The Environmental Performance of Protecting Seedlings with Plastic Tree Shelters for Afforestation in Temperate Oceanic Regions: a UK Case Study

Charnett Chau, Andrea Paulillo, Nancy Lu, Mark Miodownik, Paola Lettieri

PII: S0048-9697(21)03310-6
DOI: https://doi.org/10.1016/j.scitotenv.2021.148239
Reference: STOTEN 148239

To appear in: *Science of the Total Environment*

Received date: 8 January 2021
Revised date: 28 May 2021
Accepted date: 28 May 2021

Please cite this article as: C. Chau, A. Paulillo, N. Lu, et al., The Environmental Performance of Protecting Seedlings with Plastic Tree Shelters for Afforestation in Temperate Oceanic Regions: a UK Case Study, *Science of the Total Environment* (2021), https://doi.org/10.1016/j.scitotenv.2021.148239

The Environmental Performance of Protecting Seedlings with Plastic Tree Shelters for Afforestation in Temperate Oceanic Regions: a UK Case Study

Authors: Charnett Chau[1, 2], Andrea Paulillo[2], Nancy Lu[1], Mark Miodownik[1, 3], Paola Lettieri[1, 2*].

[1] UCL Plastic Waste Innovation Hub, University College London, London.
[2] Department of Chemical Engineering, University College London, London.
[3] Department of Mechanical Engineering, University College London, London.
* Corresponding author email: p.lettieri@ucl.ac.uk

Abstract

Restoration of forested land represents an effective strategy to achieve net-zero target emissions by enhancing the removal of greenhouse gases from the atmosphere. The most common afforestation strategy envisages planting seedlings, which are germinated and grown to the desired age at tree nurseries, with plastic shelters to increase growth and survival of trees. This article presents a comprehensive Life Cycle Assessment (LCA) study that compares the environmental performance of current and prospective scenarios for shelter-aided seedling planting compared with a base case where shelters are not employed. The study focuses on the UK, but results and conclusions are valid for other temperate oceanic regions. The scenarios investigated are a combination of different shelters materials and end-of-life (EoL) strategies. Our analysis demonstrates that (i) planting seedling without shelters is the most preferable option across most environmental impact categories (including Climate Change), and in terms of weighted results, (ii) polypropylene shelters are preferable to bio-based alternatives, including polylactic acid-starch blends and bio-polypropylene, (iii) recycling is the most environmentally advantageous EoL treatment. Our study also showed that that the carbon emissions of the scenarios investigated are negligible when compared to the amount of carbon sequestered by a tree in 25 years.

Keywords: Life Cycle Assessment, Plastic Tree Shelters, Forestry Management, Planting Seedlings, Environmental Impact, Climate Change

1. Introduction

The tenet of the Paris Agreement, and therefore of global efforts to restrain global temperature rise induced by anthropogenic emissions of greenhouse gases (GHGs), is the achievement of a balance between GHGs emissions and their removal from the atmosphere - known as "net-zero". Many countries, including the UK (*Climate Change Act 2008*), have established legally binding targets to reach net-zero emissions around mid-century (van Soest et al., 2021).

The restoration of forested land, i.e. afforestation, represents the natural and arguably the most effective solution to enhance GHG removals. The latest report of the Intergovernmental Panel on Climate Change (IPCC) recommends that an increase of 1 billion ha of woodland will be necessary to limit global warming to 1.5°C by 2050 (Masson-Delmotte et al., 2018). A number of international initiatives have been established to promote forest conservation and afforestation, including the Bonn Challenge (IUCN, 2020) and the New York Declaration on Forests (UN Climate Summit, 2014). In the UK, the Committee on Climate Change (the UK's independent climate advisory body) recommended increasing the country's woodland coverage from 13% to a minimum of 17% and ideally up to 19% by 2050 (Committee on Climate Change, 2019; Woodland Trust, 2020). A 6% increase approximately equates to one and a half million hectares of new woodland cover and between 1.5 to 2 billion trees (Woodland Trust, personal communication).

There are various strategies for afforestation. The most widely adopted is to plant seedlings that are germinated and grown to the desired age (ranging from 4 months to 3 years) at tree nurseries. Direct seeding, which entails sowing seeds directly into soil, is arguably less effective because the germination of seeds requires specific soil and weather conditions that are season dependent (Palma and Laurance, 2015). Tree nurseries use greenhouses and polytunnels to regulate the climate, thus enabling germination throughout the year. Other strategies to increase woodland cover that do not entail tree-planting include natural regeneration, which envisages a "rewilding" of land, and assisted natural restoration of forest, which include some human interventions like removal of dead plants and stamping exposed seeds into soil (Chazdon et al., 2020). The Woodland Trust intends to use a combination of forestry and woodland strategies, but it foresees planting seedlings to play a major role in meeting the woodland coverage target recommended by the Committee on Climate Change (Woodland Trust, 2020).

Planting seedlings is commonly carried out with the aid of tree shelters. These are translucent, typically plastic tubes, placed around young tree seedlings to improve growth and survival, e.g. by reducing damage from browsing animals and by creating a beneficial local microclimate (Arnold and Alston, 2012). There are two environmental concerns that arise from the use of tree shelters. First, it is unclear whether the environmental impacts associated with tree shelters manufacture and end-of-life (EoL) treatment are offset by enhanced growth and survival of the seedlings. Second, tree shelters are typically not collected after their useful period (5 years); rather, they are left to degrade in the environment and partly fragment into microplastic (Place, 2018). Mass planting of trees to fulfil the net-zero targets could therefore entail a substantial amount of plastic tree shelters to be manufactured and being left unrecovered in the environment. Arnold and Alston (2012) suggested that tree shelters are beneficial for commercial forestry due to additional wood production and for forest establishment in semi-arid areas due to savings in water consumption. However, for amenity forest establishment, they show that the environmental impacts of tree shelters manufacture outweigh those associated with additional seedling production.

In this article, we investigate the environmental impacts of alternative scenarios for shelter-aided seedling planting compared to a base case where tree shelters are not employed, using Life Cycle Assessment (LCA) and focusing on the UK as a case study. The ultimate goal is to identify the most advantageous strategy for seedling planting to support international afforestation projects in temperate oceanic regions, including the Woodland Trust’s national reforestation effort. LCA is a standardised methodology (ISO, 2006a) for assessing the environmental impacts of products from *cradle-to-grave*. The life-cycle perspective and the consideration of a number of environmental issues enables identification of trade-offs, thus providing a robust framework for decision support. This study goes beyond and extends the study by Arnold and Alston (2012) because it considers different combinations of tree shelter materials and EoL scenarios and because it focuses on forest establishment for enhancing GHG removals. Unlike Arnold and Alston's study, we also attempt to quantify the amount of plastic that might be left in the environment due to tree shelters' degradation. We note that the environmental impacts of plastic pollution (i.e. short- and long-term toxicity effects) is not yet fully quantifiable using LCA (Boucher et al., 2019). Research is currently being conducted into developing methodologies to measure plastic footprint, and progress is being made, particularly into marine ecological impacts (Boucher et al., 2019; Woods et al., 2016). More studies on the longevity of plastics, their short-term and long-term effects on the environment are necessary before pollution due to plastic leakage can be evaluated comprehensively.

This article is structured as follows: Section 2 introduces the features of the LCA study, including the definition of goal and scope, life cycle inventory data and assessment of environmental impacts; the LCA results are presented and discussed in Section 3, and the key findings are summarised in Section 4.

2. Methods

This Life Cycle Assessment (LCA) study follows the ISO standards 14040:2006 and 14044:2006 (Finkbeiner *et al.*, 2006; ISO, 2006a, 2006b) and the Product Environmental Footprint (PEF) guidelines (EC-JRC, 2012), in particular on the guidance for Resource Use and Emission Profile and on the method for environmental impact assessment. The calculation of the environmental impacts is based on the definition of a functional unit, which represents a quantitative description of the function provided by the product system (see Section 2.1). The standardised LCA methodology consists of four subsequent and iterative steps; a detailed introduction can be found in Hauschild et al. (2018). The first step - Goal and Scope Definition - frames the study in terms of the reason for carrying out the analysis and its intended application, the processes that are included in the product system (i.e., the system boundaries) and the functional unit. The next phase - Inventory Analysis - collects information about the physical flows in terms of input of resources, materials, semi-products, products and by-products and the output in terms of emissions, wastes and the final product. Taking the life cycle inventory as a starting point, the Impact Assessment step “translates” the physical flows of the product system into potential impacts on the environment and human populations. Impacts are expressed as their contributions to a set of pre-defined impact categories, each addressing a specific issue; for instance, the climate change category includes all gases contributing to the greenhouse effect. Impact assessment may also include two additional steps: normalisation and weighting. The former relates impacts in each category to the total impact from all anthropogenic activities in a reference system, usually a geographical area such as Europe. The latter enables aggregating impacts in one overall indicator via the application of weighting factors that represent the perceived severity of each environmental category. Finally, in the interpretation step, the results of the study are checked for consistency and completeness, and conclusions and recommendations based on the results of earlier phases are developed. This study was performed in GaBi Software (Sphera, 2020a), using a mixture of GaBi (Sphera, 2020b) and EcoInvent v3.5 (Wernet et al., 2016) databases.

