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WOOD AND OTHER RENEWABLE RESOURCES

Life cycle assessment of sitka spruce forest products grown in Ireland

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Abstract

Purpose The purpose of this study is to quantify the environmental impacts of Sitka spruce timber products harvested from the forestry sector in Ireland. This data is typically country-specific and is required to accurately quantify the environmental impacts associated with its production to better understand the impacts on the environment.

Methods A representative model utilising the ReCiPe midpoint approach is developed for the forest sector and the production of log products in Ireland from primary data collected from the national forestry agencies, boardmill and sawmills over a 12-month period, where the last two represent 100% and 67% of the national production volume, respectively. The model was analysed using Life Cycle Assessment (LCA) and the resulting environmental impacts of log production are presented for two different boundary conditions, namely 'cradle-to-forest road' and 'cradle-to-factory gate' which considers the transport of the logs for further processing.

Results and discussion The results are presented for the reference functional unit of 1 m^3 of Sitka spruce log product but the results are also shown for 1 rotation of 1 ha of forest area, which allows comparisons with existing studies that utilise similar metrics such as a given area of forest. The results show that typically, clearfell operations are the most significant contributor to all impact categories. The contribution of the remaining operations in descending order of magnitude are thinning operations, forest road construction and maintenance, site preparation options, seedling production and finally forest maintenance operations. The extended model ('cradle-to-factory gate' model), which includes transport or delivery, has demonstrated a significant contribution due to transport alone where it was found to be responsible for, on average, 50% of each impact category presented (excluding land occupation) highlighting its significance.

Conclusions The underlying Life Cycle Inventory (LCI) data, which quantifies the total outputs of emissions and substances to air, land and water, is presented. It can be seen that the contribution of different operations varies significantly dependent on the log type which provides important data which can be further incorporated into future studies for downstream products utilised in the construction industry.

Keywords Life Cycle Assessment (LCA) · Irish forestry · Log production · Sitka spruce · Transport

1 Introduction

In recent years, there has been a drive to reduce the impact of human activities on the environment. The construction industry is seen as a key sector in need of improvement and the ability to quantify the environmental impacts associated with construction activities is becoming increasingly important. There has been a drive within the construction industry to use more sustainable construction materials in an effort to reduce the overall environmental impact of buildings. Timber is one such material that has significant potential to contribute to the sustainable development of the built environment and reduce the impact of construction on the natural environment. Consequently, the ability

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Highlights

- Life cycle assessment of the Irish forestry sector is presented.
- Impacts are presented by log type, namely, saw log, pallet log and pulp log.
- Log transport for processing accounts for approximately 50% of all forestry product emissions.

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to effectively quantify the environmental impacts associated with forest products is required and techniques such as Life Cycle Assessment (LCA) are essential to quantify current emissions and develop policy targets as the industry transitions towards more sustainable development. There is also a growing trend towards Life Cycle (LC) or whole-life cycle thinking to be taken into consideration when addressing such issues related to accounting for emissions to the environment to avoid the risk of 'problem shifting' rather than 'problem-solving'. This can be observed throughout the European Union (EU) and United Nations (UN) (European Commission 2019; Gervasio and Dimova 2018), where it is becoming accepted that a life-cycle assessment approach to product development must be compulsory.

As a member of the EU, Ireland has placed sustainable development high on its agenda in response to growing climate change concerns. Therefore, the method identified as being most suitable to assess the environmental impact of the forest industry in Ireland throughout this study is LCA. LCA is defined through the ISO 14040 and 14,044 standards (ISO 2006a, b) as the 'Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life'. The implementation of LCA as an assessment tool is still developing as it matures and grows in popularity (One Click LCA 2022). There have been considerable activities and debates throughout the LCA community on the various approaches to undertaking an LCA, in particular, how the Life Cycle Inventory (LCI) data or the initial input–output data should be gathered.

There is an increasing tendency towards the development and use of sustainable construction materials in buildings. Buildings reportedly account for 37% of all EU CO_2eq. emissions (United Nations 2021). While much of this can be attributed to operational emissions (e.g. lighting, heating etc.), which are dispersed over the whole building life, (typically 50-year design life), as much as 11% may be attributed to the embodied carbon emissions from the materials we chose to use in construction (Röck et al. 2020). The choice of materials in construction will be increasingly scrutinised in greater detail in future and more sustainable materials will be favoured in construction.

This growing requirement and trend can be considered a significant opportunity for forestry given their renewable, and carbon capture and storage nature. It has been shown that afforestation and the increased use of timber is an important greenhouse gas (GHG) mitigation strategy (Duffy et al. 2020). Wood production in Ireland is dominated by softwoods, Sitka spruce (*Picea sitchensis* (Bong.) Carr.)) in particular, and throughout Ireland, production output is currently increasing from approximately 3.6 million m^3 of roundwood in 2016 to 7.6 million m^3 by 2035 (Department of Agriculture Food and the Marine 2021). As they are naturally grown, wood products lack the consistent homogeneity that can be found in other major building materials such as steel or concrete. For these other materials, the use of environmental data from other countries may be sufficient. However, secondary data relating to wood products from other countries are typically not suitable for use with Irish timber products due to differences in climate, tree species and forestry practices. Although the need to consider the environmental impacts of wood products in Ireland is clear, timber as a construction material poses various difficulties given the longevity of the growth cycle associated with forest products and the similar longevity of buildings (typical softwood rotations in Ireland are 35–45 years (Moore 2011) and buildings are often designed for an assumed 50-year design life (Gervasio and Dimova 2018)).

There is currently limited scientifically developed data regarding the life cycle impacts of forestry and by extension wood-based construction products that are relevant to Ireland (Murphy et al. 2015, 2014). There is a growing need to know the environmental impacts of Irish forestry and associated products as this information will help the industry understand its environmental performance and its role in Ireland's transition towards more sustainable construction and sustainable development. This will also become increasingly important as new environmental and sustainability policies are implemented including eco-labels, such as Environmental Products Declarations (EPDs), indicating the environmental impacts of a given product or service, which are growing in popularity and are becoming mandatory in various countries (One Click LCA 2022). As there is currently limited data for forest products produced from Irish forests, it is the purpose of this analysis to quantify this data, which can then be used in further studies with a focus on Sitka spruce products due to the current reliance of the forestry industry on this species.

2 Forestry in Ireland

At the beginning of the twentieth century, Ireland's woodland cover was ultimately reduced to its lowest cover (approximately 1%) since the Ice Age due to hundreds of years of over-exploitation (Department of Agriculture Fisheries and Food: Forest Service 2008). It wasn't until the 1920s, that a state-funded forestation programme was established. However, the state had declared that afforestation should only occur on poor-quality land that was unfit for farming in order to ensure it was possible to produce sufficient food for the population. The total forested area at this time was estimated to be approximately 125,000 ha or 1.5% of the total land area of Ireland (COFORD National Consultative Committee on Forest Genetic Resources 2012; Department of Agriculture Fisheries and Food: Forest Service 2008).

Over the following decades, mostly upland sites owned and managed by the state were planted with exotic conifers from northeast America as these sites were not particularly suited for broadleaf species. Sitka spruce constituted over 80% of the annual planting programme by the 1980s due to the high yield it could achieve making it the most prominent species in Ireland. However, this lack of diversity led to policy changes to introduce a wider variety of planted species. Around the same period, special grant schemes were also introduced to increase the level of afforestation in the private sector (COFORD National Consultative Committee on Forest Genetic Resources 2012; O 'Donoghue et al. 2014). Since then, the total forested area has increased to 808,848 hectares or 11.6% of the total land area (Department of Agriculture Food and the Marine 2022). The total forested area is still considerably lower than the 2020 European average of 38% (FOREST EUROPE 2020). Of the current total forested area, 49% are state-owned forests and the remaining 51% are owned by the private sector (Department of Agriculture Food and the Marine 2022). Nevertheless, Sitka spruce still represents over 44.6% of Irish forest estate and over 75% of harvested softwood (Coillte 2015a; Department of Agriculture Food and the Marine 2022).

