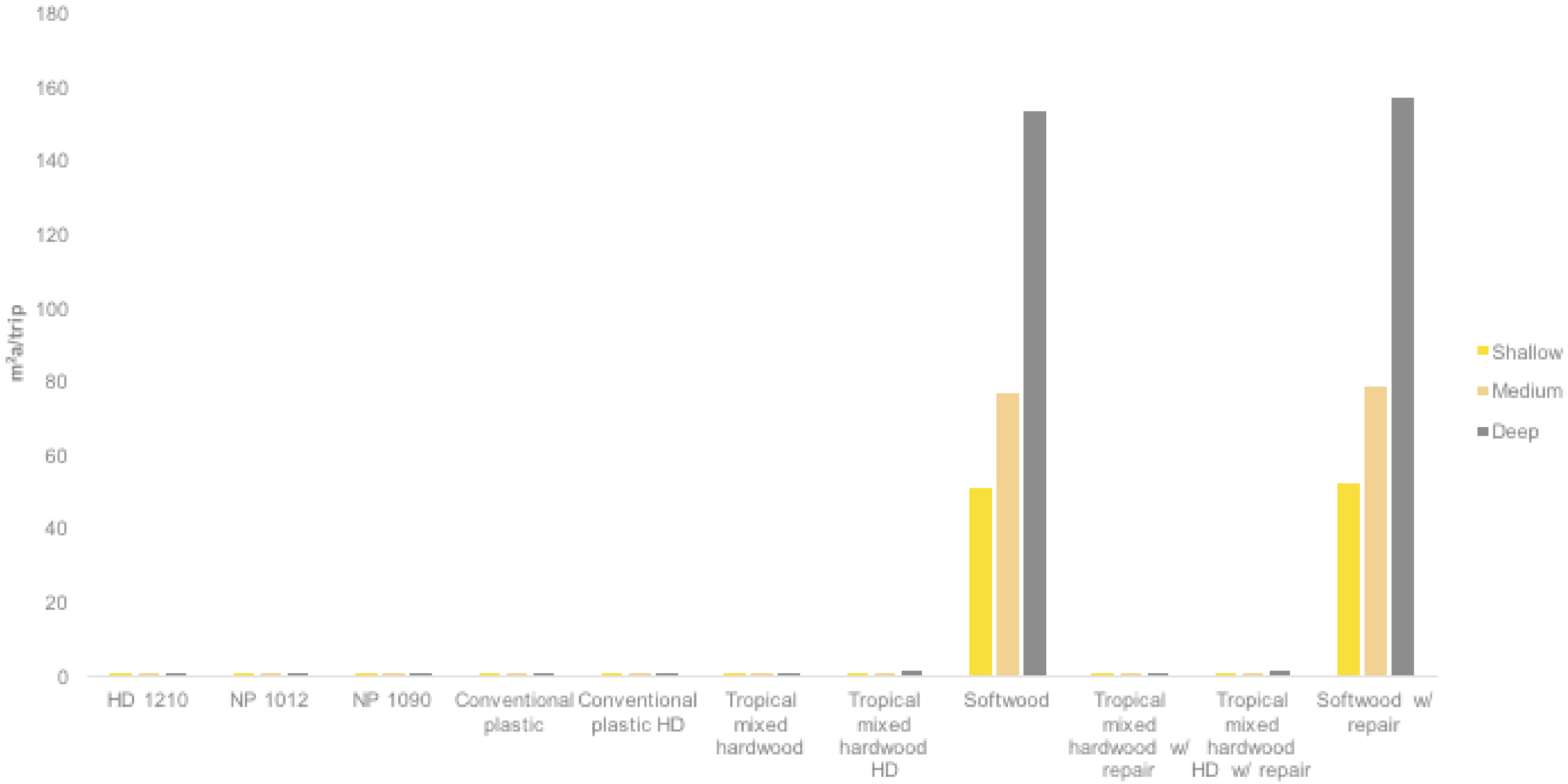

Figure 23 – Land occupation of 1 trip per pallet type in each supply chain depth, at average handling intensity.

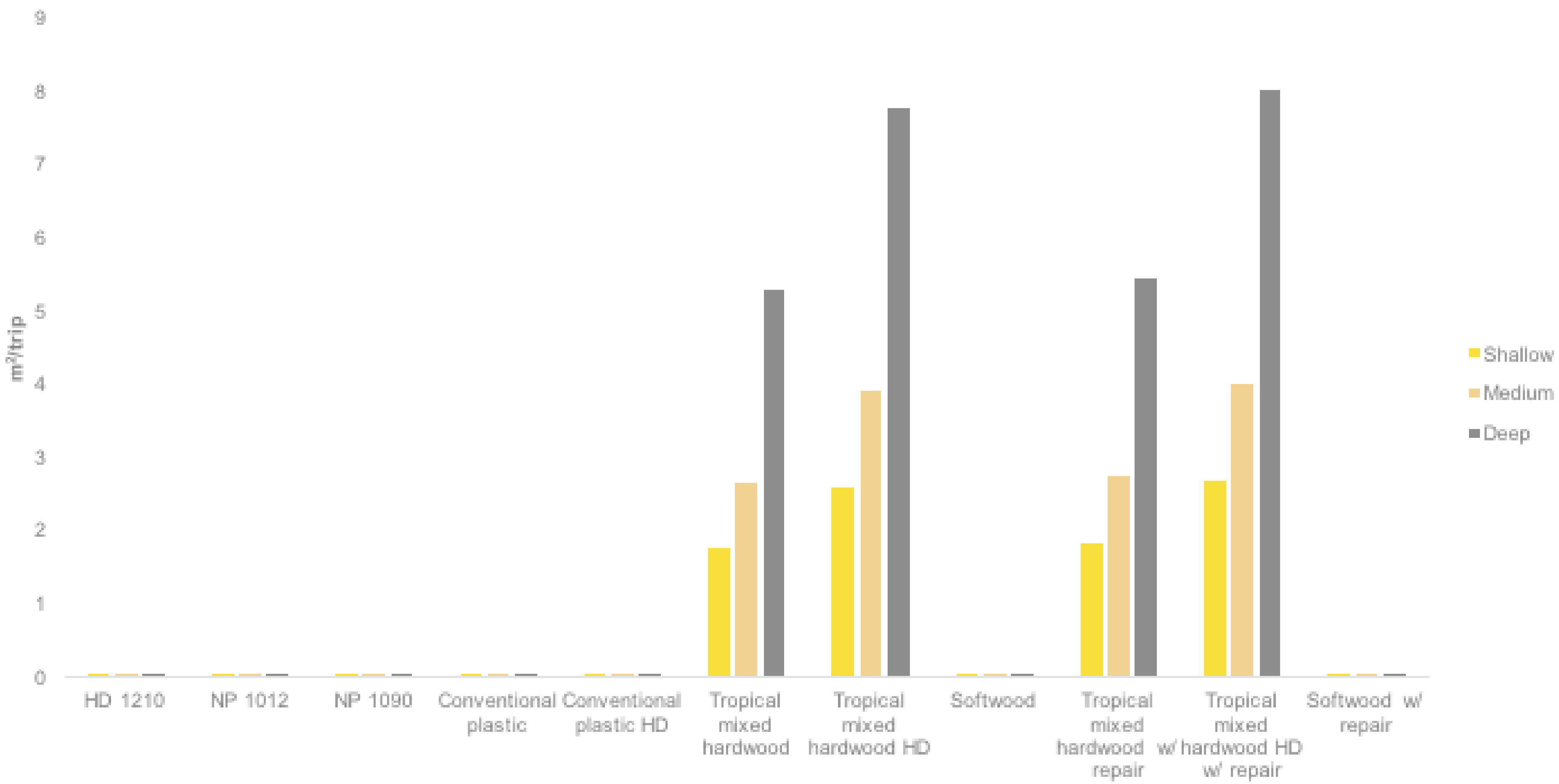

Figure 24 - Land transformation of 1 trip per pallet type in each supply chain depth, at average handling intensity.

6.2.2. Endpoint indicators

Midpoint indicators can be processed further in the impact assessment chain into endpoint indicators. Endpoint indicators convey a degree of damage to different spheres. In this study, we report on damage to human health and to ecosystems:

- The unit of an impact on human health is disability adjusted life years (DALY), which indicates years of healthy life lost.
- The unit of impact on ecosystems is species.yr, which an indicator of lost biodiversity and specimen abundance.

Because they are a step further from midpoint indicators, endpoint indicators often closely follow the formers' trends:

- Pallets with higher emissions to the environment have a higher impact on human health as well (see Figure 25). In fact, Re>Pal pallets lead to lower human health impacts than other pallet types.
- Pallets that require more land lead to higher damage to ecosystems. On this impact category, timber pallets stand out with the highest impact (see Figure 26).

6.3. Waste

This section reports on the quantities of waste generated by Re>Pal and conventional pallets, as well as on the implications of waste diversion from the environment and landfills.

6.3.1. Waste generation and net waste balance

The waste generated in the life cycle is the total of hazardous, non-hazardous and radioactive waste produced in all life cycle stages. Because Re>Pal and conventional plastic pallets use waste plastic as feedstock, we report as well on the net waste balance, which is the total waste output minus the input. See Figure 27 for graphical results.

- Re>Pal is nearly waste neutral, because the quantity of waste generated per trip during the life cycle is nearly offset by the waste taken up in manufacture.
- The waste flow in Re>Pal pallets is pronouncedly divided in input waste, which is taken up as feedstock, and output waste, resulting from life cycle activities and the pallet EOL.
- Out of all pallet types, softwood markedly generates more waste.