2.1. Goal and scope definition

The goal of this study is to evaluate the environmental performance of planting trees with and without the use of shelters to increase woodland cover. Other forms of seedling protection like perimeter fencing and coordinated herbivore control are outside the scope; the rationale is that the study wants to focus on the most prevalent tree-planting method (see Section 1). We focus on the UK as a case study, but the results and conclusions of our analysis can be applied to other temperate oceanic regions. The study investigates several current and prospective scenarios (named S2-S11) for shelter-aided planting that are combinations of different shelters materials and end-of-life (EoL) strategies; these are compared against a baseline scenario where tree shelters are not used (S1). The scenarios are summarised in Table 1.

Current guidelines on tree planting in the UK require shelters (if used) to be designed and/or maintained to last for at least five years (Rural Payment Agency and Natural England, 2020). This is known as the "establishment period"; beyond this, the likelihood of trees falling due to ordinary weathering and grazing is deemed negligible. Ponder (2003) report average annual survival rates of trees after a five-year establishment period being 99%. Before five years, annual survival rates are lower and vary amongst different types of trees (see Supplementary Materials – Table S1), but they are on average higher for trees planted with shelters. The Functional Unit (FU) of this study is "achievement of a single tree surviving the establishment period of 5 years".

Table 1: Summary of scenarios investigated.

Scenario Type	Scenarios No.	Shelter Material	Recovery	End-of-Life Option
Base Case	S1	No Shelter	N/A	N/A
Current	S2*	Polypropylene (PP)	Partial	Mix – Landfill, Incineration with and without Energy Recovery
	S3*	Polylactic Acid Blend (PLA)	Partial	Mix – Landfill, Incineration with and without Energy Recovery
	S4	PP	Partial	Recycled (down-cycling)
	S5	PLA	Partial	Recycled (down-cycling)
	S6	PLA	Not Recovered	Left for Biodegradation
Prospective	S7	PP	Full	Incineration with Energy Recovery
	S8	PLA	Full	Incineration with Energy Recovery
	S9	PP (35% recycled content)	Full	Recycled (partly recycled into tree shelters, rest down-cycled)
	S10	PLA (35% recycled content)	Full	Recycled (partly recycled into tree shelters, rest down-cycled)
	S11	Bio-PP (35% recycled content)	Full	Recycled (partly recycled into tree shelters, rest down-cycled)

*Additional scenarios were carried out to assess each individual EoL option (Supplementary Materials – Table S5).

We make the practical distinction between foreground and background system (Clift et al., 2000). The foreground system, which is depicted in Figure 1, includes trees' production at nurseries prior to planting together with the full life cycle of tree shelters, from raw material extraction to end-of-life treatment. The background system comprises activities that interact with the foreground system by supplying or receiving energy and material through a homogenous market. Primary data gathered via interviews was used to model most of the foreground system (see Section 2.2), with the remainder relying on literature data. The background system was modelled using secondary data from commercial LCA databases. The PEF recommends that "removals and emissions of biogenic carbon sources shall be kept separate in the Resource Use and Emissions Profile" (EC-JRC, 2012); this is because biogenic carbon sequestered in products may be released, for instance, at their EoL. Hence, the potential carbon sequestration by planted trees and the carbon embedded in bio-based plastic shelters are reported separately.

Tree shelters can be made of different plastic resins. In Current Scenarios (S2-S6), shelters are made with conventional polypropylene (PP) and polylactic acid–starch blends (PLA) as a bio-based alternative. Prospective Scenarios (S7-S11) also include bio-based PP and assume 35% recycled content for all resins in S9-11; notably, this assumption is in line with current UK governmental ambitions to increase recycling content in plastic products (EuPIC, 2018; Plasteurope, 2018; Victory, 2019; WRAP, 2019). During their use, tree shelters degrade due to animal grazing and weathering. Current Scenarios assume that shelters are only partially recovered or that bio-based shelters are left in-situ for biodegradation. The known resilience of fossil-based plastics in the environment and the resulting potential impacts of plastic fragments means that leaving fossil-based plastic shelters in-situ could be considered littering, which is condemned. To reflect this, we did not consider the scenario where PP shelters are left in-situ, as it should not be a tree-planting option. Prospective Scenarios consider enhanced shelter designs that avert degradation during use and therefore allow full recoverability. Therefore, this study addresses whether switching away from fossil-based to bio-based plastic shelters provides environmental benefits when plastic degradation is negated.

EoL treatment represents an additional variable in our analysis. Current Scenarios assume that shelters are treated according to the current UK mix of landfill and incineration with and without energy recovery (see Section 2.2.5) or that they are down-cycled into other products. In the Supplementary Materials, we also investigate other scenarios where the shelters undergo each individual treatment option (Table S5). The results of this analysis (Tables S9-S10) are used to inform EoL options for Prospective Scenarios, which envisage that the best EoL treatment is used; this includes incineration with energy recovery and recycling, partly into new shelters and partly into other products (down-cycling).

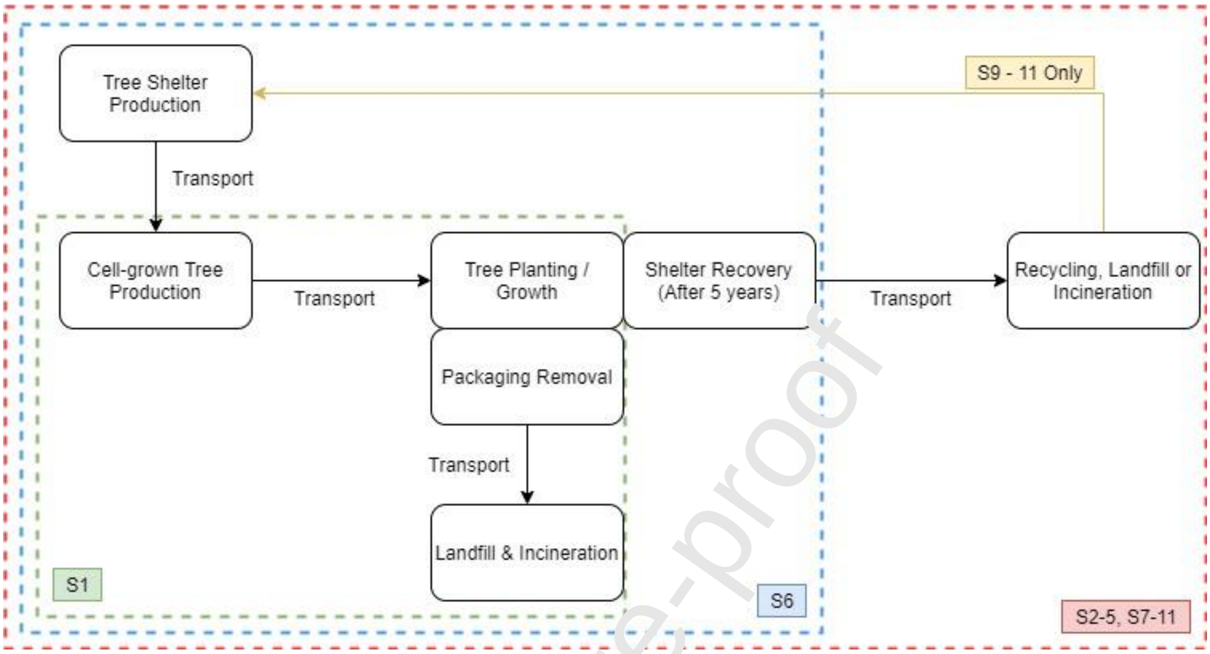


Figure 1: System boundaries of the product system for tree planting with and without shelters. [Colour required for print]

2.2. Inventory data - Assumptions and Calculations

2.2.1. Tree Survival Rates

Survival rates of new trees are dependent on multiple factors, including the length of the assumed establishment period, the type of trees and the environment in which they are planted. Table S1 in the Supplementary Materials reports survival rates for trees with ages ranging from 2 to 10 years from the literature. For the purpose of this work and in line with current guidelines in the UK (Section 0), we only consider tree survival rates for 4 and 5 years old trees. We averaged and rounded the literature data to the nearest 5% to obtain survival rates of 85% with and 50% without tree shelters (Table S1). This translates to 1.18 trees planted with shelters and 2 trees planted without shelters to achieve 1 tree surviving past the five year establishment period (i.e. the Functional Unit; see Section 2.1).