In 2021, the total roundwood production in Ireland was 4.33 million m^3 and this output is expected to increase in the coming years (Department of Agriculture Food and the Marine 2022). Most of the harvested roundwood is used by the Irish sawmill and boardmill industries, accounting for 64% and 31%, respectively (Irish Forestry and Forest Products Association 2016). The remainder of the harvested logs from Irish forests are used in the production of bioenergy, firewood and furniture. Five large sawmills and three medium-sized sawmills represent 90% of the sawn timber production in Ireland while many smaller sawmills represent the remaining 10% (Irish Forestry and Forest Products Association 2016). Three boardmills make up the boardmill industry in Ireland, one of which produces OSB while the remaining two primarily produce fibreboard.

3 LCA of Irish forests

3.1 Introduction

This section presents the goal and scope of the LCA of Irish forests, inclusive of the functional unit, system boundary, allocation procedure, assumptions and limitation within the study and presents the LCI data collection phase of the study.

3.2 Goal

This study aims to quantify the environmental impacts associated with the production of typical Sitka Spruce timber logs from Irish forests and to develop a LCI of the current forestry operations and products in Ireland. The most significant processes in terms of emissions, 'the environmental hotspots', of the production processes will also be identified allowing the problem area or areas of concern to be highlighted for future planning.

The key assumptions associated with analysing the harvested log products are described here. Although there are set guidelines for undertaking an LCA as defined by the ISO standards (ISO 2006a, b), the methodology is still evolving and there is still a lot of debate on best practice techniques, particularly in the wood products industry. The quality and representativeness of these existing LCIs are crucial to the overall accuracy of any given LCA that is being developed. Therefore, it is worth noting that unless all assumptions made for two or more studies are identical, for example on system boundaries, functional unit and allocation methodologies, then the results of the studies should not be compared. For example, Klein et al. (2015) undertook a state-of-the-art study on 28 forestry-based LCA studies and defined 25 different forestry operations. Of the 28 studies, no two had considered the same forest operations, preventing direct comparison between the studies.

3.3 System model for the Irish forestry practice

In order to assess the environmental impacts associated with the forestry industry in Ireland using LCA, a model of a typical Irish forest was created and assessed. This detailed model was developed to accurately represent the current production and maintenance practices associated with the management of a typical Sitka spruce forest in Ireland over a single forest rotation. For the purpose of this study, one rotation represents 40 years (Moore 2011). This system model includes all forestry processes from seedling production to the transport of the softwood logs from the forest site to factories (boardmill and sawmill industries) where they undergo further processing. The model was developed because standard LCA approaches were not applicable due to the variability between forests, the scale of the industry and temporal issues associated with forestry-based LCAs.

Special care was taken to ensure that the model developed was representative of the current forestry production procedures in Ireland. During the development of this model, a number of key assumptions were required. One such assumption is almost universally applied when undertaking a forestry-based LCA is the 'steady state' assumption. This assumes that Irish forests maintain a regular, unchanged forest production system with respect to carbon stock, land use, availability of nutrients and water and also forestry management systems over time given the exceedingly long production period of forest products (relative to other manufactured goods) and the developments and changes that can occur over such a time period.

The 'steady state' assumption used in this model assumes no significant changes in forestry operations over time, including land use. This implies that the total area of forested land in the geographic region of interest, in this case, the island of Ireland, remains constant over time. For this assumption to be considered true, only re-established sites can be considered in the analysis; operations associated with the afforestation of an agricultural or 'greenfield site' must be excluded. Since the area of softwood plantations in Ireland is currently increasing by less than 1% per year, the current situation in Ireland is close to satisfying this steady-state assumption (Department of Agriculture Food and the Marine 2022). However, there is still, currently, no agreement on how to effectively assess the land use impacts in the LCA methodology (Antón et al. 2007; Forster et al. 2021; Mattila et al. 2012; Michelsen et al. 2012) or more specifically how to quantify the inclusion of biodiversity from land use activities (Forster et al. 2021; Michelsen et al. 2008; Milà I Canals et al. 2007). In addition, there is also a lack of suitable data available in relation to assessing the associated environmental impacts. Therefore, in agreement with the steady-state assumption that state land use and carbon stock do not change over time, land transformation impacts are considered outside the scope of the model developed here. This is consistent with the majority of forestry-based LCAs currently available in the literature (Berg and Lindholm 2005; Forster et al. 2021; Johnson et al. 2005; May et al. 2012; Schweinle and Thoroe 1997; Seppälä et al. 1998; Sonne 2006).

3.3.1 Functional unit and harvested log properties

The reference functional unit of the forestry model analysed here is 1 m^3 of Sitka Spruce Log Product Over bark (OB) at the forest road or delivered to the factory gate depending on the system boundary assumed. After thinning and clearfell, the harvested forest products are divided into three distinct product categories based on their size including sawlog, pulp wood and pallet wood as defined in Table 1.

In any given LCA, the functional units and their properties need to be clearly defined in order to meet ISO standards and also to ensure the LCA is comparable with other studies. For a harvested wood product, these properties include the moisture content (MC) and the density of the product.

The moisture content and both the green and dry density of the log products when harvested vary significantly between products. In order to represent a typical Sitka spruce log from an Irish forest, typical values were assumed. The density and MC of the harvested forest products have a significant influence on a number of factors in the study. For example, the fuel required in log haulage is directly proportional to the green density of the product. The MC of the logs also has a significant impact on the drying operations during any processing that may be required. Finally, the dry density of the logs also directly defines the mass of carbon stored per unit volume of product. The density of the log products tends to vary depending on many factors such as forestry conditions, forest management practices, age of forest stock and also the product type. Studies conducted across Ireland report different mean dry densities for Sitka spruce produced in Irish forests. Some found a mean density of 350 kg/m^3 (Gallagher et al. 2004) while others report a calculated mean of 447 kg/m^3 (Kent et al. 2011). However, this is primarily due to the considerable variability of the density and the low sample size used in these studies. For the purpose of this study, the dry density of a typical Sitka spruce log was assumed to be 370 kg/m^3. This is relatively consistent with the meta-study undertaken by Harte et al. (Harte et al. 2014) and other Irish-based studies (Gil-Moreno et al. 2022; Mockler 2013; Simic et al. 2019) which found the dry density to be 359 kg/m^3, 372 kg/m^3, 381 kg/m^3 and 386 kg/m^3, respectively. It should also be noted that fast-grown logs typically have a lower density than slower-grown logs. In order to quantify the MC of the harvested log products in Ireland, the green densities of the products were calculated, which when combined with the dry density can provide the MC. The mass and volume of over 22,000 deliveries in 2011 and 2012 to sawmills and boardmills in Ireland were used to calculate the typical green density of the harvested logs. This data was provided from personal communication with sawmills and product manufacturers in Ireland (OSB Manufacturers 2015; Sawmills 2015) which allowed the typical green density and, in turn, the MC (wet basis) of the softwood logs extracted to the forest road to be calculated. The results were found to be 890 kg/m^3 and 58%, respectively. This is consistent with the advice provided by a harvesting expert in Coillte Teoranta, the commercial semi-state custodian of Ireland's forests, who suggested that a harvested MC of 55% is a reasonable assumption (Coillte 2015a).