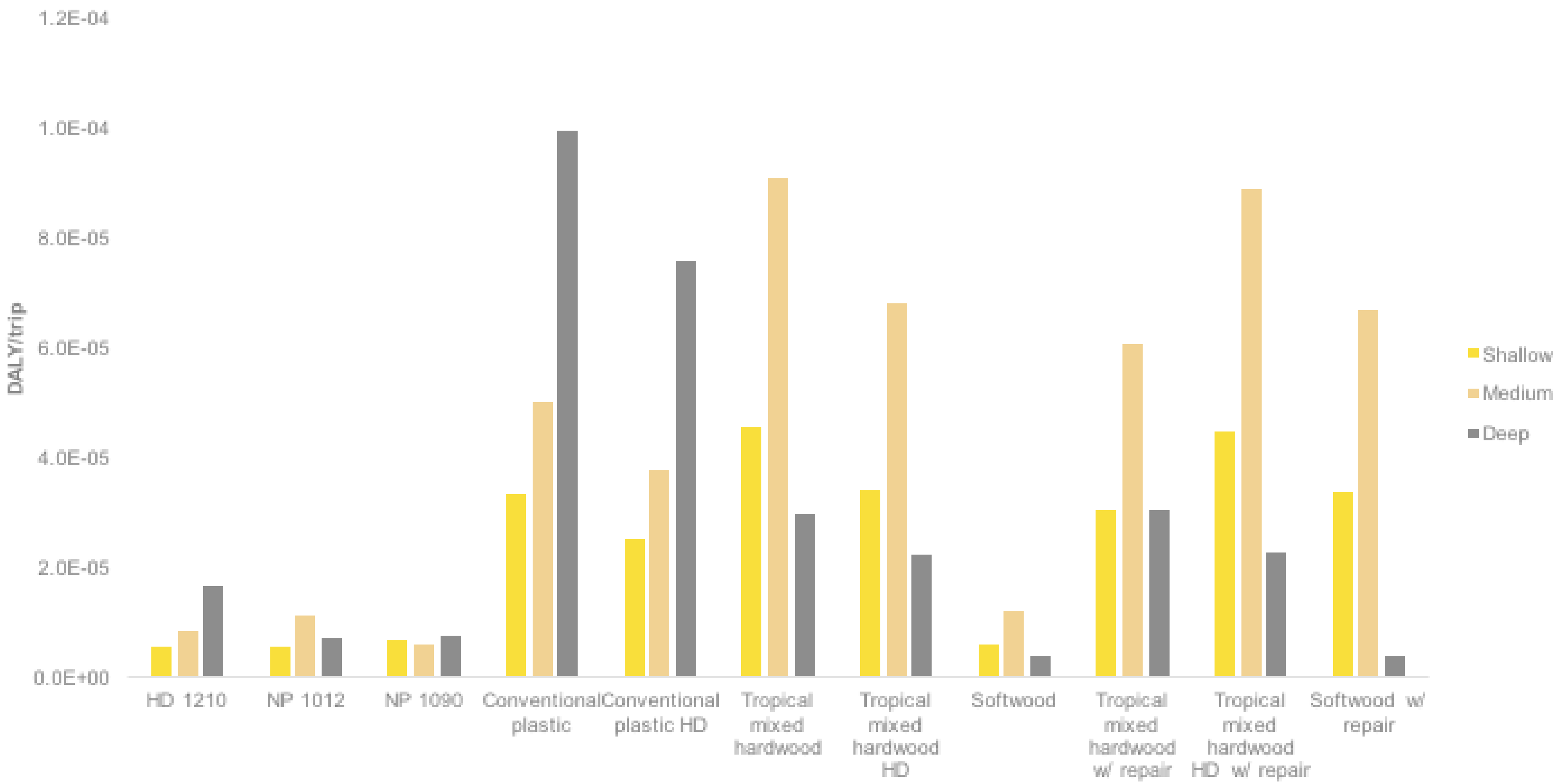

Figure 25 – Human health impact of 1 trip per pallet type in each supply chain depth, at average handling intensity.

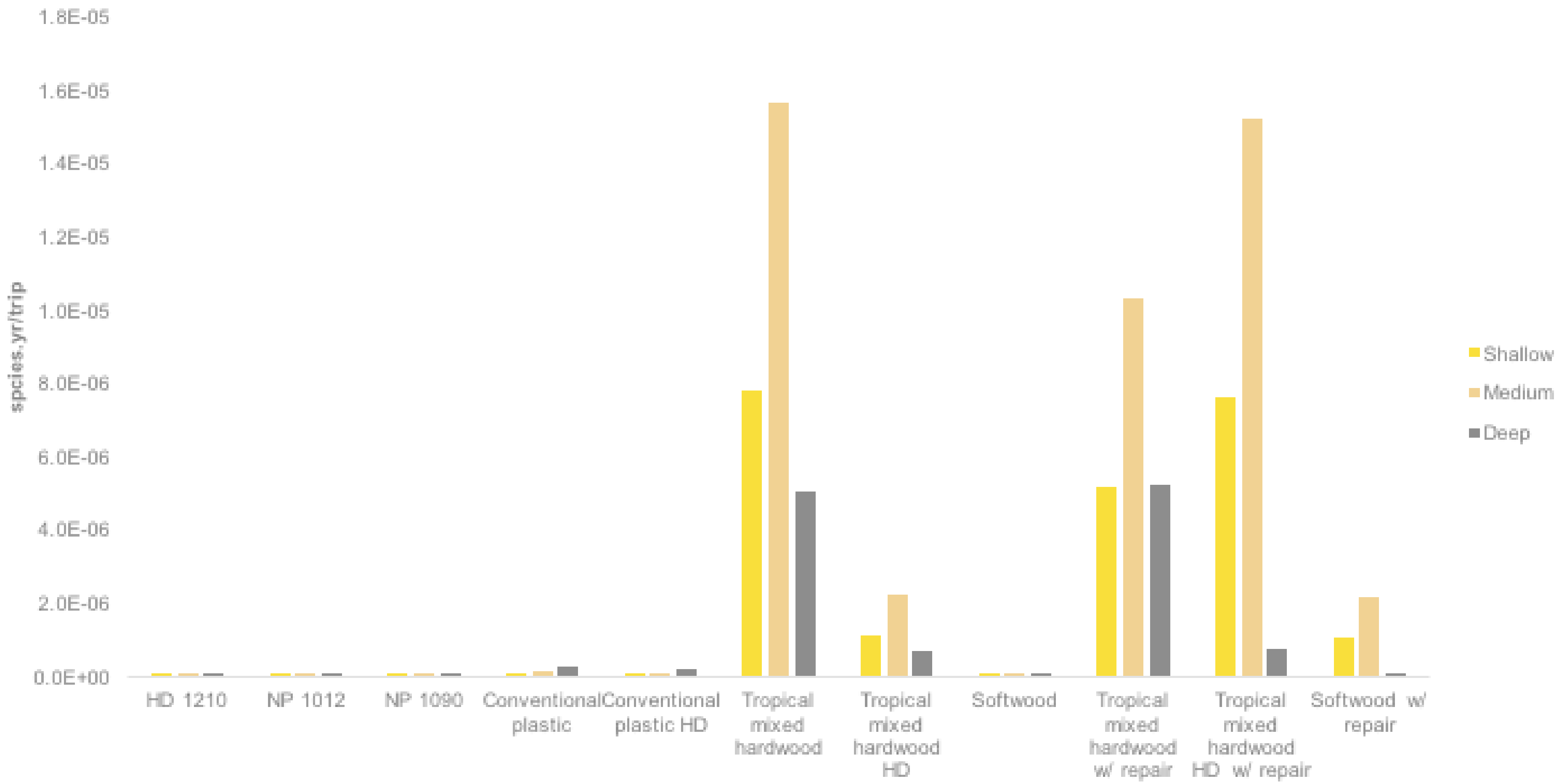

Figure 26 – Ecosystem damage of 1 trip per pallet type in each supply chain depth, at average handling intensity.

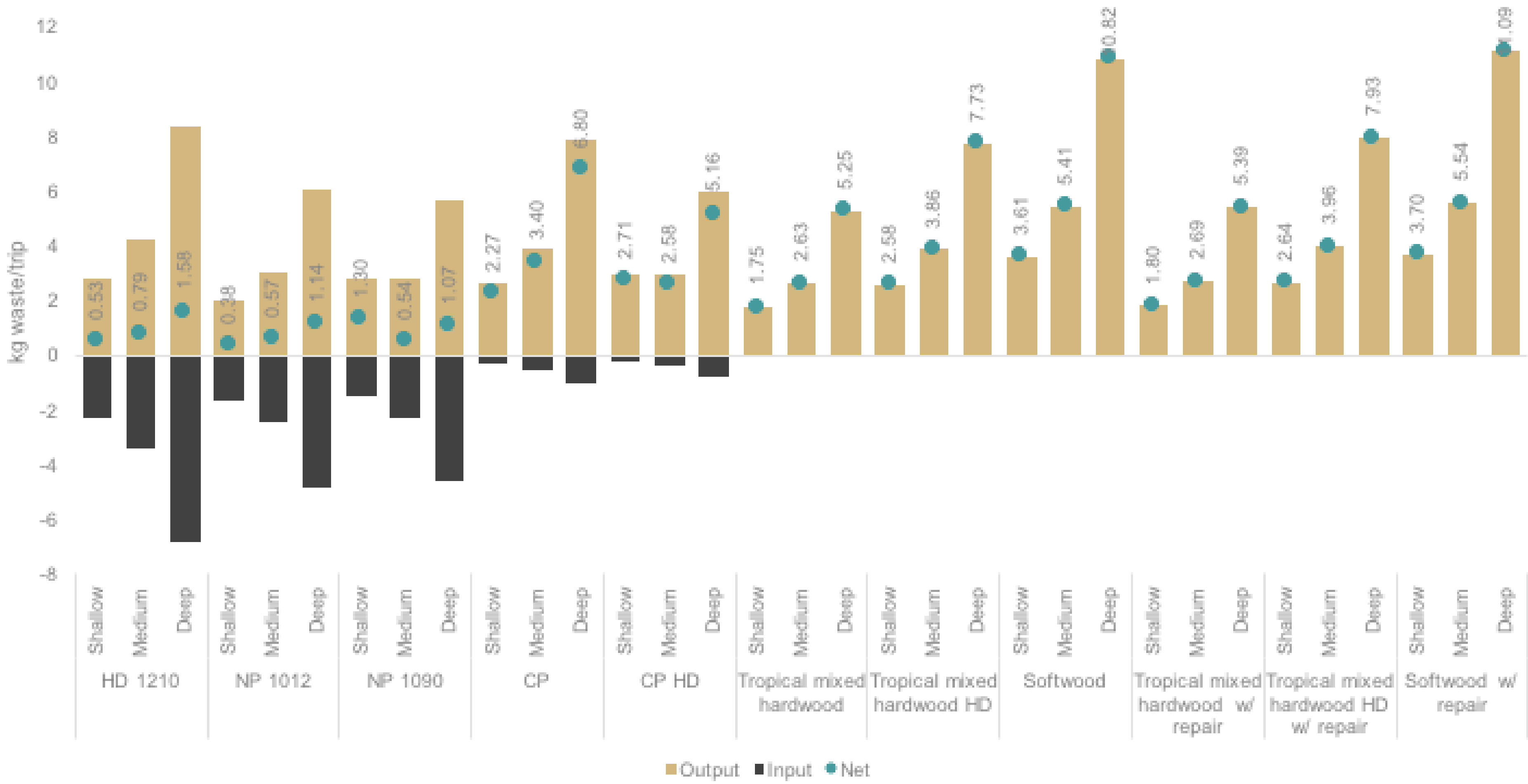

Figure 27 – Waste balance of 1 trip per pallet type in each supply chain depth, at average handling intensity. Dots are the net generated balance considering waste uptake for manufacture (input) and waste generated during life cycle (output).