2.2.2. Tree Shelter Manufacture and Degradation

Shelters were assumed to have equal dimensions to an existing Tubex - a tree shelter brand - product on the market that is made of PP (146.5 g with >99.5% of PP) and is 120 cm high (Green-tech, Retrieved 4 May 2020). The weight of PLA shelters was calculated considering the density difference between PP and PLA, whilst the weight of bio-based polypropylene was assumed the same as its conventional (fossil-based) counterpart. In the Supplementary Materials, Table S2 reports assumptions on the weights and degradation of tree shelters for each scenario; details of the calculations are reported in Table S3. Our analysis does not take into account additives. UV stabilisers were not considered because their amount is negligible - approximately 0.15% w/w and 0.05%w/w of PP and PLA shelters respectively (Rainbow Professional Ltd, personal communication); whilst colourants, which make between 0.25% to 5%w/w (Hahladakis et al., 2018), were excluded due to lack of inventory data. Tree shelters production was modelled using Gabi database process for plastic sheet production.

Shelters are typically packaged in bundles in LDPE film and sent to tree nurseries such that young trees and shelters are delivered together for planting (Alba Trees, personal communication; Rainbow Professional Ltd, personal communication). Packaging was assumed to weigh 2.68g per shelter from Arnold and Alston (2012).

In Current Scenarios (S2 to S6), we assume that tree shelters will begin degrading by year 3 (Rainbow Professional Ltd, personal communication). We model degradation as a two-step process: first as fragmentation via the action of UV light, and second as mineralisation, which generates carbon dioxide and water vapour. The role of grazing in fragmenting shelters was not modelled due to a lack of data. Data on photodegradation was obtained from Gogotov and Barazov (2012) and from Li *et al.* (2014) for PP and PLA, respectively, whilst the amount that is further mineralised was extrapolated from Fechine *et al.* (2009) and Dharmalingam (2014). Cashmore (2010) suggested that at least 50% of plastic materials are mineralised into carbon dioxide and water, whilst Arnold and Alston (2012) additionally assumed that the other 50% degrades to aldehydes, ketones, acids, esters and alcohols for polypropylene. Here we make the simplifying assumption that both PP and PLA fully mineralise to carbon dioxide and water (see Supplementary Materials for the stoichiometric equations used); this is likely to represent the worst-case scenario for Climate Change impacts. We note that aldehydes and ketones are a class of volatile organic compounds (VOCs) with strong chemical reactivity and therefore environmental impacts other than Climate Change - like Human and Environmental toxicity and Photochemical Ozone Formation - would increase if these were modelled. Following the PEF guidelines (EC-JRC, 2012), we do not model carbon sequestered in bio-based PLA and carbon emissions resulting from its degradation, rather we report embodied carbon as separate figures in impact assessment results.

As noted in Section 0, the environmental impacts of plastic pollution are not currently quantifiable with LCA. We, therefore, report in Table S2 the potential amounts of plastic fragments that accumulate in the environment for each scenario. Scenario 6, which envisage leaving PLA shelters to degrade in situ, yields the highest figure that equals ~0.01 kg per FU and 160 kilotons per 2 billion trees. Scenarios S2 to S5, where shelters are only partly recovered at the end of the establishment period, yield lower amounts in the order of ~0.03-0.04 kg per FU and ~60-70 kilotons per 2 billion trees. Prospective Scenarios generate no plastic fragments because they are assumed not to degrade during the establishment period. We acknowledge that shelters may not degrade at all, and therefore, potential plastic fragments left in the environment may amount up to the shelters' original weight; this would equate to 429kt for S6.

2.2.3. Tree Production at Nursery

Tree production at nursery was modelled in accordance with the Woodland Trust's policy on sourcing only UK-grown seedlings for planting. We modelled tree production as cell-grown based on a nursery - Alba Trees - that the Woodland Trust employs. This production method, which entails germinating and propagating trees in small cells under controlled environments, is advantageous over bare-root nurseries where trees are rooted outside because they can supply trees throughout the year and therefore have higher production capacity. Inventory data is reported in Table S4 in the Supplementary Materials and is based on a combination of data gathered onsite and from literature.

2.2.4. Transport

In our analysis, we assumed that tree shelters are manufactured in Wales, where a known manufacturer (Tubex) is located, and that trees are grown in Scotland, where Alba Tree's nursery is situated. The current procedure envisages shelters to be transported to tree nurseries, where they are combined with trees and sent to planting destinations. We approximated to 600 km the distance between the shelter production facility and the tree nursery (i.e. between the centres of Scotland and Wales) and to 300 km the distance between the tree nursery and planting site (between the centres of Scotland and UK).

2.2.5. End-of-life treatment

Current Scenarios S2 and S3 assume that shelters are treated at the end of their life according to the current UK waste treatment mix: 41% incineration with energy recovery, 16% incineration without energy recovery and 43% landfill (Department for Environment Food & Rural Affairs (Defra), 2019). In the Supplementary Materials, we also investigate the effect of different strategies that envisage each treatment option separately or a 50/50 split between landfill and incineration with energy recovery (Table S5). The analysis identifies incineration with energy recovery as being the best favourable option from an environmental perspective. We assume that this technology is employed in Prospective Scenarios S7 and S8.

Current Scenarios S4, S5 and Prospective Scenarios S9, S10 and S11 envisage recycling of tree shelters. The recycling efficiency for both PP and PLA was assumed equal to 92% from Gabi Professional database. S4 and S5 assume that plastic recyclates are of lower quality and cannot be used to manufacture new shelters; this reflects the fact that current shelters are not produced from recycled plastics and that it is deemed cost-inefficient to collect and recycle them (Yorkshire Dales

Millennium Trust, 2019). Plastic recyclates are thus down-cycled, i.e. recycled into lower quality products. S9, S10 and S11 assume that tree shelters are manufactured with 35% recycled content, which aligns with current government policy direction for plastic products (EuRIC, 2018; Plasteurope, 2018; Victory, 2019; WRAP, 2019). This entails that recycling is modelled assuming that 35% of the plastic recyclates are used to manufacture shelters, and the remainder is down-cycled like in S4 and S5.

Plastic packaging of tree shelters and young trees are at present unlikely to be recycled in the UK (Thomson et al., 2018) and were thus assumed to be treated according to the current UK waste treatment mix.

2.2.6. Allocation

Recycling and incineration with energy recovery are EoL strategies that provide additional functionalities (i.e. production of recycled materials and energy) to the product system. Multi-functional systems present a methodological challenge in LCA because environmental impacts need to be allocated between the different functions. For shelter recycling in both Current and Prospective Scenarios, we use the Resource Use and Emission Profile formula (EC-JRC, 2012), which envisage the allocation of environmental impacts based on price ratios between recycled and virgin plastics; this is reported in Supplementary Materials – Table S6. For the scenarios that assume incineration with energy recovery of tree shelters, we allocate the environmental impacts using the model Allocation at the Point of Substitution (APOS) developed by EcoInvent (Wernet et al., 2016).

2.3. Environmental Impact Assessment, Normalisation and Weighting

The Environmental Footprint (EF) 3.0 method was used to translate emissions and resources use into environmental impacts (EC-JRC, 2012); we report results for all environmental categories. We normalised the LCA results using factors developed by Sala *et al.* (2020) (Supplementary Materials – Table S7) and a scaled-up functional unit corresponding to achieving 2 billion trees surviving the establishment period, which would meet Woodland Trust's goal of increasing UK woodland cover by 6% (see Section 1). The normalisation factors represent global carrying capacities for categories of the Area of Protection (AoP) Natural Environment and tolerable/acceptable level of pollution for the AoP Human Health, whilst they adopt a Factor 2 approach, i.e. reduction of 50% of resources use, for the AOP Resources. We then weighted the normalised results to generate a single environmental impact score that enables ranking the different scenarios investigated. The weighting factors used were modified from those developed by Sala, Cerutti and Pant (2018). Their approach took into consideration public and LCA expert scorings on various aspects and criteria for each environmental impact category and the robustness of the categories' underlying models and that of normalisation factors based on global emissions. The modification of weighting factors was necessary because we did not use normalisation factors based on global emissions (see above). Our weighting factors, which are reported in Table S8 in the Supporting Materials, are obtained by multiplying weightings based on public and LCA expert scorings with factors that only account for the robustness of the environmental models.

3. Results and Discussion

3.1. Climate Change

3.1.1. Current Scenarios

Figure 2 reports Climate Change impacts of Current Scenarios for shelter-aided tree planting (S2-S6) compared with the base case scenario where shelters are not employed (S1). The chart shows that planting trees without shelters yields the lowest climate change impacts (~0.22 kg CO_2 eq.), about 3 to 4 times lower than scenarios envisaging usage of tree shelters. These results imply that the benefits of shelters in terms of enhanced survival rates do not offset the additional environmental impacts associated with their manufacture. Climate Change impacts of scenarios S2 to S6 are dominated by tree shelter manufacture (see Figure 2); further analysis identified production of plastic resin (PP and PLA) as the main contributor. By contrast, S1 Climate Change impacts originate from similar contributions of tree production and transportation.