Table 1 Forest product categories produced from Irish products (Purser 1991)

Forest Product Categories	Typical Size Range of Product	
	Top Diameter	Length
Sitka Spruce Sawlog	20 cm +	3.7 m +
Sitka Spruce Pallet wood	14 – 19 cm	2.4 – 3.7 m
Sitka Spruce Pulp wood	7 – 13 cm	1.5 – 3.8 m

3.3.2 System boundary

The system boundary adopted here follows a conventional 'cradle-to-gate' approach which assesses all major forestry operations associated with one full forest rotation from the seedling production stage to the extraction of the logs to the forest road. The 'cradle-to-gate' system boundary of the proposed forestry model is illustrated in Fig. 1 within the dashed black line. A second, expanded, system boundary was also considered, which includes the delivery of the forest products from the forest roadside to the factory gate for further processing. This is known as a 'cradle-to-factory gate' LCA within the solid black line in Fig. 1 and is common in forestry-based LCAs. The system boundary of the proposed forestry model illustrated in Fig. 1 shows the forestry production procedure in Ireland which has been subdivided into six distinct operations as follows: 1) Seedling Production, 2) Site Preparation, 3) Seedling Planting and Stand Maintenance, 4) Road Construction and Maintenance, 5) Harvesting Operations and 6) Timber Haulage. Other minor processes were ignored due to the scope of the study where such processes would be expected to have

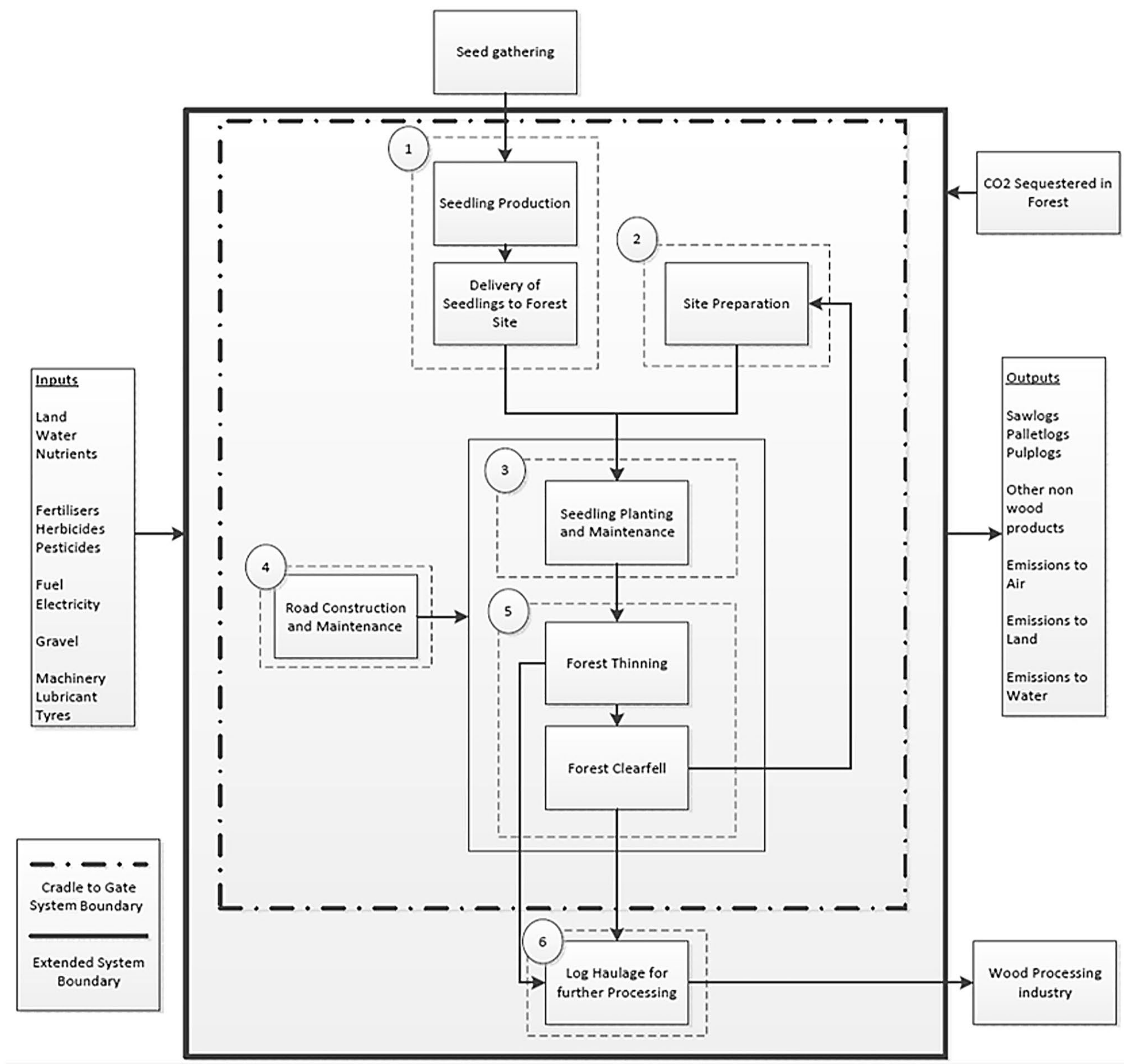


Fig. 1 System boundary of the Irish forestry model: (1) Seedling Production, (2) Site Preparation, (3) Seedling Planting and Stand Maintenance, (4) Road Construction and Maintenance, (5) Harvesting Operations and (6) Timber Haulage

an insignificant effect on the overall impact of the forestry operation. Some of the excluded forestry processes were the collection and delivery of the seeds from the national seed centre to the seedling nurseries, forest management operations such as the use of fencing and certain tending processes such as pruning, and the utilisation of forest residue including stump collection.

3.3.3 Allocation procedure

The forestry industry typically has multiple product outputs both in terms of wood-based products and also non-wood products and services such as food products and recreational services. For the purpose of this model, 100% of the environmental burden is assumed to be distributed across the forest products defined in Table 1. Based on a review of over 28 studies that examined forestry products using LCA, Klein et al. (2015) found that several allocation approaches were considered, the three most popular of which were mass, volume and economic value. Klein et al. (2015) recommended the mass-based allocation approach as the most suitable approach in a forestry-based LCA as forestry product prices vary substantially over time and between countries. Despite this many authors opted to undertake an economic allocation approach as recommended generally by the ISO standards (ISO 2006a, b). Ultimately, the major difference associated with each approach in the context of forestry products is that the economic allocation approach would allocate greater environmental impacts to the higher value products such as the sawn logs whereas the mass or volume allocation approach would assume approximately the same impacts for the same volume of goods regardless of value. There is still no consensus throughout the industry as to which approach should be used. For the purpose of this study, a mass-based allocation approach was implemented.

An additional factor that must be taken into account is the fact that the three forest products considered are produced from both the thinning and clearfell operations, which are considered separately as shown in Fig. 1. Therefore, two sets of each product type (saw, pallet and pulp logs) are produced, one from the thinning operations and one from the clearfell operations, which influences how the forestry system is modelled. As the inputs associated with each of the thinning and clearfell processes differ slightly, both sets of products will ultimately have different environmental impacts. Issues to be considered and addressed here include whether some of the direct inputs associated with the thinning operations (fuel and urea usage) should be allocated towards the final clearfell operation. Furthermore, it must be determined whether the thinning operation is solely undertaken to produce the thinned harvested products, or is undertaken to improve the quality/yield of the harvested clearfelled products; therefore in the latter case, the thinning operation should attribute some of its impacts towards them.

Figure 2a depicts forestry model 1 and the issue described above. As can be seen, the provisional impacts associated with the plantation and growth of the forest site are 100% attributed to the thinning operation, as is the use of fuel and urea for the thinning. However, the thinning operation then has two major outputs, the thinned log products and the thinned forest which is clearfelled at a later stage. This modelling approach requires that a certain proportion of the impacts due to the thinning operation be allocated to the clearfell operation and products. This would imply that the