6.3.2. Implications of waste diversion

At full capacity, the Tabanan factory can process around 25,547 tonnes of waste plastic annually and beneficiated it into pallets. Re>Pal sources waste plastic that normally would not be recycled, such as soft plastic or contaminated plastic. This constitutes a true waste stream, which is visible in the fact that the feedstock of Re>Pal pallets is burden free, in contrast to timber and conventional plastic pallets.

As stated in Section 3.5, Re>Pal cannot be credited with the diversion of waste plastic from landfill. The reason for this is twofold:

a) LCA guidelines do not allow this credit to be granted to a product that metabolises waste material.

b) To our knowledge, there is no method to estimate the environmental impact of the presence of plastics in the environment as litter or in landfill.

In this section we summarise the known facts about plastic litter and plastic landfilling, and investigate the high-level contribution of Re>Pal in addressing the problem of excess plastic in landfills and in the environment.

Plastic in landfills

Closed landfills are relatively controlled environments, where plastics can be disposed of with minimal interference with the environment. Because they are relatively stable materials, the emissions from landfilling plastics are relatively small when compared, for instance, with landfilling organic materials. The main life cycle impacts of landfilling plastics pertain to the operation of the landfill, which is relatively small (compared with the impacts of recycling operations, for instance).

The main environmental issue with landfilling plastics is the wastage of invested resources. The production of plastics depletes fossil fuels as feedstock and as energy, which are invested in a durable material that can be reprocessed for reuse several times. When plastic is landfilled, the plastic reaches the end of its useful life without yielding further value, which means that the return on that investment ceases.

The alternatives to landfill are incineration, incineration with energy generation, or recycling. The latter two are EOL pathways with added value. Recycling is often difficult because of contamination and because not every plastic material is efficiently reprocessed.

The benefit of Range International's diversion of plastic from landfill focuses on that: providing a new utility to materials, and creating a new product from a non-depleting feedstock.

Plastic pollution in the environment

Despite being a recurrent environmental topic, there is not enough knowledge on the environmental impact of plastic litter to develop a specific method to account for it (Todd, 2016; Sherrington, et al., 2016; Sherrington, et al., 2014). A small body of scientific literature points coarsely to a set of key issues, but the magnitude of causal relationships and predictive factors have not been identified and systematised. Some of these issues are:

- Toxic substances released by plastics during their slow degradation;
- Harmful interaction of marine species with plastic litter;
- Accumulation of plastics in oceanic benthic zones;
- Harmful interaction of terrestrial microorganisms with plastic debris; and
- Negative landscape effects of plastics in natural environments.

Most of these phenomena focus on the marine environment. Of the world's marine litter, 60–80% consists of plastic. It is estimated that there are 289,000 tonnes of plastic particles floating in the world's oceans (Eriksen, et al., 2014), plus 1.5 million tonnes in the beaches (Eunomia, 2016). In 2017, 5.1 billion pallets are expected to be manufactured (Freedonia, 2014). If Re>Pal were to replace 1% of that market, it would consume a quarter of the world's floating and beach plastic waste.

South East Asia is responsible for the generation of marine litter in quantities that exceed global averages, and is also a hotspot for its accumulation (Todd, et al., 2014; Eriksen, et al., 2014). The presence of plastics in coastal fringes in South East Asia is increasing, due partly to the accumulation (by slow degradation) of plastics and its increased use and improper disposal (Todd, et al., 2014).

It is known that due its very slow degradation and its buoyancy, plastics easily come into contact with marine animals, choking them or preventing their mobility. Through this mechanism, plastics affect marine biodiversity, although it is unknown how deeply or widely (Todd, et al., 2014; Sherrington, et al., 2014). It is possible that the absolute numbers of specimens and the diversity of species in the ocean is not greatly affected, simply because animals leave heavily polluted areas (Todd, 2016), depleting biodiversity only at a local level. Even so, biodiversity disturbance can also happen through the colonisation by invasive species that travel attached to plastic debris, even to terrestrial environments (Webb, et al., 2013; Moore, 2008).

It is thought that most plastic litter in the ocean has sank to the seafloor (Eunomia, 2016). There, it may disrupt the interface between seafloor sediments and the water above, disrupting benthic marine life (Moore, 2008).

In addition, plastic particles found in marine environments have been shown to contain organic pollutants with several degrees of toxicity. These compounds can be ingested by marine life, posing a direct threat to it. In addition, they bioaccumulate, becoming a threat to human health as well (Webb, et al., 2013; Moore, 2008).

In the terrestrial environment, plastic debris have negative visual impact in the landscape. They are also known to interfere with soil microorganisms, preventing them from fulfilling their ecosystem services (e.g. maintenance of soil quality) (Browne, et al., 2015).

Requirements of a method to account for impact of plastic disposal

Environmental impact assessment methods relate the output of a pollutant to the environment with an impact or multiple impacts, or the retrieval of a resource from the environment to a depletion. This relationship is examined by models that predict the causal link between the two things, based on large grounds of scientific evidence.

For instance, a climate change impact conveys the link between the output of a greenhouse gas to the atmosphere and how that greenhouse gas affects the atmosphere's capacity to regulate solar irradiation. Atmospheric physical models establish this link. The same greenhouse gas might also affect, with another magnitude, ozone layer depletion, which in turn is established by a chemical transport model.

The main knowledge gaps pertaining to the impact of plastic disposal and plastic littering surround the causal links between the presence of plastic particles, and of substances resulting from plastic degradation, and damages to the ecospheres. As outlined above, some of these links have been observed, but not systematically and statistically quantified. As such, there are no predicting factors relating plastics and a determined environmental effect, and no models have been built.

In addition, the full spectrum of environmental impact is yet unknown, particularly when it comes to substances released by plastics.

The type of products involved in the life cycle should also weigh into impacts. For example, a large source of plastic in the oceans are spills of plastic pellets from sea freight. An impact assessment method should include a degree of leakage of plastic-based materials at the raw material stage. On the other end of the spectrum, it can be argued that some plastic products are more prone to become litter than others, due to their properties or to local waste disposal legislation and infrastructure. An impact assessment model could be sensitive also to EOL routes of different products.

Finally, the location of the disposal is important, as several geographical aspects augment the impact, the dispersal and the accumulation of litter. For instance, littering near waterways (e.g. streams) promotes the accumulation of litter downstream and at beaches.

6.3.3.Timber raw material requirements

Manufacturing and using heavy duty tropical mixed hardwood pallets requires more timber than light duty pallets. Also, heavier use demands for more repair resulting in more timber demand and involving more tree felling.

Manufacturing one hardwood pallet requires 0.003 part of a tree for light duty and 0.007 t part of a tree for heavy duty. Softwood pallets require 0.004 trees (see Table 15).

Due to higher repair needs, softwood pallets require more timber in use than hardwood, with one trip with a softwood timber pallet using 0.004 to 0.011 part of a tree. This figure is lower for hardwood pallets, with heavy duty requiring up to 0.003 and light duty up to 0.005 part of a tree.

Table 15 – Trees required for the timber supply to hardwood and softwood pallets manufacture and repair per pallet and per trip under shallow, medium and deep supply chains with and without repair (average use intensity).

Pallet	Per pallet	Per trip - No repair			Per trip - With repair		
		Shallow	Medium	Deep	Shallow	Medium	Deep
Tropical mixed hardwood	0.0032	0.0011	0.0016	0.0032	0.0011	0.0016	0.0033
HD Tropical mixed hardwood	0.0071	0.0016	0.0023	0.0047	0.0024	0.0024	0.0048
Softwood	0.0045	0.0034	0.0051	0.0103	0.0035	0.0053	0.0105

7. Uncertainty and limitations of the LCA results

7.1. Highlighted assumptions and limitations of the LCI

The most important of the assumptions and limitations adopted in the inventory are listed in Table 16. Each of these have the capacity to materially affect the LCA results for the selected impact categories in this study. For some, we have conducted additional sensitivity analyses to determine the extent to which the LCA results would be affected.

Table 16 – Assumptions, choices and limitations.

Assumption or limitation	Impact on LCA results	Discussion
Air emissions from waste plastic melting and moulding from generic process	Low	Due to lack of usable emission data from the factory's exhaust, a proxy from ecoinvent database was used, listing the emissions of plastic thermoforming. It can be considered that this is a reliable dataset.
Assumptions on transport distances of feedstock plastic waste	High	Transport of feedstock plastic waste is a main driver of environmental impacts. Distances were difficult to ascertain due the fragmentation of feedstock sources. Modelling assumed all waste is currently sourced in Bali. A sensitivity analysis showed that LCA results may change by over 10% if shares of the feedstock are sourced from East Java or abroad.
Electricity mix	Low/Medium	Potential impact on results depends on the relative proportion of renewable electricity versus fossil-based electricity, which varies between islands. Island/region-specific electricity mixes are unknown. The Java–Bali interconnected grid system accounts for 70% of the electricity generated in Indonesia. A national mix can therefore be considered representative of the Bali average.
Deforestation emissions of non-certified timber pallets	High	Several aspects compound uncertainty in the estimation of emissions from deforestation: - Deforestation emissions were modelled based on generic data concerning productivity and biomass handling. - Carbon was assumed to be stored in the timber until its release at EOL. - Changes in soil carbon stocks were not included, which underestimates present estimations.