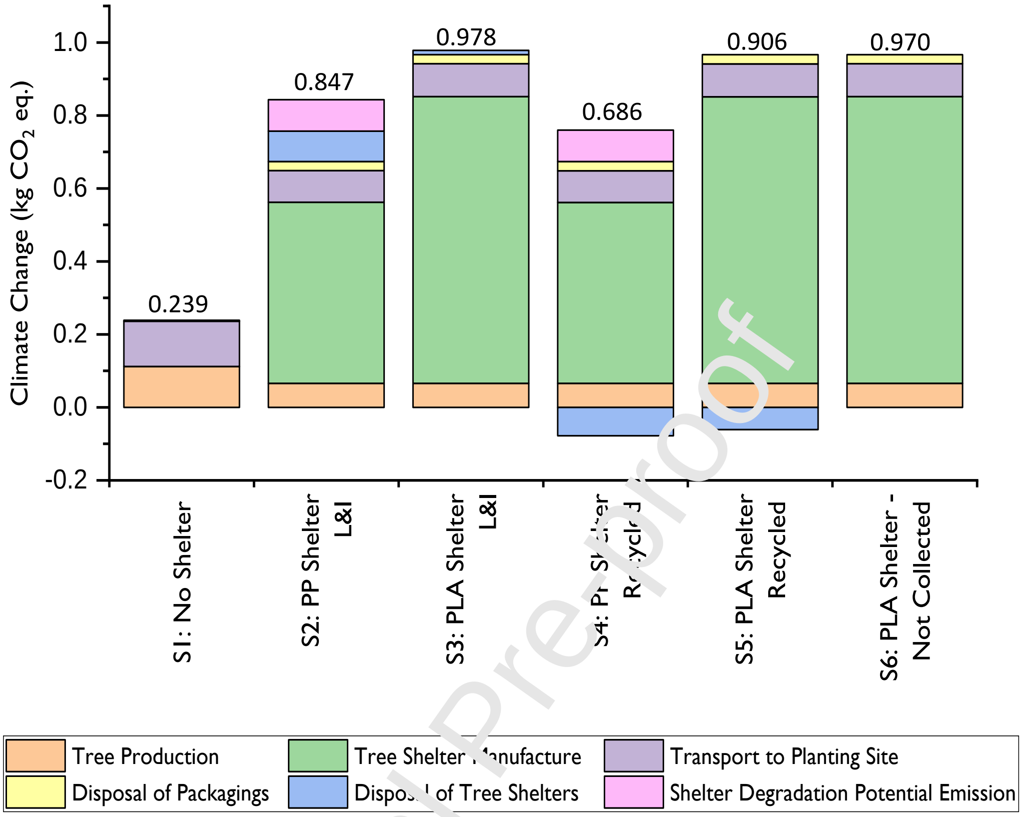


Figure 2: Climate Change for scenario 1 (base case) and Current Scenarios for shelters-aided tree planting S2 to S6. [Colour required for print]

It is essential to contextualise these results in terms of carbon sequestration potentials of trees. In Table 2, we report average figures for cumulative CO_2 sequestration of trees extracted from the US Department of Energy (1998). S1 carbon emissions represent 7.6% of carbon sequestered by a five-year-old tree, whilst those of S2-S6 between 21% and 31%. These carbon emissions become negligible (<0.5%) for all scenarios when considering a 25-year-old tree that has sequestered up to ~400 kg CO_2 (US Department of Energy, 1998). Therefore, it can be inferred that although not using shelters is the environmentally preferred option with respect to carbon emissions, the additional impacts associated with the use of shelters do not outweigh the benefit of increasing woodland cover in terms of carbon sequestration potential. In Section 3.2, we investigate whether this holds true for other environmental categories too.

Table 2: Cumulative carbon sequestration by a tree after planting. Source: US Department of Energy (1998).

Years After Planting	**Cumulative CO_2 Sequestration ($kgCO_2$/tree)**
5	3.14
25	405
50	3250

The comparative analysis reported in Figure 2 also demonstrates that PP shelters (S2 and S4) perform better than PLA ones (S3 and S5). The difference in carbon emissions is due to the manufacture of tree shelters, and more specifically to the production of the respective resins: Climate Change impacts per Functional Unit equal 0.35 kg CO_2 eq. for polypropylene (PP) and 0.61 kg CO_2 eq. for PLA. PP shelters outperform PLA ones in the Climate Change category for two reasons. First, PLA has a higher carbon footprint per kg of resin than PP (2.45 kg CO_2 eq./kg PLA and 2.12 kg CO_2 eq./kg PP); and second, PLA has a higher density than PP: we assumed that PLA shelters require a higher mass of plastic resins compared to PP shelters (see Section 2.2.2). We note that our results run contrary to those of Arnold and Alston (2012), who suggested that bio-based shelters marginally outperform fossil-based ones; we hypothesise that they assumed PLA shelters have equal weight to PP ones and that this originated the discrepancy between ours and their results. As commercial shelters typically have fixed dimensions (heights, in particular), we assumed that the material volume rather than its mass is key to the functionality of shelters; PLA shelters are therefore heavier due to their higher density compared to PP.

A critical review of LCA studies of commercial biopolymers demonstrated that Climate Change results for plastic resin production are extremely dependent on whether credits for carbon sequestered in bio-feedstock are considered (Yates and Barlow, 2013). When carbon credits are applied, PLA resins typically feature better performances than PP ones. In this study, we followed the PEF recommendations in keeping separate removals and emissions of biogenic carbon (EC-JRC, 2012); this is because biogenic carbon sequestered may be released as part of the natural carbon cycle, for instance, at the EoL of products. Table S9 reports the amounts of carbon embodied in bio-based plastic shelters and the amount that is recoverable at the end of the establishment period assumed in this study. Recycling of PLA shelters entail continued storage of biogenic carbon sequestered; if embodied carbon is credited to S5, the differences in Climate Change results with PP shelters (S2 and S4) become marginal. This implies that the choice of shelter's material with respect to carbon emission performance may not be straightforward. However, our results clearly indicate that recycling shelters (S3 and S5) yield lower carbon emissions than disposing shelter according to the current UK waste treatment mix, which is a mix of landfill and incineration split (S2 and S3). Further results reported in the Supporting Materials show that after recycling, incineration with energy recovery is the preferred EoL treatment method for shelters in terms of carbon emissions, followed by landfill and incineration without energy recovery (Tables S10 and S11).

3.1.2. Prospective Scenarios

Figure 3 reports Climate Change results for Prospective Scenarios (S7-S11) compared with the base case scenario (S1) where shelters are not employed. The chart depicts a similar trend to that found for Current Scenarios. First, Prospective Scenarios for shelter-aided tree planting do not achieve lower carbon emissions than S1. However, they yield lower differences between the base case and the best performing Prospective Scenario (S9) that has Climate Change impacts about two times higher than S1. Second, recycling tree shelters is environmentally beneficial. In Prospective Scenarios, the environmental benefits are more significant because: (i) shelters are fully recovered and recycled, and (ii) part (35%) of the plastic recyclates are used to manufacture new shelters. Our results, therefore, show that aiming for full recoverability and increased recycling represents a significant improvement in the environmental performance of shelter-aided tree planting. It must be noted that we assumed no changes in the composition of prospective resins or that these changes have negligible effects on the environmental performance. Future studies should investigate the validity of this assumption. Third, bio-based shelters (including bio-PP) have higher Climate Change impacts than the conventional, fossil-based ones due to increased carbon emissions associated with resin production. As in Current Scenarios, carbon embodied in bio-based shelters due to carbon sequestration from the growth of feedstock was not considered in the LCA model. However, because

Prospective Scenarios assume shelters to be fully recoverable and recyclable, the amount of carbon embodied in bio-based shelters, after their use, is larger than that of Current Scenarios (see Table S9); therefore, crediting the amount of carbon sequestered would decrease significantly the Climate Change impacts of S10 and S11.