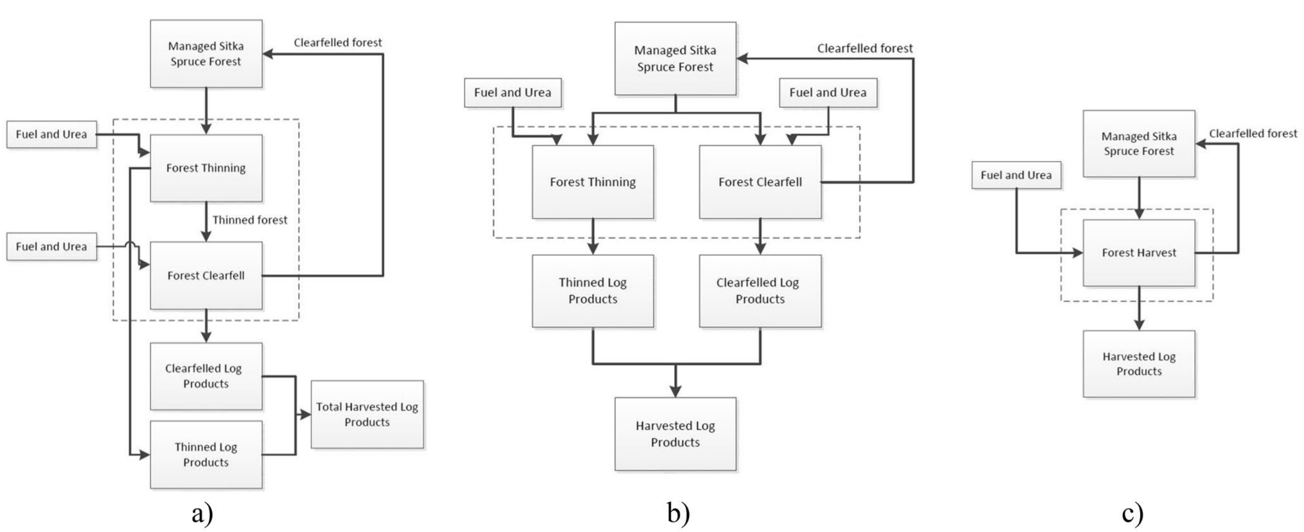


Fig. 2 Allocation Model: **a** Model 1: 100% allocated to thinning operation, **b** Model 2: directly allocated between thinning and clearfell operations and **c** Model 3: combined into one single harvesting operation

clearfelled logs would also take a proportion of the urea and fuel used in the thinning operations. This model implies there is a significantly higher environmental impact associated with similar clearfelled logs than thinned logs as a proportion of the impacts associated with the thinned logs are allocated to the clearfelled logs.

Figure 2b shows a second allocation model of the same system. The major difference shown here is that the impacts associated with the managed forest are directly allocated between both the thinning and clearfell operations as opposed to being 100% allocated to the thinning. Using this model, the forest management impacts are distributed to the thinning and clearfell products processes similar to the previous model. However, this allows the direct fuel and urea usage from the thinning and clearfell processes to be attributed to the thinning and clearfell harvested logs, respectively. This model ultimately assumes that the grown forest can be subdivided into two given areas, namely for thinning and for clearfelling and allows the differences between the thinning and harvesting operations to be reasonably assessed.

Figure 2c demonstrates a third approach which combines both the thinning and clearfell operations together into one single harvesting operation. This model may be representative of the real-life situation, however, as shown, only the impacts associated with the combined harvested forest products can be analysed therefore significant detail is lost. Most forestry-based LCAs make this simplification as most upstream processes such as the manufacturing of sawn timber or OSB are only concerned with the average harvested product itself, regardless if it came from a thinning or clearfell operation. However, the difference associated with the thinning and clearfell operations in terms of fuel and urea usage cannot be assessed from this approach which would be beneficial in highlighting the environmental hot spots throughout the forestry industry in Ireland. Upon assessing the advantages and disadvantages of each allocation approach, the model depicted in Fig. 2b was assumed as the default model when analysing the total environmental impacts associated with the production of the harvested log products throughout this study. This version allows the varying effects of both the thinning and harvesting operations to be clearly assessed and also reduces the level of allocation required, which is in agreement with the ISO standards which state that allocation should be avoided when possible (ISO 2006a).

3.3.4 Data quality and uncertainty

The primary data was gathered predominately from experts within Coillte Teoranta, the commercial semi-state custodian of Ireland's forests. However, further data was also sourced from Teagasc, the State Forestry Advisory Board that deals primarily with private forests (Teagasc 2015), and from local forest managers and forestry contractors. Secondary data was then derived from published studies and databases where primary data was not available as detailed in Section 3.4. This combination of data supplied from both the public and private sectors was crucial in order to ensure a complete and representative model of the Irish forestry industry throughout the country. It should also be noted that the most influential forestry processes in terms of environmental impact were identified prior to initiating the data collection phase of the study. Such processes were the fuel used throughout harvesting processes, the log haulage distances from the forest road to the manufacturing plants and the gravel usage associated with the establishment and maintenance of forest roads for harvesting. The sampling intensity while collecting data was biased towards these processes. While every effort was made to source reliable data from numerous sources for defined product systems given the predefined system boundaries and inherent limitations of data gathering, some unknown environmental impacts may not be captured in the analysis.

3.3.5 LCIA methodology

The LCI of the forestry model developed here was conducted using LCA software SimaPro (V8.0.3.14) (Pré 2015), which incorporates the Ecoinvent LCI database (V.3.3) (Ecoinvent 2016) adapted to European conditions. Using this software tool and database, the total list of emissions to air, water and land and also the resources used throughout each procedure in the forestry process was quantified.

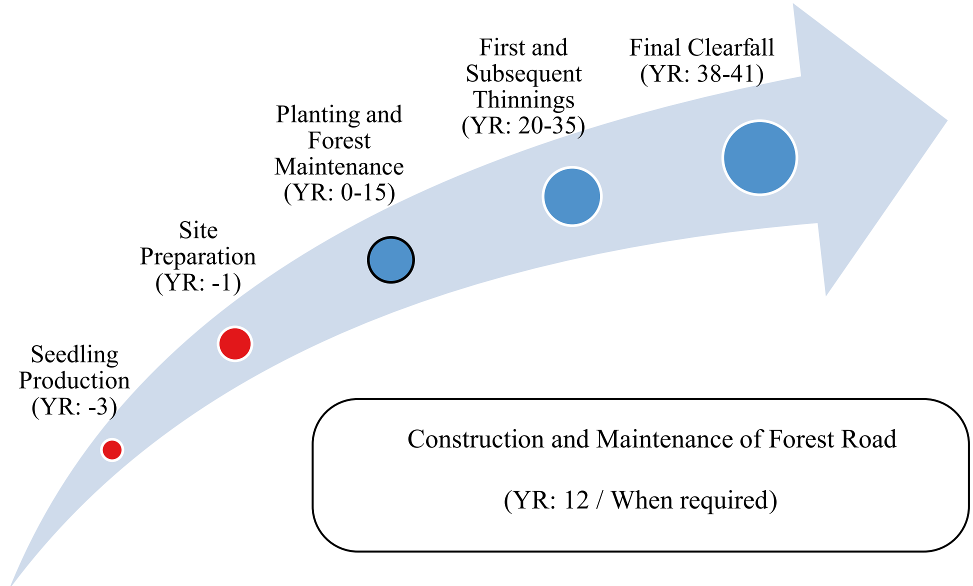
The ReCiPe midpoint hierarchic perspective, which is incorporated within the SimaPro software, was chosen as the LCIA methodology. ReCiPe is a comprehensive methodology and includes over 18 midpoint indicators such as ozone depletion, acidification, eutrophication and climate change and is widely accepted throughout the LCA community and the wood-based product LCA community.

Individual models for each of the forestry products described here were analysed using the ReCiPe methodology. The results are then discussed further with a specific focus on the global warming potential (GWP) impacts.

3.4 LCI data collection

A timeline of the forestry contr is shown in Fig. 3 which considers, seedling production and site preparation (red dots) prior to the planting of the forest and the beginning of the forest rotation inclusive of first and subsequent thinnings and the final clear fell (shown in blue dots). Each forestry operation is described in the following sections and the

Fig. 3 Typical softwood forest chronosequence in Ireland



inputs and outputs associated with each and the associated assumptions are presented.