Assumption or limitation	Impact on LCA results	Discussion
		We considered only the deforestation impacts on aboveground biomass, which we quantified as per modelling approach of ecoinvent datasets for non-certified wood. We further assumed that simulating emissions from soil without site-specific data would compound uncertainty.
Pallet durability and replacement and repair needs	High	Because Re>Pal pallets are new to the market, the durability and replacement needs of Re>Pal stocks were estimated and tested using both scenario modelling and Monte Carlo uncertainty analysis, in order to see if the overall results from the study would change non-empirical data.
Timber pallet disposal in landfill	Medium	It is highly uncertain how timber decomposition occurs in landfill, which in turn affects the estimation of greenhouse gas emissions from timber disposal. This study took a standard approach, using timber landfilling processes from the Australian LCI database with slow and fast decomposition rates.
End of life pathways	High	EOL emissions are heavily weighted in the results and are dependent on the disposal/recycling option. To reduce the bias effect, we assumed that a pallet has an equal probability of being disposed of in every available option.
Pallet displacement	Low	Place displacement distances and transport modes were arbitrated in the scenario analysis. Transport turned out to be an important contributor to the footprint. However, the relevance of this arbitration is low, because the same distance and modal split was given to every pallet, eliminating bias between pallets.

7.2. Uncertainty analysis of the carbon footprint

The Monte Carlo setup consisted of 10,000 repetitions of the impact assessment and displayed results with a 95% confidence interval. The outputs of this analysis are:

- Probabilistic distributions: the probability each value of the possible values of the footprint;
- Descriptive statistics: for example, the mean, media, standard deviation; and
- Range: maximum and minimum value the footprint could have within the 95% confidence interval.

The results are largely dependent on the number of trips done by a pallet depending on the roughness of handling. The graphs in Figure 28 and Figure 29 show the result of the uncertainty analysis.

The results suggest a number of outcomes:

- The stress resulting from handling intensity can lead to largely differing carbon footprints for the same pallet on the same service trip. Hence, the typical footprint of a pallet in its service life will change depending on how it is handled.
- Despite variability, statistically there is very high confidence that Re>Pal maintains a lower cradle-to-grave footprint than its counterparts.

7.2.1.Probability density curves

The possible range of variation translates directly the full range of results of the footprints resulting from the Monte Carlo sampling. Figure 28 show the probability density distribution for the cradle to grave LCA for medium depth supply chains, modelled using Monte Carlo simulation over 10,000 runs. In Figure 28 the *typical* carbon footprints used throughout this study have been indicated.

Figure 29 shows the cumulative probability for the same modelling.

A few observations:

- The *typical* carbon footprint is not the median or average carbon footprint of the assessment;
- Within 95% confidence:
  - NP1210 have a footprint between 1.3 – 11.8 kgCO_2eq per trip
  - Tropical mix hardwood pallets with repair have a footprint between 9.2 – 50.3 kgCO_2eq per trip.
  - Conventional plastic pallets have a footprint between 9.3 – 34.8 kgCO_2eq per trip.
  - Softwood pallets with repair have a footprint between 12.8 - 83.2 kgCO_2eq per trip.
- There is 5% of less probability that timber or conventional plastic pallets have a lower carbon footprint than 10.8kgCO_2eq per trip. There is less than 5% probability that the NP1210 pallet has more than 10.8kgCO_2eq per trip.

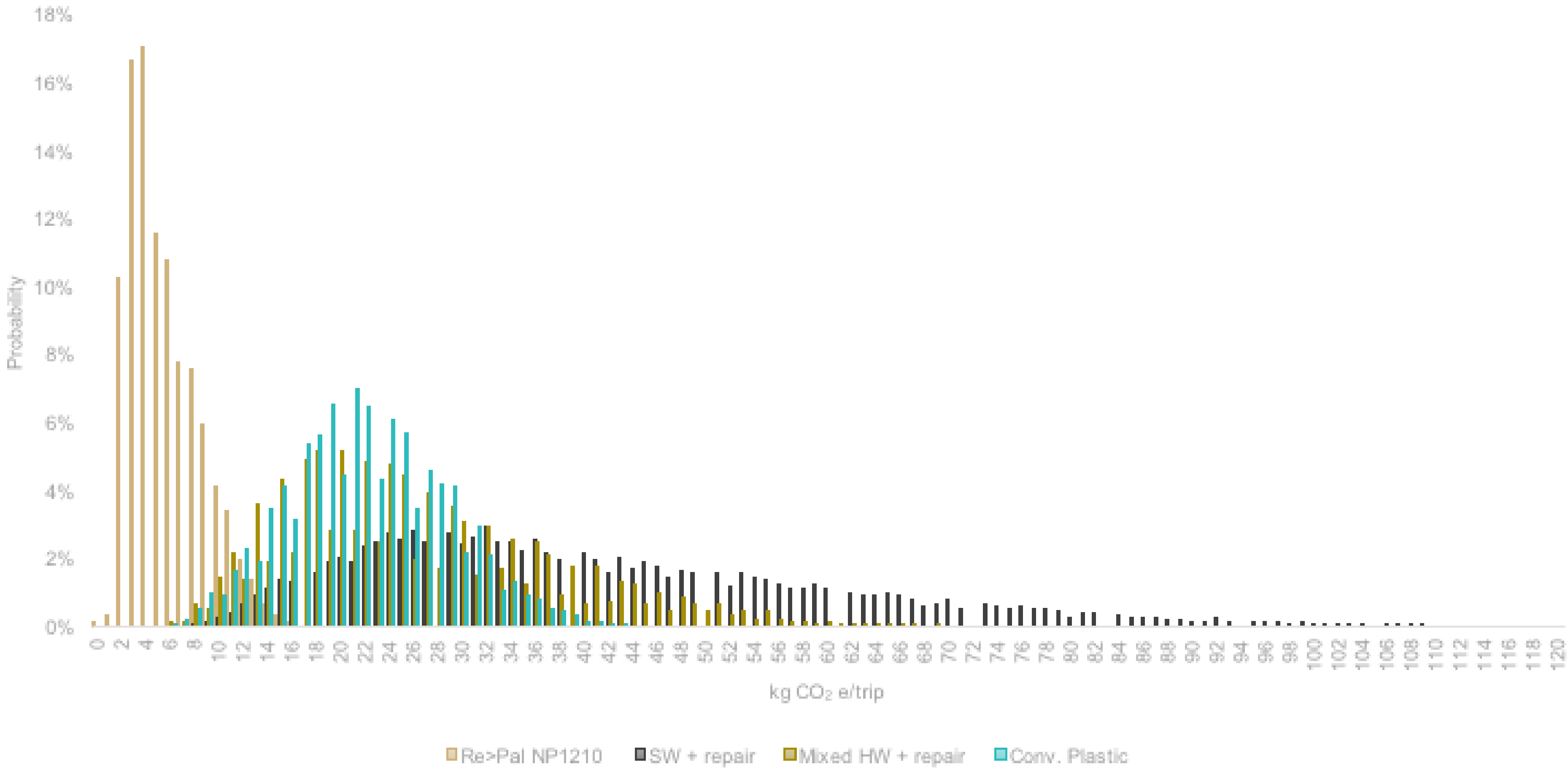

Figure 28 – Carbon footprint probability density curves for medium supply chain depth, cradle to grave life cycle, Monte Carlo simulation (10,000 runs). The typical carbon impacts used in the LCA are indicated with coloured arrows.

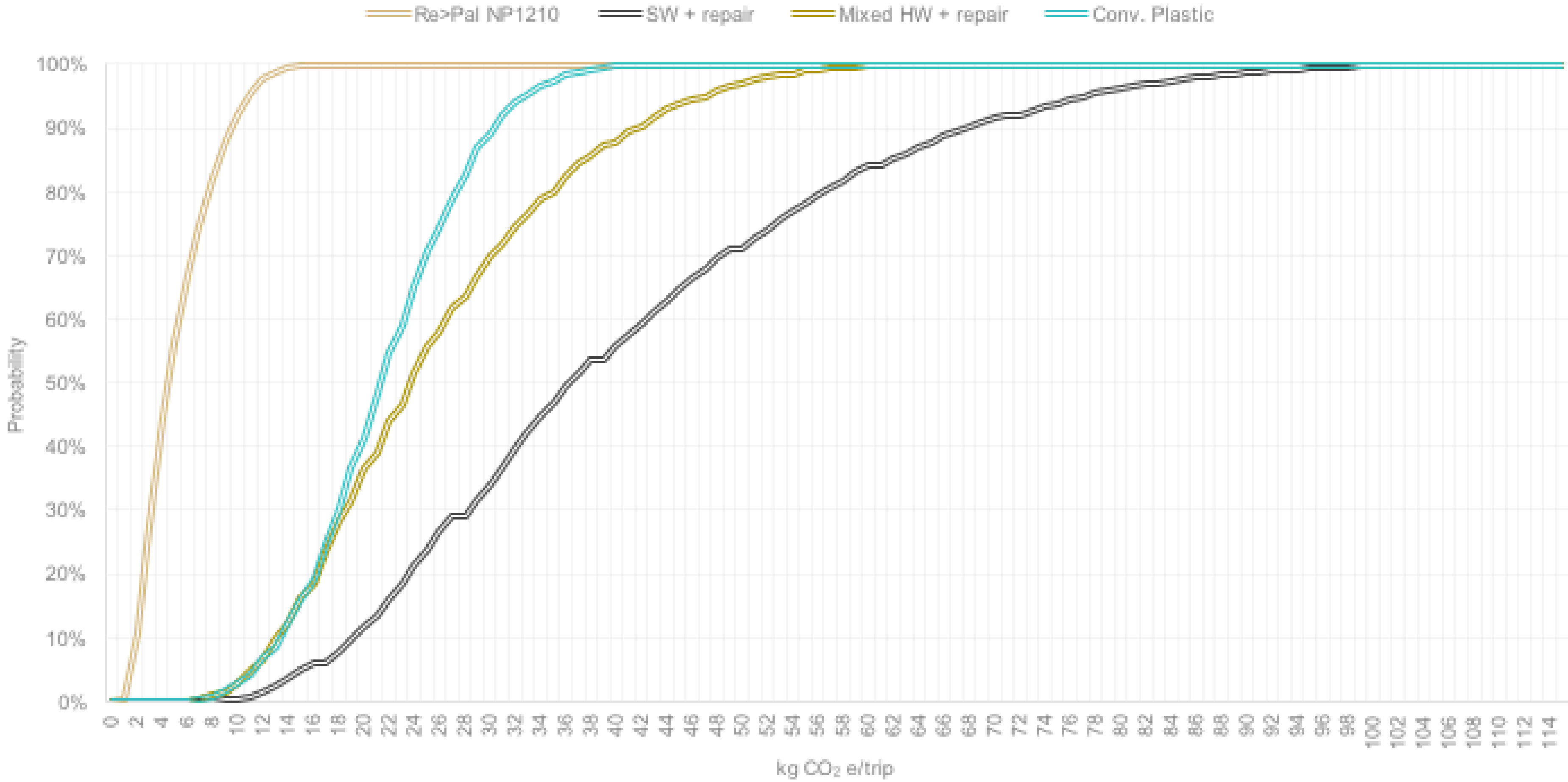

Figure 29 – Cumulative carbon footprint probability curves for medium supply chain depth, cradle to grave life cycle, Monte Carlo simulation (10,000 runs).