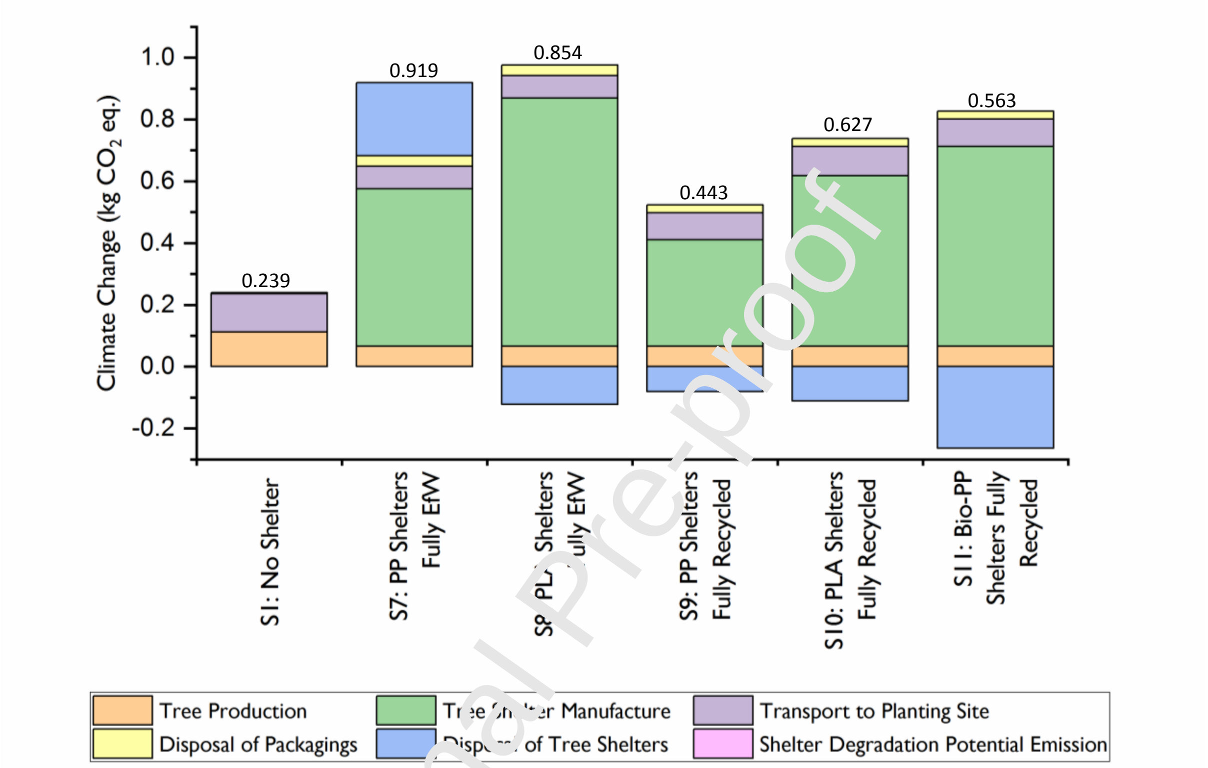


Figure 3: Climate Change results for S1 (base case) and Prospective Scenarios for shelters-aided tree planting S7 to S11. [Colour required for print]

3.2. Other Impact Categories

3.2.1. Current scenarios

Table 3 reports environmental impacts other than Climate Change for Current Scenarios (S2-S6) compared to the base scenario (S1). The table shows that S1 yields the lowest impact in nearly half of environmental categories (seven out of fifteen) and the highest in four: Eutrophication – freshwater, Ozone Depletion, Resource Use – minerals and metals and Water Scarcity. Hot-spot analysis revealed that the increased production of trees at nursery contributed highly towards Water Scarcity due to the watering of seedlings and towards the other three categories due to the supply of copper oxide as part of fungicide production. PP shelters (S2 and S4) generate the lowest impact in four environmental categories, including three of the four categories where S1 underperforms; Scenario S5 (which envisages PLA-based shelters and partial recycling) represents the best performing option in the remaining category: Ozone Depletion. Our results show that the choice of a tree planting option is not straightforward and entails consideration of several environmental trade-offs; further interpretation of the results is thus necessary, in particular, to investigate whether the increase in environmental impacts associated with S1 outweigh the desirable decrease in other categories. This is addressed in Section 3.4, where we discuss weighted environmental impacts.

S3 and S6 (where PLA tree shelters are employed and either landfilled/incinerated or left at the planting site to biodegrade) represent the least preferred option; they generate the highest values in nearly half of the environmental categories (seven out of fifteen) and average values in the remainders. The two scenarios significantly underperform S1 in four categories: Cancer Human Health Effects, Ionising Radiation, Land Use and Non-cancer Human Health Effects. Hot-spot analysis showed that the production of shelters and particularly the supply of starch and polylactic acid represent the key contributors towards these categories. This is in part attributed to the larger weight of PLA shelters (see Section 2.2.2 and Section 3.1.1); for instance, this affects Ionising Radiation results, which are heavily influenced by energy consumption per kg of plastic resin production. In part, it is also attributed to additional processes like crops farming and feedstock treatment that are required to manufacture PLA, which affect Land Use and Human Health Effects.

The results reported in Table 3 do not incorporate the full range of potential environmental impacts of using fossil- and bio-based plastic shelters because those caused by plastic fragments are not yet quantifiable (see Section 0 and Section 2.2.2). Studies on in vitro toxicity of plastic products show that neither PP nor PLA is without toxic effects on microorganisms (Green et al., 2016; Zimmermann et al., 2019); hence, toxicity impacts are likely to increase for scenarios where shelters are allowed to fragment (S2-S6) regardless of the plastic resin type. However, there is currently insufficient knowledge to warrant assumptions on whether either fossil-based or biodegradable plastic has more or equal impact when left to degrade in situ. More studies on the fate, exposure and effect of plastic, and plastic additives are necessary to begin quantifying the toxicity of plastic fragments in the environment (Boucher et al., 2019).

Table 3: Environmental impact results for Scenario 1 (base case) and Current Scenarios for shelters-aided tree planting S2 to S6. The lowest and highest values for each environmental category are highlighted in green and red, respectively. L&I = Landfill and Incineration. [Colour required for print]

		Current UK Waste Split		**Down-Cycling**		
	S1 - No Shelters	**S2 - PP Shelters, L&I**	**S3 - PLA Shelters, L&I**	**S4 - PP Shelters, Recycled**	**S5 - PLA Shelters, Recycled**	**S6 - PLA Shelters, Not Collected**
Acidification, Terrestrial and Freshwater [Mole of H+ eq.]	1.61E-03	2.53E-03	4.21E-03	2.23E-03	3.84E-03	4.21E-03
Cancer Human Health Effects [CTUh]	1.31E-10	1.27E-10	1.18E-09	1.27E-10	1.03E-09	1.18E-09
Ecotoxicity, Freshwater [CTUe]	9.02E+00	6.55E+00	1.71E+01	6.8[illegible]E+00	1.59E+01	1.71E+01
Eutrophication, Freshwater [kg P eq.]	2.20E-04	1.45E-04	1.73E-04	1.[illegible]2E-04	1.66E-04	1.72E-04
Eutrophication, Marine [kg N eq.]	2.00E-04	4.22E-04	1.27E-03	[illegible].78E-04	1.12E-03	1.25E-03
Eutrophication, Terrestrial [Mole of N eq.]	1.95E-03	4.33E-03	1.32E-02	3.84E-03	1.17E-02	1.31E-02
Ionising Radiation - Human Health [kBq U235 eq.]	1.45E-02	1.73E-02	9.82E-02	2.56E-02	9.33E-02	1.00E-01
Land Use [Pt]	4.93E-01	4.68E-01	4.15E+01	5.66E-01	3.57E+01	4.15E+01
Non-cancer human health effects [CTUh]	1.11E-08	1.03E-08	6.40E-08	9.97E-09	5.63E-08	6.39E-08
Ozone Depletion [kg CFC-11 eq.]	1.19E-09	8.67E-10	7.00E-10	8.23E-10	6.99E-10	7.00E-10
Photochemical Ozone Formation, Human Health [kg NMVOC eq.]	5.13E-04	1.86E-03	2.13E-03	1.54E-03	1.93E-03	2.12E-03
Resource Use, Energy Carriers [MJ]	3.73E+00	1.67E+01	1.43E+01	1.43E+01	1.37E+01	1.45E+01
Resource Use, Mineral and Metals [kg Sb eq.]	5.55E-06	3.26E-06	3.79E-06	3.29E-06	3.72E-06	3.79E-06
Respiratory Inorganics [Disease incidences]	7.3[illegible]E-09	1.93E-08	3.12E-08	1.63E-08	2.81E-08	3.13E-08
Water Scarcity [m³ world equiv.]	1.17E+00	6.63E-01	9.08E-01	6.19E-01	8.37E-01	9.00E-01

3.2.2. Prospective Scenarios

Table 4 reports results for Prospective Scenarios (S7-S11) compared to the base case (S1). Similar to what was found for Current Scenarios, the table shows that S1 remains the best option, generating the lowest impact values in seven out of fifteen environmental categories, but the highest in the same four categories discussed in Section 3.2.1. PP shelters (S7 and S9) yield lower impact values than S1 in eight impact categories and do not generate the highest value in any category. Bio-based shelters result favourable only with respect to ozone depletion (S10 and S11) and water scarcity (S11). The table also shows that PP shelters (S7 and S9) are environmentally advantageous compared to bio-based options (both PLA, S8 and S10, and bio-PP, S11, shelters) when they are assumed to be fully recoverable at the end of the establishment period. S7 and S9 yield lower impact values in most impact categories compared to bio-based shelters (S8, S10, and S11) disposed of with the same EoL option, particularly for the Land Use impact category.