3.4.1 Seedling production

The first process considered in this study is defined as the 'seedling production stage'. Many life-cycle studies have been conducted on the seedling production process, however, the most detailed have focused on indoor/greenhouse-based nursery conditions (Aldentun 2002; Schlosser et al. 2003; Timmermann and Dibdiakova 2014) which required far more electricity but less fuel usage compared to outdoor nurseries which are the primary source for Sitka Spruce seedlings in Ireland. Coillte operates four nursery centres, which supply between 21 and 25 million plants per year to the forest market sector (Coillte 2021). The primary data gathered in relation to seedling production in Ireland was provided directly from Coillte (Coillte 2015a) and includes all significant material and energy inputs associated with the total production of 24 million seedlings from the Irish nurseries across Ireland over a twelve-month period between 2013 and 2014. The seedlings' growth was assisted at the Coillte nurseries using water and a number of fertilisers, totalling approximately 230 t, over the twelve-month period (a combination of primarily 12,6,18 NPK, a nitrogen/sulphur top dressing and a small number of micronutrients). Some herbicides and pesticides were also used in order to protect the seedlings at their early stage of production. These include cypermethrin and Flexcoat (a plant polysaccharide) used to prevent pine weevil damage and also metam sodium used for soil sterilisation. Coillte has found that the combination of cypermethrin and Flexcoat has facilitated a 25% reduction in cypermethrin usage in its nurseries (Coillte 2015b). Other major inputs for seedling production include the fuel usage required for the tractors, forklifts and other machinery used on site. Over 24 tractors were used year-round over the nursery sites, which span over 220 ha. Electricity usage was also a major input to be considered as it powered both the electric heaters required to aid in the growth of the plants and also the refrigeration in order to preserve the plants when required. The delivery of the seedlings to their forest site was also considered. It was estimated that the average distance from the nursery to the forest sites was approximately 175 km.

The inputs and outputs considered in the production of the seedlings are quantified in Table 2. Of the 24 million seeds, approximately 1.5 million were exported while the remainder were delivered to pre-prepared sites in Ireland, ready for planting.

3.4.2 Site preparation

Once the grown seedlings are ready to be planted, they are transported to a pre-established forest site to begin the forest rotation. Site establishment is essential in both the afforestation of a greenfield site and the reforestation of an existing clearfelled forest site. The aim of this process involves preparing the ground for planting to increase the probability of the planted seedling's survival and ultimately, to maximise the timber yield for the forest site. Site preparation or site establishment refers to cleaning, draining and all other preparation of the forest site prior to planting. Presently in Ireland, approximately 2,000 ha of afforestation occurs each year, which, compared to the 808,848 ha of existing forest sites, is a relatively small change to the overall forest estate in Ireland (< 1%) (Department of Agriculture Food and the

Table 2 Material inputs and outputs associated with seedling production to produce and deliver 1000 seedlings to the forest site

Process		Quantity	Unit
Mass of seeds received from the seed orchard		0.56	kg
Electricity used		19.67	kWh
Water used		1.08	m^3
Fertilisers used	Total used	9.58	kg
	Total by respective nutrient	3.14	kg
Pesticides and herbicides		1.50	l
Fuel usage	Diesel for on-site machinery	99.00	MJ
	Petrol for on-site machinery	31.40	MJ
	Heating oil	4.50	MJ
Average distance delivered to forest site		175	km

Marine 2022). For this reason, for the forestry model developed here a reforestation site is considered, which is also consistent with the steady-state assumption outlined above.

In Ireland, a combination of windrowing and mounding is considered the most popular method for site establishment. Based on data provided by both Coillte (Coillte 2015a) and Teagasc (Teagasc 2015), it was found that over 60% of re-established sites use this combined approach, whereas approximately 30% use windrows only. Finally, less than 10% of sites use other methodologies such as ripping or straight planting. Due to its widespread usage, it was decided that the windrowing and mounding approach would be assumed for the forestry model developed here. Besides being the most popular method, it is also the most energy-intensive of the methodologies used and hence is considered the most conservative approach for the model.

Data collected from experts (Coillte (Coillte 2015a) and Teagasc (Teagasc 2015)) showed that it takes approximately 8 h with an excavator to prepare 1 ha of forest site for planting using the windrowing and mounding methodology. Fuel usage data from the excavators were also provided by Coillte forest managers which assumed approximately 12 L of fuel was used per hour per excavator. Therefore, it was possible to calculate the total fuel required to re-establishing a typical forest site in Ireland as shown in Table 3.

Although stump removal and residue recovery are being tested on certain trial sites in Ireland, it is not common practice in Ireland. Ideally, after clearfell, stumps of no more than 5–10 cm are left which can be ignored during site preparation.

Table 3 Fuel usage requirement in the site preparation/re-establishment of 1 ha of forest site

Process	Quantity	Unit
Fuel usage by excavators	96	l/ha
Area of clearfelled forest site	1	ha

3.4.3 Seedling planting

Once the sites are prepared, 2 to 3-year-old seedlings are planted by hand. This happens within 3 years of the site being clearfelled. In Ireland, the standard planting density associated with Sitka spruce is 2,500 seedlings per hectare. It takes several years until forest crops can be considered 'well-established' and during this time they are monitored carefully to ensure they reach their maximum potential in terms of timber quality and yield. Fertilisers, herbicides and pesticides are typically used throughout each forest rotation, which can have a significant environmental impact on the surroundings depending on their location, particularly in terms of water and soil quality. The quantity of pesticides considered in the forestry model was calculated based on detailed data provided by Coillte on their annual pesticide and herbicide usage data by volume and by active ingredient (Coillte 2015a). The average amount of pesticides and herbicides required to maintain one hectare of a typical Irish forest over one full rotation is shown in Table 4 in terms of the combined mass of their active ingredients, cypermethrin and glyphosate.

Table 4 Average pesticides and fertilisers required for 1 ha of Sitka spruce forest

Process		Quantity	Unit
Pesticide	Cypermethrin	0.075	kg
	Glyphosate	0.053	kg
Fertiliser	Granulated Rock Phosphate	58.66	kg
	Un-ground Mineral Phosphate	9.85	kg
	Fertiliser (22.7, 2.5, 5 NPK)	3.66	kg
	Calcium Ammonium Nitrate	0.41	kg
	Fertiliser—General	0.33	kg
	Urea for Fertilisation (Excluding urea applied during harvesting)	1.03	kg

In Ireland, a significant amount of the land available for forestry is deficient in nutrients, therefore on such nutrient-deficient sites, several fertilisers are used in order to ensure the forest can grow successfully and ultimately maximise the potential yield from forest sites. Fertilisers are typically applied initially as the seedlings are planted and then as required throughout the remainder of the forest rotation. A number of fertilisers are used throughout Ireland, the most common of which is phosphorus-based, typically distributed in the form of rock phosphate. Other fertilisers are used when considered necessary such as potassium- and nitrogen-based fertilisers. Shown in Table 4 is the average amount of fertilisers required to maintain 1 ha of Sitka Spruce over one forest rotation based on Coillte's total annual fertiliser usage data between 2011 and 2014.

3.4.4 Road construction and maintenance

The construction and maintenance of forest roads are often considered outside the scope of typical forestry-based LCA studies. However, when considered, they are regularly found to have a significant impact on the total environmental footprint of forest operations, particularly in relation to gravel usage. In Ireland, typical forest roads are between 3.4 m to 5.5 m wide depending on the purpose of the road and on average are constructed approximately 10–15 years after planting. An analysis of data on the percentage of road stock upgraded and financial standards by Coillte shows that they are expected to last approximately 32 years until a subsequent upgrade (Coillte 2015a). After the initial road construction, routine inspections and necessary maintenance are also essential in order to maximise the operational lifespan of the road.

Standard guidelines are in place in relation to the spacing and density of forest roads in Ireland (Ryan et al. 2004). However, each site must be considered individually, and its requirements must be carefully assessed and adhered to. Based on data provided by road engineers and forest managers involved with forest road construction (Coillte 2015a), it was calculated that forest harvest roads are typically constructed at a density of 21.23 m/ha in Ireland. The Coillte forest road network consists of approximately 8100 km of forest roads with 40 km of forest road built each year and a further 75 km upgraded. All roads are also maintained as required. Various road construction methodologies are used when constructing harvest roads, however, the vast majority of roads are constructed from crushed gravel or stone as excavated roads or floating roads. These two types of road represent approximately 60% and 30% of all road construction in Coillte forests, respectively. Excavated roads were estimated to require approximately 1–1.5 tonnes of crushed gravel per linear meter of construction. Floating roads involve constructing the road over the existing soil. This road construction methodology is estimated to take between 3—3.5 tonnes of crushed gravel per linear meter of construction. Primary material and energy usage data were collected from Coillte road engineers and forest managers in addition to direct material usage data from the 'Coillte Forest Information Systems' (Coillte 2015a). However, due to the huge variability associated with road construction and maintenance between forest sites and the difficulty in gathering suitable primary data, only the total gravel usage and the fuel usage of the excavator were considered in the scope of the study. Other materials such as geotextile grids, PVC pipes, and bridge construction were not considered as part of this study as they are only required on a small percentage of forest sites.