7.3. Sensitivity analyses

There are at least two aspects of Re>Pal's LCA that are likely to vary circumstantially, influence the environmental impact, and are, to a degree, under Range International's control.

a) The geographical source of feedstock is likely to shift as Range International grows its production lines. Transport of feedstock is the sole source of impact from raw material provision, and changes to the distance between factory and source will influence the emissions of manufacture. We explored the effect of this shift in this sensitivity analysis.

b) The EOL of Re>Pal pallets falls outside of Range International's present responsibility. We assume that Re>Pal pallets will end up in landfill because they can only be recycled at Re>Pal and because incineration is unlikely, unless the pallets end up in countries with industrial waste to energy incineration infrastructure.

In the sensitivity analysis, we investigated the effect of implementing a product stewardship program, which would entail the backhauling and reprocessing of pallets by Range International.

7.3.1. Waste feedstock source distance

Range International's plans include a diversification of waste sources, which will reach to East Java and internationally.

In the base analysis in this study, it was assumed that presently all waste feedstock is sourced domestically (Bali and East Java). This sensitivity analysis estimates the climate change impact variation if for different sourcing rates between Bali, Indonesia and overseas in several randomised waste source combinations.

The assessment (see Figure 30) shows that Range International can expect its pallets to have higher emissions if less waste is sourced in the proximity of the factory but being still domestically sourced. However, this increase is not proportional to distance since sea transport has a lower impact than road transport. In fact, sourcing all waste from overseas and relying mostly on sea shipping would have a lower impact that sourcing waste from up to a 380 km radius by road.

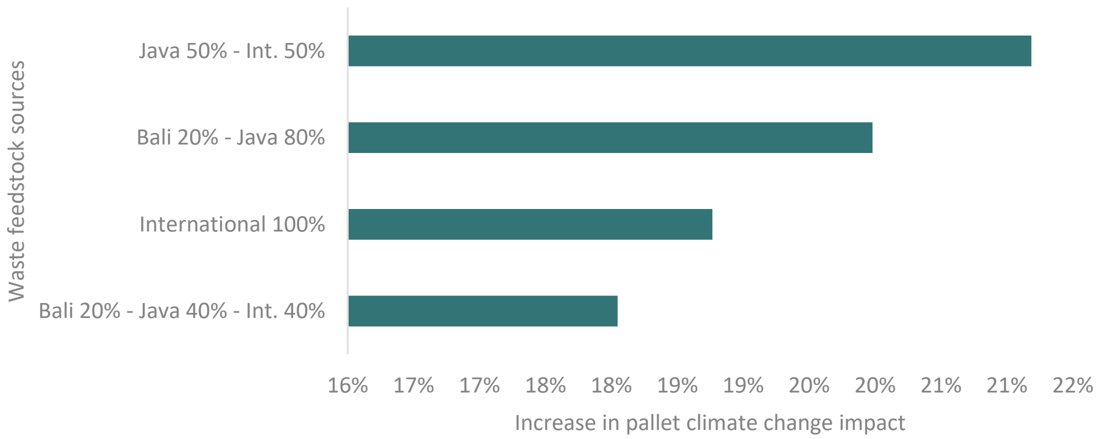

Figure 30 – Variation of Re>Pal cradle-to-gate greenhouse gas emissions with different feedstock source mixes.

7.3.2.End of life

This sensitivity analysis compares the life cycle impact of landfilling with that of recovering retired pallets by backhauling them to the Tabanan factory and reprocessing them.

The modelling is done only on shallow supply chain scenarios and for the NP 1210 pallet, as the difference we aim to measure is proportional for the remaining scenarios. We emphasise also that the transport distance is not a relevant factor because we are reading relative results: a shorter or longer distance would have lower or higher absolute results, but the difference between the baseline and the sensitivity analysis variation is the same.

This assessment shows that recycling Re>Pal pallets increases the carbon footprint from 11% to 33%. This increase is due to the backhauling of pallets (see Figure 31).

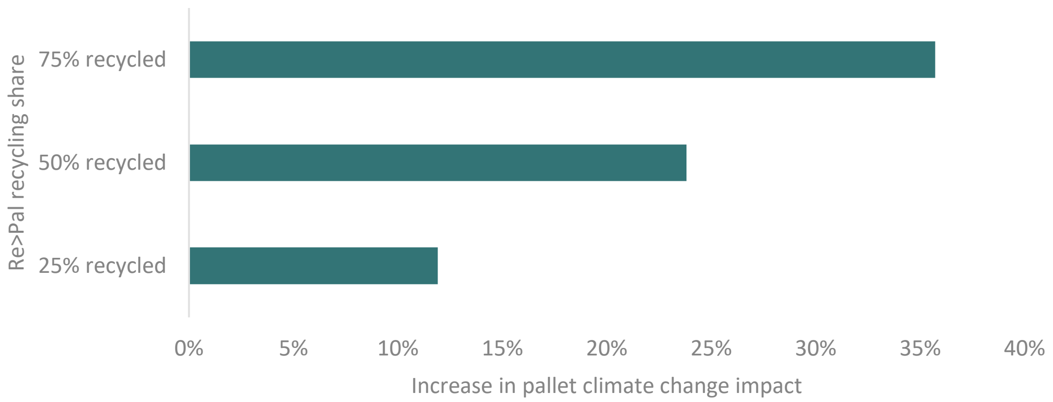

Figure 31 – Sensitivity analysis showing variation of Re>Pal cradle-to-gate greenhouse gas emissions with EOL option.

If Re>Pal were to institute a stewardship programme, waste pallets would become part of the feedstock mix and replace some of the plastic waste. The impact of the raw material provision would then change, as the sourcing distance would change as well. Also, the waste output of the factory, which accounts for 26% of the carbon footprint, would decrease in proportion to the penetration of waste pallets in the mix. This is because waste pallets are presumably a contaminant-free feedstock. By introducing catchment areas, the emissions from backhauling pallets can be limited.

7.4. Modelling approach to LCA

In this study, consequential LCA could have given us insights on the effect of the demand of Re>Pal pallets for waste plastic. It would also have been able to assert the substitution of timber pallets, replying then to the question of how many trees are saved by Re>Pal.

Under attributional LCA, it cannot be claimed that replacing a timber-based product with a non-timber based product directly relates to avoided tree felling. The effects of such a substitution throughout a supply chain can only be estimated when economic factors are considered, such as supply and demand elasticities.

For instance, reducing the demand for timber pallets within a supply chain may not lead to less timber felling overall because the timber will be supplied to another supply chain. Still, the burden of tree felling does not enter the supply chain where the pallets are used. Hence, a product or supply chain only “saves” trees from felling compared with a possible business as usual (BAU) inventory where the supply chain is concerned. In other words, the trees may not be saved, but rather sacrificed elsewhere and another product is to blame.

We can speculate that consequential LCA would not have picked up on a signal from the increased demand from waste plastic, unless: (i) it implied importing waste plastic from longer distances; (ii) it implied the use of more valuable waste plastic, such has HDPE scrap, which is not a surplus material.

7.5. Discussion

The results indicate that Re>Pal has a lower impact than conventional timber or plastic pallets across a number of environmental impact indicators, including climate change and human health. However, the results are dependent on several (conservative) assumptions applied in this study, including:

- Accounting for biogenic carbon flows in tropical mixed wood pallets;
- Pallet lifespan and repair/replacement needs of the different pallet types; and
- EOL options/scenarios.

While the first main assumption is an inherent difficulty of LCA; the latter two are inherent to the use chains of Re>Pal. Re>Pal is a new product, which has not been on the market long enough for significant data on its use and repair to be available.

We aimed to be open to uncertainty in this life cycle and populated the LCA model with uncertainty data, which we subjected to an uncertainty analysis. Our results show that variability is possible but not likely, and that under the current modelling conditions Re>Pal is the pallet with the least environmental impact.

8. Recommendations and perspectives

8.1. Steps to lowering impacts

Even though the LCA results paint a positive image of Re>Pal, there are opportunities for further improvement. In this section we outline targets, the measures required to achieve them and possible implications.

A) Lowering the carbon footprint

Using renewable electricity, making the most of Indonesia's natural resources or photovoltaic installations, would significantly lower the carbon footprint. Photovoltaic panels would reduce the footprint by 67%. This would make Re>Pal more climate friendly than certified pine pallets.

B) Waste neutral manufacture

Re>Pal rejects 15% of the waste that comes into the factory. If this fraction could be reduced, the manufacture of Re>Pal pallets could be waste neutral. The footprint would also be lower.

If using waste more efficiently implied the selection of better quality waste, this could have a trade-off in the value of absorbing low-quality, unrecyclable plastic.

C) Waste neutral life cycle

Re>Pal can be criticised for marketing a product that can only be landfilled at its EOL. In this sense, giving a new life to a waste product can be perceived as displacing the problem.

Re>Pal could counter this criticism with a take-back initiative, where retired pallets from a catchment area could be brought back to the factory and turned into new pallets.

The impact backhauling of pallets could replace the impact of transporting waste plastic from its source. In addition, retired pallets could be a more efficient feedstock in support of waste neutrality.

8.2. Communication

Care should be used before using or quoting these results until the assumptions used are confirmed.

The bullet points below provide recommendations for the adequate communication of the findings of this study.