Table 4: Overall environmental impact result for Scenario 1 (base case) and Prospective Scenarios for shelters-aided tree planting S7 to S11. The lowest and highest values for each environmental category are highlighted in green and red, respectively. EfW = Energy from Waste. [Colour required for print]

	S1 - No Shelters	**S7 - PP Shelters, Fully EfW**	**S8 - PLA Shelters, Fully EfW**	**S9 - PP Shelters, Fully Recycled**	**S10 – PLA Shelters, Fully Recycled**	**S11 – Bio-PP Shelters, Fully Recycled**
Acidification, Terrestrial and Freshwater [Mole of H+ eq.]	1.61E-03	2.34E-03	4.08E-03	1.63E-03	2.39E-03	3.07E-03
Cancer Human Health Effects [CTUh]	1.31E-10	1.08E-10	1.16E-09	1.21E-10	4.94E-10	2.27E-09
Ecotoxicity, Freshwater [CTUe]	9.02E+00	5.56E+00	1.63E+01	7.10E+00	1.12E+01	7.83E+00
Eutrophication, Freshwater [kg P eq.]	2.20E-04	1.44E-04	1.72E-04	1.36E-04	1.47E-04	1.41E-04
Eutrophication, Marine [kg N eq.]	2.00E-04	3.62E-04	1.22E-03	2.80E-04	6.11E-04	2.52E-03
Eutrophication, Terrestrial [Mole of N eq.]	1.95E-03	3.74E-03	1.28E-02	2.78E-03	6.26E-03	8.19E-03
Ionising Radiation - Human Health [kBq U235 eq.]	1.45E-02	-5.55E-03	8.10E-02	3.03E-02	6.47E-02	3.92E-02
Land Use [Pt]	4.93E-01	2.21E-01	[illegible].13E+01	6.35E-01	1.48E+01	1.69E+01
Non-cancer Human Health Effects [CTUh]	1.11E-08	9.79E-09	6.33E-08	9.59E-09	2.89E-08	2.79E-08
Ozone Depletion [kg CFC-11 eq.]	1.19E-09	8.67E-10	7.00E-10	7.44E-10	6.99E-10	6.99E-10
Photochemical Ozone Formation, Human Health [kg NMVOC eq.]	5.13E-04	1.69E-03	2.00E-03	9.19E-04	1.18E-03	2.32E-03
Resource Use, Energy Carriers [MJ]	3.73E+00	1.35E+01	1.19E+01	8.73E+00	9.75E+00	4.96E+00
Resource Use, Mineral and Metals [kg Sb eq.]	5.55E-06	3.26E-06	3.77E-06	3.29E-06	3.48E-06	3.31E-06
Respiratory Inorganics [Disease incidences]	7.32E-09	1.75E-08	2.96E-08	1.05E-08	1.63E-08	2.63E-07
Water Scarcity [m³ world equiv.]	1.17E+00	6.95E-01	9.47E-01	5.61E-01	6.10E-01	5.24E-01

Hot-spot analysis shows that even with full recovery and full recyclability of shelters, the origin of the plastic resin continues to have a major influence over the environmental performance of tree shelter products. The contribution of Tree Shelter Manufacture towards each impact category in S9 and S10 - where PP and PLA shelters were assumed fully collected for recycling – is lower than that in S4 and S5 - where shelters were assumed to be partially collected for recycling (see Supplementary Materials - Tables S12-22 for process percentage contributions). This indicates that there is potential for the impacts associated with shelter production to reduce further if closed-loop recycling is enhanced. Nonetheless, the environmental impacts of shelters-aided tree planting are, on average, about eight times higher than the impact values generated by S1.

Our results demonstrate that prospective PP-based scenarios may attain similar environmental performances to S1. However, this will require additional research and development efforts to ensure plastic materials used for tree shelters can withstand weather and animal grazing throughout their designated use (i.e. tree's establishment period) to enable their full recovery for recycling. It will also be necessary to develop complementary enforcement and/or incentive strategies on the collection of shelters after the establishment period; this should include how this should be carried out, e.g. tracking the number of shelters and their location.

3.3. Normalisation

In the Supplementary Materials –Tables S23 and S24, we report normalised environmental impacts for the base case scenario and both Current and Prospective Scenarios. The Land Use category for bio-based shelter scenarios (S3, S5, S6, S8, S10 and S11) yield the highest normalised impacts. Figures for Current Scenarios range between 38 and 45 million person equivalents, approximately 56-67% of the UK population (Office for National Statistics, 2020). This implies that mass planting of trees in the UK to achieve a 6% increase in woodland cover would use up between half and two-thirds of global carrying capacity for land use that is allocated to the UK using a per-capita principle. Normalised impacts for fully recycled PLA and bio-PP shelters are lower, at 18 million person equivalents, roughly 27% of the UK population.

The second highest normalised impact category is Respiratory Organics for bio-PP shelters (S11); the figure approximately equals 10.5% of the UK population, an order of magnitude higher than all other scenarios for the same impact category. Hot-spot analysis on S11 reveals that bio-based PP resin manufacturing represents the major contributor to this category. Although both PLA and bio-based PP are both derived from biomass feedstock, the specific crop used is the causal factor for the environmental impact differences in plastic tree shelter production. Bio-based PP is assumed to be derived from sugarcane whilst PLA from corn starch. Farming of either crops entails specific environmental impacts. Irrigation demand and fertiliser use (and leaches) for corn farming are recognised to cause water stress and nutrient pollution (Barton and Clark, 2014). Sugarcane is not only linked to water overuse and leaching of chemicals from fertilisers, but also to habitat clearance, discharge of effluents from sugar mills to freshwater bodies and air pollution from pre-harvest burning of the crop (Oyugi, 2016; WWF, 2005). The conventional practice of pre-harvest burning for sugarcane may explain the value for Respiratory Organics in bio-PP shelters (S11); to this end, "green cane" harvesting, which envisages no pre-harvest burning, has been proposed as an environmentally advantageous strategy (Núñez and Spaans, 2008). Further to this, bio-based plastics can also be manufactured using waste materials, such as food waste (Perotto et al., 2018; Tsang et al., 2019) or the organic fraction of municipal solid waste (Ivanov et al., 2014). This avoids the environmental impacts associated with agriculture practices and is thus likely to improve the environmental performance of bio-based shelters.

For PP shelters scenarios (S2, S4, S7, and S9), the highest normalised values (~ 3% of the UK population) are associated with Climate Change and Resource Use – Energy Carriers. For both categories, the causal factor is the use of fossil fuels to manufacture PP. Results obtained for PP shelters for these impact categories are also relatively similar to values generated by PLA and bio-PP shelters scenarios where the same EoL treatment is assumed, despite PP shelters require fossil fuels for resin manufacturing. This is because more energy is used to manufacture the heavier PLA shelters.

For S1, the highest normalised impacts were Ecotoxicity – Freshwater, Land Use and Eutrophication –Freshwater. These can be attributed to the production of trees at the tree nursery, which requires the use of compost and pesticides. Like conventional PP shelter scenarios, the highest impacts for S1 are low, with normalised impacts being equal to ~1.5% of the UK population.

3.4. Weighting

Table 5 reports weighted environmental scores for all scenarios investigated. Weighting enables ranking various options investigated from the most to the least environmentally preferred; we note that the weighted results are heavily dependent on the specific factors applied; different factors may yield substantially different results. Our results indicate that the base scenario (S1) is overall the most advantageous tree planting option, followed by PP-based shelters-aided tree planting, in particular, the Prospective Scenario where they are fully recoverable and recycled partly into new shelters. The least preferred options include those using PLA shelters without collection at the end of the establishment period (S6) and with collection under Current Scenarios and treated in landfill and by incineration (S3). The weighted scores also confirm the results presented in Section 3.1 and 3.2 indicating that recycling is the overall most favourable EoL life treatment, followed by incineration with energy recovery, landfill and incineration without energy recovery.

However, it should be noted that the recovery and recycling of plastic tree shelters are not straightforward and may never be. After five years of growth of vegetation around the trees, species such as grasses and brambles often get entangled with the tree shelters. This occurs concurrently with the embrittling of the plastic, which means that removable after five years often results in the cracking and shattering of the tree shelter as it is pulled out of the entangled vegetation. Currently, this embrittled plastic, even if all the small pieces can be collected, has a negative value for recyclers and is only suitable for incineration. The monitory cost of such a collection in terms of manpower for a site with hundreds or thousands of 5-year-old tree shelters distributed across a terrain further adds to the practical difficulties. Hence, even the Prospective Scenarios that compete with S1 based on assumptions of recycling of the shelters look unlikely to be viable in practice.