The incorporation of the 'Steady-State' assumption into the forestry model developed here assumes that the same quantity of gravel, fuel and other materials are used consistently each year in the construction and maintenance of the forest road network. If the steady-state assumption was assumed true in the case of Coillte's forest road network, it would be valid to assume that the average volume of gravel reportedly used per year was distributed over Coillte's entire road network, of approximately 8,100 km. However, when examining historic data it is also clear that the young nature of Irish forests and the rapid decrease in the Coillte afforestation programme in the mid-90 s make it difficult to apply such an assumption and risk underestimating the impacts if focusing only on recent data. To avoid this issue, the material usage data that was provided by the Coillte at a national level was combined with primary data on the required material and fuel use of both excavated and floating roads in Ireland provided by road engineers and forest managers from site-specific scenarios. This data was used to quantify the typical gravel and fuel requirements at each harvest road operation stage throughout the forest life cycle. This was then incorporated into the proposed forest model developed here. Using this hybrid approach that combines both national and site-specific data it was determined that approximately 2.66 and 1.09 tonnes of gravel are required to construct and upgrade one meter of a typical harvest road in Ireland, respectively. Roads are maintained as needed, which can range from every 2 years for busy roads to seldom, if ever, for minor, spur roads so it is difficult to define the exact volume of gravel required to maintain any given

Table 5 Energy and fuel requirements associated with the construction and maintenance of 1 m of typical harvest road over one rotation

Process	Quantity	Unit
Gravel used in initial road construction	0.89	t
Gravel used to upgrade roads	0.86	t
Gravel used to maintain road when required	0.12	t
Excavator usage	45.00	MJ

Table 6 Average harvesting yields associated with thinning and harvesting operation over 1 rotation from 1 ha of a typical Sitka spruce forest in Ireland

Parameter	Thinning operation				Average thinning	Final clearfell	Total harvest
	1	2	3	4			
Year	20	25	30	35	-	40	-
Gross volume harvested (m^3)	63	63	63	63	252	420	672
Net volume harvested over bark (m^3)	55.13	55.13	57.33	57.33	224.91	396.9	621.81
Average Diameter Breast Height (cm)	13	14	18	25	-	-	-
% of Pulp logs	71%	67%	30%	16%	46%	4%	-
% of Pallet logs	28%	32%	55%	46%	40%	9%	-
% of Saw logs	1%	1%	15%	38%	14%	87%	–
	100%	100%	100%	100%	100%	100%	
Total volume of logs harvested							
Pulp logs (m^3)	39.14	36.93	17.20	9.17	102.44	13.89	116.34
Pallet logs (m^3)	15.43	17.64	31.53	26.37	90.99	37.31	128.29
Saw logs (m^3)	0.551	0.55	8.60	21.79	31.49	345.30	376.79
Total logs (m^3)	55.13	55.13	57.33	57.33	224.91	396.50	621.41

road. Therefore, it was assumed, based on the overall gravel usage by Coillte between 2010 and 2014 that 0.004 tonnes of gravel were used each year on each meter of road constructed. Excavators were reported to construct 7 m of a typical forest road on average per hour. This equates to approximately 62 MJ per meter of construction. This is assumed to reduce to approximately 31 MJ per meter of construction for upgrading forest roads.

For the purpose of the model described here, it was assumed that the life expectancy of the forest road is three forest rotations e.g. 120 years, which is in line with other forestry-based LCA studies. The final requirements associated with the construction and maintenance of a typical forest road in Ireland over one rotation was calculated to be 1.87 tonnes of delivered gravel and 45 MJ of fuel usage for excavator work as shown in Table 5. All secondary data such as the delivery of the gravel were assumed using the Ecoinvent database.

3.4.5 Harvest operations

Various harvesting methodologies are used in Ireland and both thinning and final clearfell processes are discussed here together due to their operational similarities and similar data sources. In Ireland, a mechanised cut-to-length (CLT) felling system and a forwarder extraction methodology are the most commonly used for both thinning and final clearfell practices. CLT logging or harvesting is a felling system in which trees are delimbed and crosscut to their desired length directly at the stumps prior to extraction. It accounts for over 90% of harvesting operations across Ireland (Phillips 2004). Once the trees are cut, the harvested logs are extracted to the forest road using a forwarder.

The felling operations during a rotation length can be subdivided into two distinct processes; the thinning process (which can be further subdivided into the initial thinning and then subsequent thinnings) and the final clearfell at the end of the forest rotation. The total volumes of the harvested log by each product harvested for 1 ha of a typical Sitka spruce forest in Ireland are shown in Table 6. Once the trees are harvested at each thinning stage or at the final clearfell, they are sorted on site into product types based on their size (Table 1).

In order to quantify the total environmental impact associated with the harvesting operations detailed fuel usage and efficiency data for harvesters and forwarders were collected directly from private harvesting contractors (Harvesting Contractors 2015) and were combined with harvesting machinery data collected by Teagasc (2015). Combining both data sources, 20 harvesting and forwarding machines were assessed. Based on the types of machines used, their respective power, average hours of use in a given year and the average volume of logs harvested per machine, the energy requirement associated with harvesting and

Table 7 Energy requirements associated with forestry harvesting operations for 1 m^3 of the harvested log from Irish forests

Process		Quantity	Unit
Thinning Operations	Harvesting	52.6	MJ / m^3
	Forwarding	28.1	MJ / m^3
	Total	80.7	MJ / m^3
Clearfell Operations	Harvesting	39.5	MJ / m^3
	Forwarding	28.1	MJ / m^3
	Total	67.6	MJ / m^3

Table 8 GWP Impact associated with 1 tkm of log product depending on Vehicle Category Class

Vehicle Category Class by Gross Vehicle Mass (t)	3.5–7.5	7.5–16	16–32	> 32
GWP (kgCO2eq.)	0.485	0.228	0.171	0.110

extracting 1 m^3 of log to the forest road was calculated and is shown in Table 7.

In order to avoid butt rot and the spread of diseases, in particular, *Heterobasidion* (Fomes/Butt Rot), stumps are required to be treated using urea directly after felling in both the thinning and harvesting operations. The urea usage during felling operations was estimated to be approximately 0.75 l/m^3 of harvested log based on details provided by Teagasc and harvesting contractors (Harvesting Contractors 2015; Teagasc 2015). As the urea usage is directly

Table 9 Total material and energy requirements associated with the management of a typical Sitka spruce forest over a single rotation in Ireland

	Process		Quantity	Unit
Inputs	**Clearfelled Forest Site Ready for Planting**		1	ha
		Clearfelled forest site	1	ha
		Diesel required for excavator usage	3,456	MJ
	Sitka Spruce Seedlings		2,500	-
		Fertilisers Required	7.86	kg
		Pesticides Required	0.98	kg
		Electricity Required	49.17	kWh
		Water Used	2,701	kg
		Diesel Usage	247.50	MJ
		Petrol Usage	0.05	kg
		Other Fuel Usage	11.25	MJ
		Weight Transportation Distance	43.75	tkm
	Forest Maintenance		1	-
		Fertilisers Used	15.5	kg
		Pesticides Usage	0.13	kg
	Road Construction and Maintenance		20.1	m
		Gravel Required to Construct Road	17,877	kg
		Gravel Required to Upgrade Road	17,325	kg
		Gravel Required to Maintain Road	2,461	kg
		Diesel Usage Required for Road Operations	906	MJ
	Thinning Operations		1	-
		Diesel Required by Harvesters	11,822	MJ
		Diesel Required by Forwarders	6,320	MJ
		Urea Required	223	kg
	Clearfell Operations		1	-
		Diesel Required by Harvesters	15,658	MJ
		Diesel Required by Forwarders	11,142	MJ
		Urea Required	393	kg
Outputs	**Logs Produced from Thinning**		224.9	m^3
		Saw log Product	31.5	m^3
		Pallet wood Products	91.0	m^3
		Pulp wood	102.4	m^3
	Logs Produced from Clearfell		396.5	m^3
		Saw log Product	345.3	m^3
		Pallet wood Products	37.3	m^3
		Pulp wood	13.9	m^3
		Clearfelled Site	1	ha