- An independent life cycle assessment has demonstrated that Re>Pal has the lowest environmental impacts compared with functionally equivalent alternatives.
- Re>Pal offers an alternative, produced using plastic waste, with a low environmental footprint, and with no risk of illegal logging and deforestation.
- "All pallets, from cradle-to-grave, use resources and energy, and have associated emissions.
- Re>Pal is arguably the most resource efficient and lowest emission alternative"
- Re>Pal pallets are almost "waste neutral", because the waste output throughout their life cycle, from cradle-to-grave, is nearly offset by the waste used as feedstock" and/or Re>Pal uses large quantities of low-value, hard to recycle plastic waste, which has been diverted from landfills and from becoming litter. The benefit of doing so is that, contrary to plastic and timber pallets, Re>Pal is produced from a burden free feedstock.

8.3. Closing knowledge gaps

Re>Pal is invested in its mission to absorb waste plastic from streams where it would end up either in landfill or littering the environment. Aside from being granted a burden free feedstock, which is a benefit other pallet types do not have, the real savings and benefits of using this waste – to the planet, people and economy – remain unclear.

This lack of clarity arises from data gaps in science: we do not know how and in what magnitude plastics at their EOL cause damage to the environment and to society. Research points towards a problem of significant and concerning magnitude, but well accepted impact assessment methodologies like LCA do not have a method to account for the problem, because its exact pathways and fates are unknown.

Re>Pal could aim for the clarification of what its contribution to “the plastic problem” is by aligning with research initiatives and procuring knowledge build upon the topic of the environmental impact of plastics in the environment.

8.4. Conclusions

This study has developed a significant amount of pallet life cycle data for internal and public consumption. The study offers a holistic assessment of a broad range of pallet options, using ISO compliant LCA methodology. The authors hope that to enhance the sustainability of global trade and logistics, Range International, other pallet providers and stakeholders will use the research to communicate life cycle impacts and benefits of various pallets, and for continued research and development.

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APPENDIX A: LCA standards and references

There is a range of complementary or otherwise largely compatible LCA standards and guidelines available. The leading initiatives are set out below, in order of generality.

ISO14040 and ISO14044

ISO14040 describes the principles and framework for the LCA. It does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA.

ISO14044 specifies requirements and provides guidelines for LCA: definition of the goal and scope of the LCA; the LCI phase; the LCIA phase; the life cycle interpretation phase; reporting and critical review of the LCA; limitations of the LCA; relationship between the LCA phases; and conditions for use of value choices and optional elements.

APPENDIX B. Background data

The following background data sources were used to model the product life cycles from cradle-to-grave/cradle-to-gate:

- **ecoinvent v3.2:** The ecoinvent Centre holds the world's leading database with consistent and transparent, up-to-date LCI data. The ecoinvent v3 database contains LCI data from various sectors such as energy production, transport, building materials, production of chemicals, metal production, and fruit and vegetables. The entire database consists of over 10,000 interlinked datasets, each of which describes an LCI on a process level.
- **Australian National Life Cycle Inventory Database (AusLCI):** A major initiative currently being delivered by the Australian Life Cycle Assessment Society (ALCAS). The aim is to provide and maintain a national, publicly-accessible database with easy access to authoritative, comprehensive and transparent environmental information on a wide range of Australian products and services over their entire life cycle.
- **AusLCI shadow database:** ALCAS have developed a "shadow database" to provide consistent, quality background data to the AusLCI database. This shadow database fills most of the gaps in the supply chain as AusLCI is being developed. The shadow database is based on the ecoinvent unit process database, but with a number of adjustments to bring the data more in line with the Australian industrial environment.
- **Australasian Unit Process LCI:** The main Australasian database in SimaPro, which has been developed for use with LCA in Australia over the past 12 years. The original database was developed as part of a project funded by the four state-based environmental protection authorities', the commonwealth government and the Cooperative Research Centre for Waste Management and Pollution Control. The project partners were the University of New South Wales and the Centre for Design at RMIT University. The database has been added to over time by different public projects and its upkeep is coordinated by Life Cycle Strategies.

The following sections describe the background processes and amendments made for this study.

Table A 1 – Background processes.

Process	Modelling	Data
Re>Pal		
Manufacture inputs		
Water	Unit process retrieved from ecoinvent 3.2	*Tap water {RoW}| market for | Alloc Def, U*
Electricity	Unit process retrieved from ecoinvent 3.2	*Electricity, high voltage {ID}| market for | Alloc Def, U*
Forklift use	Unit process retrieved from ecoinvent 3.2	*Energy, from diesel/AU U with Diesel {GLO}| market group for | Alloc Def, U*
Manufacture outputs		
Wastewater	Unit process retrieved from ecoinvent 3.2	*Wastewater, average {RoW}| treatment of, capacity 1E9l/year | Alloc Def, U*
Emissions	Adapted from ecoinvent 3.2: all elements excluded except for emissions to air	*Thermoforming of plastic sheets {RoW}| processing | Alloc Def, U*
Mixed solid waste	Unit process retrieved from ecoinvent 3.2	*Municipal solid waste {RoW}| treatment of, sanitary landfill | Alloc Def, U*

Process	Modelling	Data
End of life		
Landfill	Unit process retrieved from ecoinvent 3.2	*Waste plastic, mixture {CH}| treatment of, sanitary landfill | Alloc Def, U*
Timber pallets		
Manufacture inputs		
Hardwood	Adapted from ecoinvent 3.2: biogenic carbon adapted to non-certified forestry	*Roundwood, meranti from sustainable forest management, under bark {MY}| hardwood forestry, meranti, sustainable forest management | Alloc Def, U*
Softwood	Unit process retrieved from ecoinvent 3.2	*Sawnwood, softwood, dried (u=10%), planed {RoW}| market for | Alloc Def, U*
Nails	Unit process retrieved from ecoinvent 3.2	*Steel, low-alloyed {GLO}| market for | Alloc Def, U*
Electricity	Unit process retrieved from ecoinvent 3.2	*Electricity, medium voltage {ID}| market for | Alloc Def, U*
Forklift use	Unit process created from AusLCI and from ecoinvent 3.2	*Energy, from LPG/AU U* *With Liquefied petroleum gas {RoW}| market for | Alloc Def, U*

Process	Modelling	Data
Raw material packaging	Unit process retrieved from ecoinvent 3.2	*Folding boxboard/chipboard {GLO}| market for | Alloc Def, U*
Manufacture outputs		
Wood waste	Unit process retrieved from ecoinvent 3.2	*Shavings, hardwood, loose, measured as dry mass {GLO}| market for | Alloc Def, U*
Cardboard waste	Adapted from ecoinvent 3.2: excluded avoided production of virgin cardboard	*Recycling cardboard, with 75% virgin fibre/AU U with Electricity, medium voltage {ID}| market for | Alloc Def, U*
End of life		
Burning	Adapted from ecoinvent 3.2: all elements excluded except for emissions to air	*Waste softwood, untreated {CH}| treatment of, municipal incineration | Alloc Def, U {RoW}*
Landfill	Adapted from AusLCI: same processes but with ecoivent 3.3 {GLO} equivalents	*Waste treatment, wood and wood waste, low degradation assumption, at landfill/AU U and Waste treatment, wood and wood waste, at landfill/AU U*
Recycling	Unit process retrieved from ecoinvent 3.2	*Wood chips, from post-consumer wood, measured as dry mass {RoW}| treatment of waste wood, post-consumer, sorting and shredding | Alloc Def, U*

Process	Modelling	Data
Mulching	Unit process retrieved from ecoinvent 3.2	*Wood chips, from post-consumer wood, measured as dry mass {RoW}| treatment of waste wood, post-consumer, sorting and shredding* **|** *Alloc Def, U*
Conventional plastic pallets		
Manufacture inputs		
Plastic	Adapted from ecoinvent 3.2: includes HDPE scrap and energy required to reprocess it	*Polyethylene, high density, granulate {GLO}| market for* **|** *Alloc Def, U*
Electricity	Unit process retrieved from ecoinvent 3.2	*Electricity, medium voltage {ID}| market for | Alloc Def, U*
Forklift use	Unit process created from AusLCI and from ecoinvent 3.2	*Energy, from LPG/AU U* *with Liquefied petroleum gas {RoW}| market for | Alloc Def, U*
Carbon black	Unit process retrieved from ecoinvent 3.2	*Carbon black {GLO}| market for* **|** *Alloc Def, U*
End of life		

Process	Modelling	Data
Landfill	Unit process retrieved from ecoinvent 3.2	*Waste plastic, mixture {CH}*| *treatment of, sanitary landfill* **|** *Alloc Def, U*
Recycling	Adapted from ecoinvent 3.2: excluded avoided production of virgin plastic	*Mixed plastics (waste treatment) {GLO}*| *recycling of mixed plastics* **|** *Alloc Def, U*
Transport		
Road	Unit process retrieved from ecoinvent 3.2	*Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}*| *market for* **|** *Alloc Def, U*
Sea	Unit process retrieved from ecoinvent 3.2	*Transport, freight, sea, transoceanic ship {GLO}*| *market for* **|** *Alloc Def, U*
Air	Unit process retrieved from ecoinvent 3.2	*Transport, freight, aircraft {GLO}*| *market for* **|** *Alloc Def, U*

APPENDIX C. Emissions of deforestation

We assumed that mixed tropical hardwood is harvested non-sustainably. Overall, tropical hardwood pallets contribute to net deforestation.

Because this study models generic, non-case specific timber pallets, we did not use a specific case to estimate a deforestation emission of timber sourced in Indonesia. Alternatively, we modelled an average emission associated with harvesting 1 m^3 of non-sustainable mixed tropical hardwood. To estimate this emission, we:

- Calculated the emission during deforestation; and
- Assessed the extent to which the timber sourced for pallets is accountable for deforestation.

C.1 Carbon loss at deforestation

The value of carbon that is lost can be:

- Calculated at product level, as modelled by LCA databases (De Schryver, et al., 2012) – the approach taken in this study;
- Modelled for specific LUC events in particular regions, resorting to satellite imagery analysis or field measurements; and
- Calculated at area level with default values provided by the Intergovernmental Panel on Climate Change (IPCC, 2006).

Deforestation implies two removals of carbon from the land: one consisting of the carbon removed in the wood and in collateral that is not replenished, another due to disturbance of soil. Disturbance of carbon stocks in soil, below ground biomass and litter/deadwood are not included. To estimate the biogenic carbon stock in tropical mixed hardwood and its emissions from deforestation, we took the following steps:

1. We partitioned aboveground biomass into extractable wood and wood that is burned or degraded (De Schryver, et al., 2012) (see Figure A 1).