The practical difficulties of recovering tree shelters are where a biodegradable plastic shelter made from PLA might prove to be important environmentally. However, the full biodegradability of these materials requires a specific set of environmental conditions, and without being able to guarantee those, the environmental fate of PLA in this scenario becomes uncertain. Recycling of PLA shelters would be beneficial but suffers from the same problems as PP tree shelters whilst having none of the advantages. Thus at present, our results do not favour the use of bio-based plastics for tree shelters, but we acknowledge that novel formulation from bio-waste materials might enhance the environmental performance of bio-based shelters (see Section 3.3).

We also note that our results are dependent on the assumed trees' survival rates (see Section 2.2.1). Literature studies show higher variability in the survival rates of trees grown without shelters (2% to 90%) than trees planted with shelter protection (67% to 100%) (Conner et al., 2000). Hence, if the actual survival rate is significantly lower than that assumed for S1 (planting without shelters), shelter-aided tree planting scenarios may be environmentally preferable. To this end, we performed a break-even analysis to identify the survival rate values for the unprotected scenario (S1) that would equate S1 weighted scores to those of other scenarios; this is reported in the Supplementary Materials – Table S25. The analysis showed that the weighted score of S1 would equate to that of S9 (PP shelters with full recovery and recycling) if the survival rate of unsheltered trees equals 37.6% and to that of S4 (where PP shelters are recovered partially for recycling) with a rate of 27.7%. The survival rate of unsheltered trees needs to be lower than 10% for bio-based shelters to be environmentally preferable.

In addition, we conducted a simple sensitivity analysis using the lower and upper boundary of survival rates provided by Conner et al. (2000) (Table S25). Where the employment of tree shelters can achieve 100% tree survival, the survival rate of unsheltered trees must at least be 44.3% or else S9 is environmentally preferred. A lower survival rate of 29.7% is sufficient for S1 to be preferable to S9 when the survival rate of sheltered trees equal 67%. We note that the survival rate of non-shelter-protected seedlings can be increased by means of other forms of protection; however, the additional activities must be considered in the balance and appropriately compared to other scenarios.

Table 5: Aggregated environmental Impact score for each scenario – post normalisation (per capita) and weighting. Results presented are x10^7 values. The colour scale goes from green (lowest value) to red (highest value) was applied. L&I = Landfill and Incineration, EfW = Energy from Waste. [Colour required for print]

		Current UK Waste Split		**Down-Cycling**			**Shelter Fully Recoverable Scenarios**				
	S1 - No Shelters	**S2 - PP Shelters, L&I**	**S3 - PLA Shelters, L&I**	**S4 - PP Shelters, Recycled**	**S5 - PLA Shelters, Recycled**	**S6 - PLA Shelters, Not Collected**	**S7 - PP Shelters, Fully EfW**	**S8 - PLA Shelters, Fully EfW**	**S9 - PP Shelters, Fully Recycled**	**S10 - PLA Shelters, Fully Recycled**	**S11 – Bio-PP Shelters, Fully Recycled**
Overall Environmental Impact	2.48	5.12	39.7	4.47	34.6	39.7	4.97	38.9	3.30	15.9	22.1

4. Conclusion

This article presented a comprehensive Life Cycle Assessment (LCA) study that compared current and prospective scenarios for shelter-aided seedling planting with a base scenario where shelters are not employed. The study focuses on the UK and the Woodland Trust national reforestation effort, but the results and conclusions are applicable to other temperate oceanic regions. Current Scenarios envisage either partial collection of shelters at the end of the five-year establishment period or that bio-based shelters are left to degrade in situ. Prospective Scenarios assume better designs and thus full recoverability. The Functional Unit is represented by the achievement of one tree surviving the establishment period of five years. The life-cycle inventory is based on a mix of data collected by the Authors and literature data for the foreground system; Gabi and EcoInvent databases are used for background activities.

LCA results show that planting seedlings without shelters yield the least carbon emissions amongst the scenarios investigated. However, carbon emissions associated with planting trees with and without tree shelters become negligible when considering the amount of CO_2 sequestered by a tree over 25 years, suggesting that the choice should be based on other environmental categories. The comparison for other categories highlights numerous environmental trade-offs; for instance, on a total of fifteen categories, planting seedling without shelters generated the lowest impacts in seven and the highest in four. Weighted LCA results indicate that planting seedling without shelters is overall the best option from an environmental perspective, even compared to best-case Prospective Scenarios for shelters-aided planting.

Our analysis also demonstrates that PP shelters are generally preferable to bio-based alternatives, including PLA and bio-PP, in both Current and Prospective Scenarios. Land Use for bio-shelters scenario yield the highest normalised impacts, representing up to 67% of the UK’s per capita allowance of global carrying capacities. We also considered the possibility of leaving PLA shelters to bio-degrade in the environment; this scenario yielded the worst environmental performance in most categories and in terms of weighted results. Finally, our analysis of end-of-life treatment options revealed that recycling is the most favourable in both Current and Prospective Scenarios, with closed-loop recycling outperforming down-cycling. However, we note there are practical difficulties in collecting and recycling plastic tree shelters that may mean that these Scenarios are not viable.

Acknowledgements

This work was funded by the EPSRC and UKRI, under grant EP/S024883/1, and carried out at the UCL Plastic Waste Innovation Hub with support from Professor Lettieri's LCA Group. We would like to thank the Woodland Trust, Alba Trees, Rainbow Ltd. and Danielle Purkiss for their assistance in data gathering activities; thank Danielle Purkiss further for her drawing of the graphical abstract and, thank Fabio Grimaldi and Martina Pucciarelli from Professor Lettieri's LCA Group and the Woodland Trust for their valuable feedback on our study.

References

Alba Trees, n.d. In-Person Interview Date: 26 November 2019.

Arnold, J.C., Alston, S.M., 2012. Life cycle assessment of the production and use of polypropylene tree shelters. J. Environ. Manage. 94, 1–12. https://doi.org/10.1016/j.jenvman.2011.09.005

Barton, B., Clark, S.E., 2014. Water & Climate Risks Facing U.S. Corn Production How Companies & Investors Can Cultivate Sustainability A Ceres Report.

Boucher, J., Dubois, C., Kounina, A., Puydarrieux, P., 2019. Review of plastic footprint methodologies.

Cashmore, S., 2010. The Photodegradation Resistance of Polymer Coatings for Pre-finished Steels.

Chazdon, R.L., Lindenmayer, D., Guariguata, M.R., Crouzeilles, R., Rey Benayas, J.M., Lazos Chavero, E., 2020. Fostering natural forest regeneration on former agricultural land through economic and policy interventions. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/ab79e6

Clift, R., Doig, A., Finnveden, G., 2000. The Application of Life Cycle Assessment to Integrated Solid

Waste Management. Part 1 - Methodology. Process Saf. Environ. Prot. 78, 279–287. https://doi.org/10.1205/095758200530790

Committee on Climate Change, 2019. Net Zero Technical Report 269-.

Conner, W.H., Inabinette, L.W., Brantley, E.F., 2000. The use of tree shelters in restoring forest species to a floodplain delta: 5-Year results. Ecol. Eng. 15, S47–S56. https://doi.org/10.1016/S0925-8574(99)00071-3

DECC, 2008. Climate Change Act.

Department for Environment Food & Rural Affairs [Defra], 2019. UK Statistics on Waste.

Dharmalingam, S., 2014. Biodegradation and Photodegradation of Polylactic Acid and Polylactic Acid/ Polyhydroxyalkanoate Blends Nonwoven Agricultural Mulches in Ambient Soil Conditions, Doctoral Dissertations.

EC-JRC, 2012. Product Environmental Footprint (PEF) Guide. European Commission Jt. Res. Cent. 154.

EuRIC, 2018. Landmark vote by the European Parliament - Binding Recycled Content Target for Plastics in Beverage Bottles voted by the European Parliament.

Fechine, G.J.M., Rosa, D.S., Rezende, M.E., Demarquette, N.R., 2009. Effect of UV radiation and pro-oxidant on PP biodegradability. Polym. Eng. Sci. 49, 123–128. https://doi.org/10.1002/pen.21230

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., Klüppel, H.-J., 2006. The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. Int. J. Life Cycle Assess. 11, 80–85. https://doi.org/10.1065/lca2006.02.002

Gogotov, I., Barazov, Sk., 2012. The effect of ultraviolet light and temperature on the degradation of composite polypropylene, International Polymer Science and Technology.