Table 10 Cradle-to-forest road ReCiPe results for various forest products produced (1 m^3) in Irish forests

Environmental Impact Category	1 ha	1 m^3					
	1 ha of Forest Area	Average product produced	Average Thinned Product	Average Clearfelled Product	Average Saw log Produced	Average Pallet log Produced	Average Pulp log Produced
Climate change (kg CO2 eq.)	6.53E+03	1.05E+01	1.13E+01	1.01E+01	1.02E+01	1.09E+01	1.11E+01
Ozone depletion (kg CFC-11 eq.)	4.08E – 04	6.57E – 07	7.08E – 07	6.28E – 07	6.35E – 07	6.85E – 07	6.98E – 07
Terrestrial acidification (kg SO2 eq.)	4.77E+01	7.67E – 02	8.26E – 02	7.34E – 02	7.42E – 02	8.00E – 02	8.14E – 02
Freshwater eutrophication (kg P eq.)	5.43E – 01	8.75E – 04	9.00E – 04	8.60E – 04	8.64E – 04	8.89E – 04	8.94E – 04
Marine eutrophication (kg N eq.)	2.69E+00	4.34E – 03	4.70E – 03	4.13E – 03	4.18E – 03	4.54E – 03	4.62E – 03
Human toxicity (kg 1,4-DB eq.)	7.96E+02	1.28E+00	1.31E+00	1.26E+00	1.27E+00	1.30E+00	1.30E+00
Photochemical oxidant formation (kg NMVOC)	7.18E+01	1.16E – 01	1.26E – 01	1.09E – 01	1.11E – 01	1.21E – 01	1.24E – 01
Particulate matter formation (kg PM10 eq.)	2.28E+01	3.66E – 02	3.97E – 02	3.49E – 02	3.53E – 02	3.83E – 02	3.91E – 02
Terrestrial ecotoxicity (kg 1,4-DB eq.)	4.49E-01	7.22E – 04	7.43E – 04	7.10E – 04	7.13E – 04	7.34E – 04	7.38E – 04
Freshwater ecotoxicity	2.31E+01	3.72E – 02	3.82E – 02	3.67E – 02	3.68E – 02	3.78E – 02	3.80E – 02
Marine ecotoxicity (kg 1,4-DB eq.)	2.56E+01	4.12E – 02	4.26E – 02	4.04E – 02	4.06E – 02	4.20E – 02	4.23E – 02
Ionising radiation (kBq U235 eq.)	4.47E+02	7.20E – 01	7.65E – 01	6.94E – 01	7.00E – 01	7.45E – 01	7.56E – 01
Agricultural land occupation (m^{2}a)	1.00E+04	1.62E+01	1.62E+01	1.62E+01	1.62E+01	1.62E+01	1.61E+01
Urban land occupation (m^2)	5.14E+01	8.27E – 02	8.39E – 02	8.19E – 02	8.21E – 02	8.34E – 02	8.36E – 02
Natural land transformation (m^2)	2.33E+00	3.75E – 03	3.98E – 03	3.62E – 03	3.65E – 03	3.87E – 03	3.93E – 03
Water depletion (m^3)	4.38E+03	7.04E+00	7.26E+00	6.92E+00	6.95E+00	7.17E+00	7.21E+00
Metal depletion (kg Fe eq.)	3.30E+02	5.31E – 01	5.60E – 01	5.15E – 01	5.19E – 01	5.47E – 01	5.54E – 01
Fossil depletion (kg oil eq.)	2.19E+03	3.53E+00	3.79E+00	3.38E+00	3.41E+00	3.67E+00	3.74E+00

proportional to the volume harvested it is considered here rather than as part of the forest maintenance process.

3.4.6 Timber haulage

The most common form of log transport from the forest road to the processing facility in Ireland is by articulated truck or truck and trailer. To accurately quantify the environmental impact associated with the transportation of the harvested forest products from the forest site using the SimaPro software, specific haulage data was required in terms of 'Vehicle Category Class' and 'Gross tonne-kilometre hauled' per delivery (Ecoinvent 2016; Pré 2015; Spielmann et al. 2007). The GWP impacts associated with 1 tkm of log product depending on Vehicle Category Class are presented in Table 8.

To quantify the timber haulage impact associated with the harvested forest products produced in Ireland, detailed log delivery weights and distances were collected from sawmills and the OSB boardmills. Detailed sawn and pallet log delivery data was provided in terms of individual deliveries from two of the five largest sawmills in Ireland (over 23,000 specific deliveries quantified using on-site weigh-bridges) and average delivery data from another sawmill, which cumulatively represents the delivery of over 1.1 million m^3 of roundwood logs. The mean delivery distance from each forest to the sawmill was found to be 95.00 km, 89.11 km and 92.16 km for each of the three sawmills that provided data. The overall weighted average distance was then found to be 92.14 km per cubic meter of log based on the volume of logs each sawmill processed in that given year. A further 18,000 deliveries from 246 forests were analysed, which provided pulp logs to an OSB manufacturing plant. The average distance to each forest was found to be 183.2 km. The resultant weighted average distance per load was calculated to be 169.84 km. Using the primary weigh-bridge delivery data and mass and moisture content data provided from the aforementioned sawmills and OSB manufacturing plant (OSB Manufacturers 2015; Sawmills 2015), the average