Figure A 1 – Deforestation: fractions of above ground biomass that are utilised in wood products or disposed of and burned or left to degrade.

2. We assumed that the carbon in extractable wood is an uptake during wood production that is carried on until the EOL, when it is fully or partially emitted. This corresponds to 1,750.65 kg CO_2/m^3 [13].
3. We assumed that 51% of the extracted wood will be used, with the remaining 28% being meant for other wood products. We used economic allocation factors of 86% roundwood and 14% for by-products to distribute impacts (De Schryver, et al., 2012).
4. The remaining carbon is released upon harvesting. The emission factors for burnt biomass are in Table A 2.For degraded wood, total conversion into CO_2 was assumed (De Schryver, et al., 2012).

Table A 2 – Emission factors of biomass burning (IPCC, 2006).

Greenhouse gas	Emission factor (kg/kg biomass)
CO_2	1.5800
CO	0.1040
CH_4	0.0068
N_2O	0.0002

C.2 Timber pallets as a driver of deforestation in South East Asia

Concerning the causality of LUC, we took a conservative approach to capture the known, quantifiable reality of non-sustainable timber sourced for pallets in Indonesia, without smearing LUC emissions in successive probable land uses.

Felling of non-managed forests can be driven by logging or by the implementation of a new land use that follows the logging such as pasture, cropland or, in the South East Asian context, often palm oil plantations (Henders, et al., 2015; Kissinger, et al., 2012). The commodities that are generated in the sequence of a forest being cleared may be burdened with the LUC emission. There is no consensus on how to calculate the burden of deforestation on different commodities resulting from the same deforestation episode.

Several published studies examine deforestation drivers, using spatial analysis of LUC patterns, historical data and/or the market models to trace LUC back to demands for commodities (Goh, et al., 2016; Henders, et al., 2015).

Deforestation is rampant in Indonesia, suggesting that in land where forest is cleared another land use will take place. Presently, governmental efforts have slowed down deforestation rates, but afforestation is not yet significant. A study funded by the Norwegian and UK governments admits that 70% of deforested land in (sub)tropical Asia is motivated by wood logging. An uncertain percentage seems to be driven by palm oil plantations. The uncertainty arises from the fact that palm oil has often been grown in already degraded forests (Kissinger, et al., 2012). Regardless, these two commodities are pointed out in other studies as the two most likely causes for a forest to be cleared in Indonesia. By contrast, the same study points out that the worldwide trend is for agriculture to be a main driver (causing 80% of deforestation).

[13] Hardwood density: 1,190 kg/m^3. Carbon content: 47%.

Hence, as per our approach, a tropical hardwood pallet built in Brazil would have a negligible embedded deforestation emission, as most of the burden of clearing land would be on beef or soy production. In Indonesia, as explained before, wood products are a proximal cause of deforestation, suggesting that a mixed tropical wood pallet will, in 70% of the cases, have motivated forest clearing.

In sum, we allocated the responsibility of deforestation to the pallet, ignoring subsequent land uses, but only in the measure of how likely it is that the timber drove deforestation. For this, we:

1. Excluded successive land uses and considered only the proximal LUC driver, as outlined in Davis et al, 2014;
2. Assumed the likelihood of wood logging being the proximal LUC driver in Indonesia, which is approximately 70%; and
3. Used that likelihood as the share of the LUC emission attributable to the wood harvested and used in a mixed tropical wood pallet.

APPENDIX D. Life cycle impact assessment results

Table A 3 – Re>Pal cradle-to-grave LCIA results per life cycle stage. Results are per pallet.

Pallet	Supply chain	Climate change (kg CO_2 eq.)				Cumulative energy demand (MJ eq.)			
		Raw materials	Manufacture	Transport	End of life	Raw materials	Manufacture	Transport	End of life
NP 1210	Shallow	0.07	0.41	0.84	0.14	1.45	1.10	3.29	12.99
	Medium	0.10	0.61	1.25	0.21	2.18	1.64	4.93	19.49
	Deep	0.21	1.22	2.51	0.43	4.36	3.29	9.86	38.97
NP 1090	Shallow	0.06	0.38	0.79	0.13	1.37	1.03	3.09	12.20
	Medium	0.10	0.57	1.18	0.20	2.05	1.55	4.63	18.31
	Deep	0.19	1.15	2.36	0.40	4.10	3.09	9.26	36.61
HD 1210	Shallow	0.10	0.57	1.16	0.20	2.03	1.53	4.58	18.08
	Medium	0.14	0.85	1.75	0.30	3.04	2.29	6.88	27.13
	Deep	0.29	1.70	3.49	0.60	6.08	4.58	13.75	54.25

Table A 4 – Cradle-to-grave LCIA midpoint results of all pallets on climate change, energy use and waste. FU = 1 trip. Note that waste output is not the net waste balance, but the result of waste output of the LCIA.

Pallets	Climate change (kg CO_2 eq.)			Cumulative energy demand (MJ eq.)			Waste output (kg)		
	Shallow	Medium	Deep	Shallow	Medium	Deep	Shallow	Medium	Deep
Re>Pal HD 1210	1.45	2.18	4.36	24.85	37.27	74.54	2.79	4.18	8.36
Re>Pal NP 1012	1.37	2.05	4.10	16.76	25.14	50.29	2.00	3.00	6.01
Re>Pal NP 1090	2.03	3.04	6.08	17.84	26.77	53.53	1.88	2.82	5.64
Conventional plastic	9.21	13.81	27.63	156.42	234.63	469.26	2.61	3.92	7.84
Conventional plastic HD	6.99	10.48	20.97	206.11	309.16	618.32	1.98	2.97	5.95
Tropical mixed hardwood	7.20	10.80	21.60	212.19	318.28	636.56	1.75	2.63	5.25
Tropical mixed hardwood HD	10.59	15.88	31.77	312.04	468.06	936.12	2.58	3.86	7.73
Softwood	10.28	15.42	30.84	387.90	581.85	1163.70	3.61	5.41	10.82
Tropical mixed hardwood w/ repair	7.32	10.99	21.97	217.02	325.53	651.07	1.80	2.69	5.39
Tropical mixed hardwood HD w/ repair	10.78	16.16	32.33	319.30	478.95	957.91	2.64	3.96	7.93
Softwood w/ repair	10.42	15.63	31.26	396.28	594.42	1188.83	3.70	5.54	11.09

Table A 5 – Cradle-to-grave LCIA midpoint results of all pallets on acidification, eutrophication and fossil fuel use. FU = 1 trip.

Pallets	T. acidification (kg SO_2 eq.)			F. eutrophication (kg P eq.)			Fossil fuel depletion (kg oil eq.)		
	Shallow	Medium	Deep	Shallow	Medium	Deep	Shallow	Medium	Deep
HD 1210	8.58E-03	1.29E-02	2.57E-02	6.47E-05	9.70E-05	1.94E-04	0.55	0.82	1.65
NP 1012	6.16E-03	9.24E-03	1.85E-02	4.36E-05	6.54E-05	1.31E-04	0.39	0.59	1.18
NP 1090	5.79E-03	8.68E-03	1.74E-02	4.64E-05	6.96E-05	1.39E-04	0.37	0.56	1.11
Conventional plastic	3.72E-02	5.58E-02	1.12E-01	5.85E-04	8.77E-04	1.75E-03	4.25	6.38	12.76
Conventional plastic HD	2.83E-02	4.24E-02	8.48E-02	4.44E-04	6.66E-04	1.33E-03	3.23	4.84	9.68
Tropical mixed hardwood	1.82E-02	2.74E-02	5.47E-02	1.57E-04	2.36E-04	4.72E-04	1.27	1.90	3.81
Tropical mixed hardwood HD	2.68E-02	4.02E-02	8.04E-02	2.32E-04	3.47E-04	6.95E-04	1.87	2.80	5.60
Softwood	4.23E-02	6.34E-02	1.27E-01	4.13E-04	6.19E-04	1.24E-03	2.78	4.18	8.35
Tropical mixed hardwood w/ repair	1.84E-02	2.76E-02	5.51E-02	1.62E-04	2.42E-04	4.85E-04	1.28	1.92	3.83
Tropical mixed hardwood HD w/ repair	2.70E-02	4.06E-02	8.11E-02	2.38E-04	3.57E-04	7.13E-04	1.88	2.82	5.63
Softwood w/ repair	4.28E-02	6.42E-02	1.28E-01	4.23E-04	6.35E-04	1.27E-03	2.81	4.22	8.44

Table A 6 – Cradle-to-grave LCIA midpoint results of all pallets on land occupation and land transformation. FU = 1 trip.

Pallets	Land occupation (m^2a)			Land transformation (m^2)		
	Shallow	Shallow	Medium	Deep	Medium	Deep
HD 1210	0.03	0.05	0.09	0.00	0.00	0.00
NP 1012	0.02	0.03	0.07	0.00	0.00	0.00
NP 1090	0.02	0.03	0.06	0.00	0.00	0.00
Conventional plastic	0.13	0.19	0.38	0.00	0.00	0.00
Conventional plastic HD	0.10	0.14	0.29	0.00	0.00	0.00
Tropical mixed hardwood	0.32	0.48	0.95	1.76	2.65	5.29
Tropical mixed hardwood HD	0.47	0.70	1.40	2.59	3.89	7.78
Softwood	51.13	76.70	153.39	0.01	0.01	0.02
Tropical mixed hardwood w/ repair	0.33	0.49	0.98	1.82	2.72	5.45
Tropical mixed hardwood HD w/ repair	0.48	0.72	1.44	2.67	4.01	8.01
Softwood w/ repair	52.52	78.78	157.57	0.01	0.01	0.02

Table A 7 – Cradle-to-grave LCIA endpoint results of all pallets on human health and ecosystem damage. FU = 1 trip.