Green-tech, n.d. Tubex Standard [Product Specification] [WWW Document].

Green, D.S., Boots, B., Sigwart, J., Jiang, S., Rocha, C., 2016. Effects of conventional and biodegradable microplastics on a marine ecosystem engineer (Arenicola marina) and sediment nutrient cycling. Environ. Pollut. 208, 426–434. https://doi.org/10.1016/J.ENVPOL.2015.10.010

Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E., Purnell, P., 2018. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. J. Hazard. Mater. 344, 179–199. https://doi.org/10.1016/J.JHAZMAT.2017.10.014

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2018. Life Cycle Assessment: Theory and Practice. Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3

International Organization for Standardisation, 2006a. ISO: 14040: Environmental Management - Life cycle assessment — Principles and framework.

International Organization for Standardisation, 2006b. ISO 14044: Environmental Management — Life Cycle Assessment— Requirements and Guidelines 3, 1–46.

IUCN, 2020. The Bonn Challenge.

Ivanov, V., Stabnikov, V., Ahmed, Z., Dobrenko, S., Saliuk, A., 2014. Production and applications of crude polyhydroxyalkanoate-containing bioplastic from the organic fraction of municipal solid waste. Int. J. Environ. Sci. Technol. 12, 725–738. https://doi.org/10.1007/s13762-014-0505-3

Li, Y., Chen, C., Li, J., Susan Sun, X., 2014. Photoactivity of Poly(lactic acid) nanocomposites modulated by TiO2 nanofillers. J. Appl. Polym. Sci. 131, n/a-n/a. https://doi.org/10.1002/app.40241

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T., 2018. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. IPCC. https://doi.org/10.1017/CBO9781107415324

Núñez, O., Spaans, E., 2008. Evaluation of green-cane harvesting and crop management with a trash-blanket, Sugar Tech. https://doi.org/10.1007/s12355-008-0005-1

Office for National Statistics, 2020. Population estimates - Office for National Statistics [WWW Document].

Oyugi, B.A., 2016. Socio-Economic impacts of sugarcane farming on livelihoods and the biophysical environment in Transmara subcounty, Kenya.

Palma, A.C., Laurance, S.G.W., 2015. A review of the use of direct seeding and seedling plantings in restoration: what do we know and where should we go? Appl. Veg. Sci. 18, 561–568. https://doi.org/10.1111/avsc.12173

Perotto, G., Ceseracciu, L., Simonutti, R., Paul, U.C., Guzman-Puyol, S., Tran, T.N., Bayer, I.S., Athanassiou, A., 2018. Bioplastics from vegetable waste: Via an eco-friendly water-based process. Green Chem. 20, 894–902. https://doi.org/10.1039/c7gc03368k

Place, S., 2018. Plastic with a purpose [WWW Document]. Inst. Chart. For.

Plasteurope, 2018. EU Plastics Strategy: Waste management group welcomes ENVI committee support for mandatory recycled content | Plasteurope.com [WWW Document].

Ponder, F., 2003. Ten-year results of tree shelters on survival and growth of planted hardwoods, Northern Journal of Applied Forestry. https://doi.org/10.1093/njaf/20.3.104

Rainbow Professional Ltd, n.d. Phone Interview Date: 05 August 2019.

Rural Payment Agency, Natural England, 2020. TE5: Supplement for use of individual tree-shelters [WWW Document].

Sala, S., Cerutti, A.K., Pant, R., 2018. Development of a weighting approach for the Environmental Footprint, Publications Office of the European Union. https://doi.org/10.2760/945290

Sala, S., Crenna, E., Secchi, M., Sanyé-Mengual, E., 2020. Environmental sustainability of European production and consumption assessed against planetary boundaries. J. Environ. Manage. 269, 110686. https://doi.org/10.1016/j.jenvman.2020.110686

Sphera, 2020a. GaBi - Life Cycle Assessment LCA Software [WWW Document].

Sphera, 2020b. GaBi databases [WWW Document].

Thomson, H., Illingworth, K., McCoach, H., Jefferson, M., Morgan, S., 2018. PlasticFlow 2025: Plastic Packaging Flow Data Report, Wrap.

Tsang, Y.F., Kumar, V., Samadar, P., Yang, Y., Lee, J., Ok, Y.S., Song, H., Kim, K.H., Kwon, E.E., Jeon, Y.J., 2019. Production of bioplastic through food waste valorization. Environ. Int. https://doi.org/10.1016/j.envint.2019.03.076

UN Climate Summit, 2014. New York Declaration on Forest.

US Department of Energy, 1998. Method for Calculating Carbon Sequestration by Trees in Urban and Suburban Settings, Voluntary Reporting of Greenhouse Gases.

van Soest, H.L., den Elzen, M.G.J., van Vuuren, D.P., 2021. Net-zero emission targets for major emitting countries consistent with the Paris Agreement. Nat. Commun. 12, 1–9. https://doi.org/10.1038/s41467-021-22294-x

Victory, M., 2019. Europe R-PET content targets unrealistic | [WWW Document]. ICIS.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230.

https://doi.org/10.1007/s11367-016-1087-8

Woodland Trust, 2020. Emergency Tree Plan for the UK Emergency Tree Plan for the UK: How to Increase Tree Cover and Address the Nature and Climate Emergency.

Woodland Trust, n.d. Email Correspondence: July 2019.

Woods, J.S., Veltman, K., Huijbregts, M.A.J., Verones, F., Hertwich, E.G., 2016. Towards a meaningful assessment of marine ecological impacts in life cycle assessment (LCA). Environ. Int. https://doi.org/10.1016/j.envint.2015.12.033

WRAP, 2019. Plastics Market Situation Report.

WWF, 2005. Sugar and the Environment.

Yates, M.R., Barlow, C.Y., 2013. Life cycle assessments of biodegradable, commercial biopolymers—A critical review. Resour. Conserv. Recycl. 78, 54–66. https://doi.org/10.1016/J.RESCONREC.2013.06.010

Yorkshire Dales Millennium Trust, 2019. Plastic Tree Tubes Who needs them?

Zimmermann, L., Dierkes, G., Ternes, T.A., Völker, C., Wagner, M., 2019. Benchmarking the in vitro toxicity and chemical composition of plastic consumer products. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.9b02293

CRediT Author Statement

Charnett Chau: Conceptualisation, Methodology, Formal Analysis, Investigation, Writing – Original Draft, Writing – Review & Editing, Visualisation, Project Administration.

Andrea Paulillo: Formal Analysis, Validation**,** Writing – Original Draft, Writing – Review & Editing.

Nancy Lu: Methodology, Formal Analysis.

Mark Miodownik: Conceptualisation, Writing – Review & Editing, Supervision, Funding Acquisition.

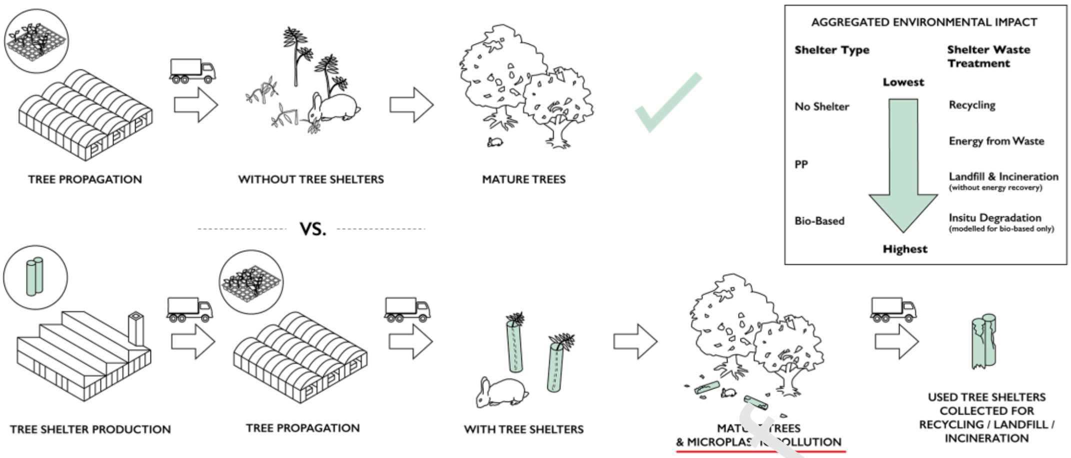
Paola Lettieri: Resources, Writing – Review & Editing, Supervision, Funding Acquisition.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical abstract



Research Highlights:

- Plastic waste pollution should be considered when increasing woodland cover.
- We compared the environmental impact of planting trees with and without shelters.
- Planting seedlings without tree shelters is the environmentally preferable option.
- Currently, PP shelters are preferable to bio-based alternatives (PLA and bio-PP).
- Recycling is the most environmentally advantageous after-use treatment for shelters.