Pallets	Human health (DALY)			Ecosystem damage (species.yr)		
	Shallow	Medium	Deep	Shallow	Medium	Deep
HD 1210	5.51E-06	8.26E-06	1.65E-05	1.74E-08	2.61E-08	5.21E-08
NP 1012	5.57E-06	1.11E-05	6.91E-06	1.76E-08	3.52E-08	2.39E-08
NP 1090	6.45E-06	5.98E-06	7.38E-06	2.17E-08	1.96E-08	2.61E-08
Conventional plastic	3.32E-05	4.98E-05	9.97E-05	7.69E-08	1.15E-07	2.31E-07
Conventional plastic HD	2.52E-05	3.78E-05	7.56E-05	5.84E-08	8.75E-08	1.75E-07
Tropical mixed hardwood	4.55E-05	9.10E-05	2.97E-05	7.83E-06	1.57E-05	5.07E-06
Tropical mixed hardwood HD	3.40E-05	6.80E-05	2.23E-05	1.10E-06	2.20E-06	7.15E-07
Softwood	5.93E-06	1.19E-05	3.71E-06	1.87E-08	3.74E-08	1.17E-08
Tropical mixed hardwood w/ repair	3.03E-05	6.06E-05	3.03E-05	5.17E-06	1.03E-05	5.22E-06
Tropical mixed hardwood HD w/ repair	4.45E-05	8.91E-05	2.27E-05	7.61E-06	1.52E-05	7.34E-07
Softwood w/ repair	3.35E-05	6.69E-05	3.95E-06	1.07E-06	2.15E-06	1.25E-08

APPENDIX F. Full peer-review reports

First review report

By Wouter Achten, ULB

On

Report for Range International - Pallet Life Cycle Assessment and Benchmark

By Edge Environment

Comments, questions and suggestions related to compliance to the ISO standard 14044

- page 17: System diagrams: I would suggest to incorporate more detail in the system diagrams. I have the feeling that more unit processes could be shown that are part of the system, including the ones excluded from the assessment. This exclusion can than be clearly visualized by incorporating the system boundaries in the diagrams as well. Further, I would suggest to make the occurrence of by-products more clear in the diagrams, and lastly I would suggest to quantify the reference flow in the different diagrams.

- page 18: Reference unit

- Terminology: Is there a specific reason why the 'conventional' "functional unit" is not used as term?
- From the explanation given here the reference unit, or functional unit, is not totally clear. It is 1 trip of what exactly? One trip of a pallet? Or, one trip of a pallet transporting a certain volume? Or, one trip of a pallet transporting a certain mass?
- At this moment in the text it is also not clear how functional equivalence will be guaranteed given the different potential life times, the different sizes of the pallets, and (maybe?) the different load capacity, … . Further in the text it becomes more clear, but I would suggest that you already explain a bit in this section and make reference to the section where you detail that out.
- Later on (section4.2) there is also mention of a 'round trip' which could create confusion on the functional unit.
- P 31 – This part clarifies a lot, however it is not clear if this relates to a specific function, e.g transportation of a certain volume or mass of goods.

- page 19: Environmental impact assessment. Among the 18 mid-point impact categories that ReCiPe calculates there are several non-selected impact categories which might be relevant for your comparison. Thereby I think about the (eco-)toxicity impacts. Therefore I think it is necessary to elaborate a clear justification of your selection (and thus of why the not-assessed impact categories provided by ReCiPe were 'excluded' from the assessment).

- page 19: Co-product allocation:

- Actually this section is not very clear to me. It seems like you select economic allocation (which later in the text is also applied), but in the last paragraph it seems like you do not do allocation. I suggest to streamline this paragraph a bit more.

- On the economic allocation: The economic allocation holds least priority regarding the ISO standards, and should be used when avoiding allocation by system boundary expansion and allocation by mass are not possible, or not desirable. In this context a justification to use the economic allocation (and thus the reasons why the other more prioritized procedures were not used) should be described.
- The argument to not to do allocation (because values are highly uncertain and small) is linked to the previous point, as it indicated that also the economic allocation procedure is not consequently applicable throughout the life cycle. However, quid with another allocation procedure?
- Regarding sensitivity, the standards suggest that sensitivity analyses should also be considered regarding methodological choices likely to affect the results, like allocation.

- page 20 (section 3.39): At the end of the paragraph it is finally not clear which of the discussed mechanisms are finally taken into account. On the deforestation it is clear (certainly with the appendix), however for the temporary storage it is not clear how and what is exactly included in the analysis or not. Regarding the clarity on system boundaries I would suggest to clarify this.

- page 21 section 3.3.11: The ISO standards indicate that also time-related coverage, geographical coverage, reproducibility, etc. should be discussed.

- p 21 – section 3.3.12 – Although a correct and conform approach is used in setting the cut-off, the paragraph does not clearly give a cut-off rule. It explains that a parameter with a variation of above 10% needs more investigation, and below 10% estimations could be allowed, and earlier it is stated that exclusion can be done based on a certain threshold percentage… but in the end no real clear exclusion rule is described. I suggest to clarify this.

Other comments

- p12 – Recycled plastic has the same advantages as the virgin plastic, yet an extra bullet point is added: 'fully recyclable' which is already covered by the advantages of the virgin plastics.

- p12 - Regarding the 'averts landfill costs' I wonder from which perspective that this is seen. From the perspective of the pallet producer or user, no costs seem to be extra averted as compared to the virgin plastic pallet producer, as this latter is also recyclable. From the societal perspective, or from the perspective of the plastic waste producer the recycled plastic pallet indeed seems to divert a waste plastic flow to a useful product, whereas it would otherwise end up in a waste treatment system, e.g. landfill.

- p 12 – For virgin plastic the complex and difficult manufacture (compared to wood) is mentioned. How is this for the recycled plastic? Advantage or Disadvantage?

- p 33 – The landfilling of waste wood is not so common in Europe. I understand that it is the practice in this context. Often methane production of landfills is flared or captured for energetic valorization. Regarding the methane emissions mentioned for the wood pallet landfill scenario, I wondered if these methane emissions are considered as direct emissions in the evaluation and if this is in line with the practices in the context of the study, i.e. that the methane is not flared (CO_2 emission instead of CH_4 emissions), nor captured for energetic valorization.

- p 57 – I would appreciate if you clarify that the column 'impact on LCA results' refers to the LCA results for the selected impact categories in this study.

Form or small remarks

- p 13 line 1: ware ➔ were

- p 15 first bullet point: Terminology: Instead of using loss of 'ecosystem services' I would suggest to stick to the 'conventional' terms of the end-point impacts (or areas of protection):

ecosystem quality (as impact on ecosystem services in LCA represents a certain set of methodological developments beyond the classical impact assessments).

- p16 – compliance to ISO 14044, instead of ISO 14040.

- p 17 last paragraph: It is a bit strange to first read that there are 3 types, but that one type will not be modelled, and then read that 3 types will be assessed. If I understand well you asses 2 types, and of 1 type you assess 2 'versions'.

- p 19 – For terrestrial acidification, freshwater acidification, fossil fuel depletion, land occupation and land transformation, reference is made to footnote 1: I suppose this should be footnote 2.

- p 19 – For cumulative energy demand no reference is made to the impact assessment method that will be used for this.

- p 21 – first line of section 3.3.11: ecoinvent v3.2: The appendix mentions version 3.3

- p 23 – Tree saved calculation: Good that you call for caution. You could also bring to caution that it is not always *de facto* bad to cut trees (e.g. in a sustainability forest management system).

- p 63: I would suggest to also show the 'current' situation (initial model) in these graphs.

- p 65: Final point: as it indeed depends on what would have happened with the waste plastic if it was not used for the pallets, I have the impression that the last of the options seems the most correct.

- Table A1: Forklift use: Why these forklifts run on diesel and the others on LPG?

- Table A1: Not clear why the timber pallets need packaging and the others not.

- Table A2: 2 times CO2?

Second review report

System diagrams

OK

Reference unit

In general OK, the clarification is clear, however

- I would suggest to make the 'use of two reference units' (cfr. Response letter) also explicit in the 3.3.4. section.
- I would suggest that the 2nd paragraph makes reference to the section where the aspects it describes are explained more detailed.

Environmental Impact Categories :

The ISO standards indeed allow quite some liberty in methods, and impact category selection. However, a justification should be given. Therefore I would suggest to add your justification on your selection in the report, so that this is transparent.

Further, if cumulative energy demand, global warming potential, fossil fuel depletation, land use and land transformation already fulfill the goal of the study, why was it decided to add some more categories (e.g. eutrophication and acidification) and why these and not others? (e.g. toxicity)

Further also the end-point indicators on damage to human health and damage to ecosystems are reported. These damage indicators aggregate several mid-point indicators which are not reported at the mid-point level (e.g. toxicity). Why was it decided to do this in this way? (e.g. toxicity indicators, you report them indirectly via end-point, why not directly via mid-point?)

This comment is not to challenge your decisions, as your decisions are possible within the ISO framework. This comment intends to suggest to incorporate the justification of these decisions in the report.

Co-product allocation

For me this section is still rather confusing. The section actually starts by saying that an economic allocation procedure is selected for allocation. However, no justification for this decision is given as such. The ISO standards set priorities (first system boundary expansion, second allocation based on physical characteristics, and last allocation based on non-physical characterization), and asks for justification of the choice, or reasons why the priority was not followed. This could be seen as one point.

Another point is that afterwards you say that you do actually do not perform allocation. 1) so, why to discuss an allocation procedure in the first place, if afterward you consider allocation is actually not needed in your situation? 2) a part of the justification of not performing allocation is the highly uncertain and small value of the by-products which makes the economic allocation less 'relevant'. However, this latter is already based on your selection of your allocation rule (feels like a kind of circular reasoning, if you see what I mean). Do the flows represent a significant mass? Is so, would mass allocation have been 'relevant'?

I would suggest to rewrite this paragraph in the following way (based on my understanding of what happened – on which I am not sure):

I would start to explain where in the system there are other material outflows than the one needed for your reference unit. For these outflows I would then describe if they pose an allocation problem and if allocation is needed (allocation is needed when processes produce co-products which could have a positive economic value in another life cycle than the one under study, and in case of open loop recycling).
Then you describe that most of the material outflows (you could cite them) are recycled internally, or are material flows which go to waste treatment (and thus do not present a positive economic value in another life cycle) for which no allocation is needed. For the other outflows which could represent a very low and uncertain economic value in another life cycle, you decide, based on being conservative, not to allocate… And, finally you describe that for the HDPE scrap you need an allocation, which you describe and justify. For the background system you can keep the sentence as it is.

I hope that this suggestion is linked to what you wanted to report and what happened, and also explains a bit more my confusion on the current section description.

Cut-off

It would be good if you can state what 'as per standard in ecoinvent and AusLCI' exactly means. % of mass flow, % of impact contribution, …