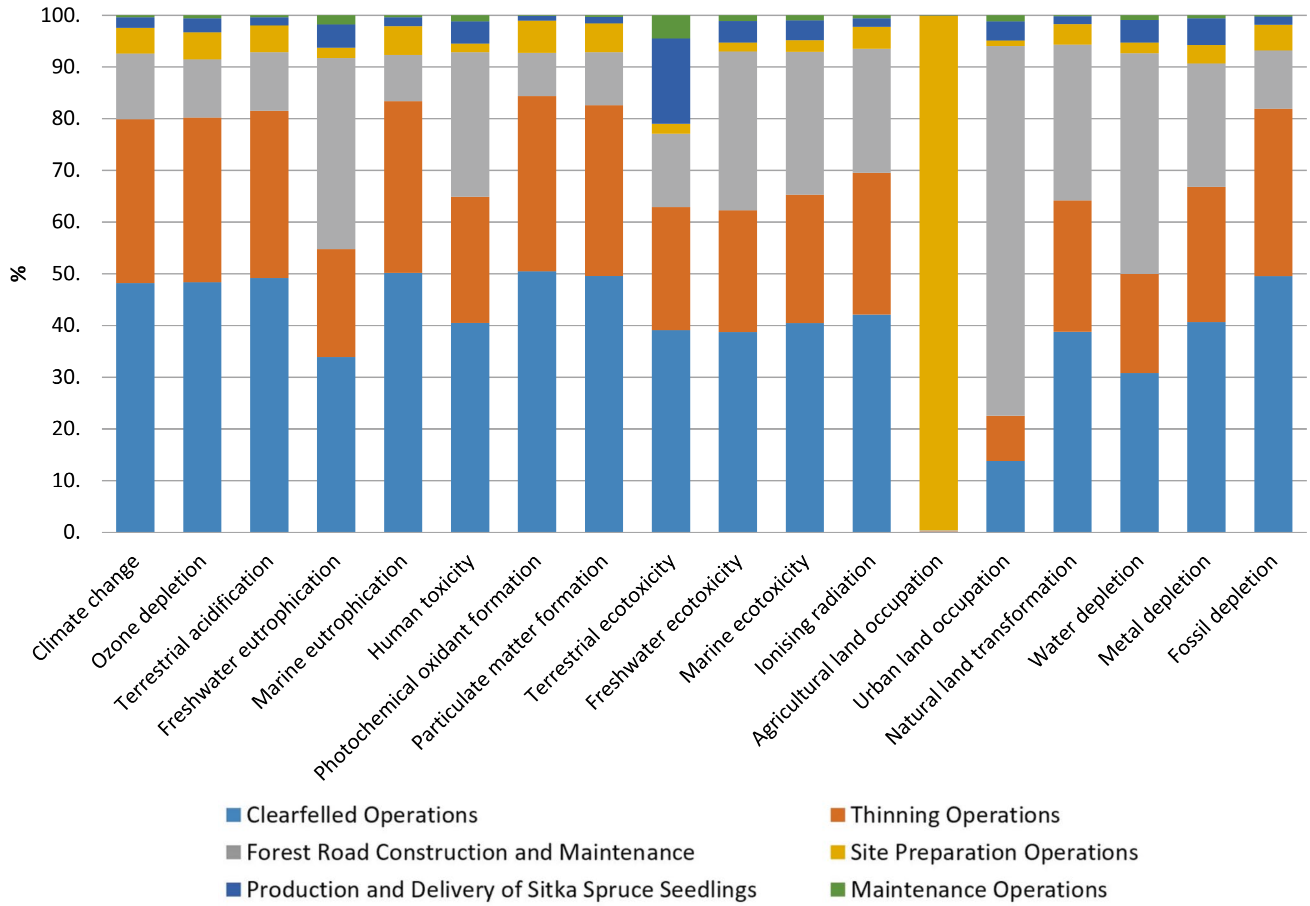


Fig. 4 Cradle-to-forest road ReCiPe results: LCIA process contribution – 1 m^3 Average forest product

weight of the load and, in turn, the 'Vehicle Category', was quantified for the log haulage considered here. It was found that the average volume of the load per delivery is approximately 28.03 m^3. This equates to an approximate mass of just less than 24 metric tonnes depending on the density and moisture content of the load. As this weight excludes the weight of the truck itself, it is safe to assume that the log haulage considered in the model was undertaken using a truck of weight class > 32 tonnes (GWP = 0.110 kgCO2eq.).

3.5 Inputs and outputs

The total inputs and outputs associated with a single rotation of 1 ha of a typical Sitka Spruce Forest in Ireland are summarised in Table 9 for the cradle-to-forest road.

4 LCA results

The model of the forestry industry in Ireland was assessed in this study provisionally using the ReCiPe LCIA methodology. The ReCiPe midpoint approach converts the considerable amount of LCI data produced into 18 midpoint indicators, which allows the resultant data to be analysed and discussed with greater ease. The reference functional unit of the model analysed here is 1 m^3 of Sitka spruce log product but results are also shown for 1 rotation of 1 ha of forest area, which allows comparisons with studies that utilise similar metrics such as a given area of forest. The model analysed was the default 'cradle-to-forest road' model developed using a mass-allocation approach presented in Model 2 (Fig. 2b). The 'cradle-to-forest road' model is presented as representative of the average current primary softwood forest products produced throughout Ireland and can be incorporated into any future LCA studies for all wood product industries in Ireland. Using the ReCiPe LCIA methodology, the 'cradle to forest road' model was initially analysed, and the results are shown in Table 10 for each of the key functional units mentioned above. The ReCiPe impact categories are presented graphically in Fig. 4 to produce 1 m^3 of average forest product produced in Irish forests. This figure shows that typically, clearfell operations are the most significant contributor to all impact categories with the exception of certain categories such as 'Agricultural land occupation' and 'Urban land occupation'. The contribution of

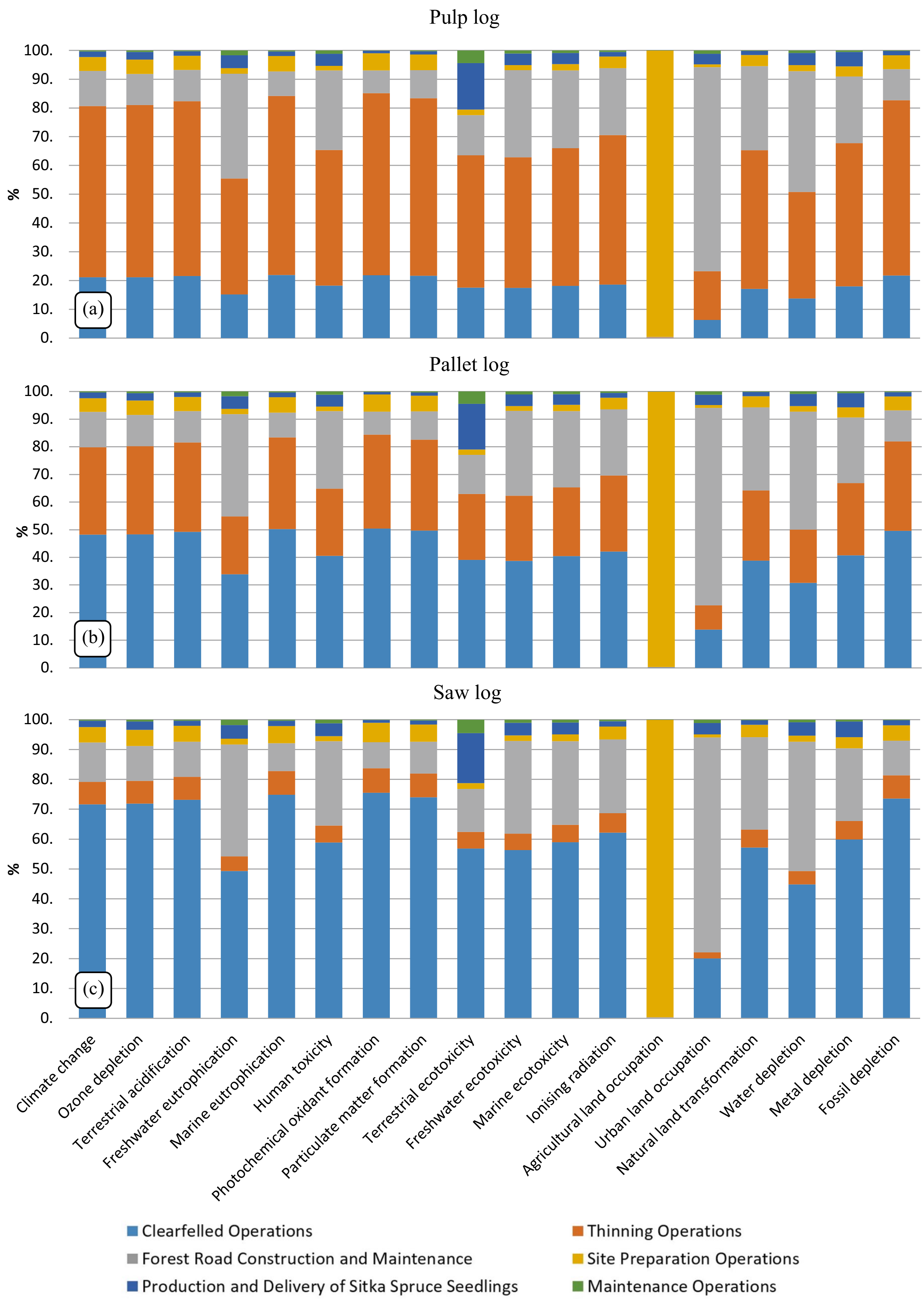


Fig. 5 Cradle-to-forest road ReCiPe results: LCIA process contribution – 1 m^3 of **a** Pulp log, **b** Pallet log and **c** Saw log

Table 11 Cradle-to-factory gate ReCiPe results (Incl: Delivery) for various forest products produced (1 m^3) in Irish forests

Environmental Impact Category	1 ha	1 m^3							
	1 ha of forest area	Average product produced	Thinned product (Sawn or Pallet)	Thinned product (Pulp)	Clearfelled product (Sawn or Pallet	Clearfelled product (Pulp	Average Saw log produced	Average Pallet log produced	Average Pulp log produced
Climate change (kg CO2 eq.)	1.29E+04	2.08E+01	2.03E+01	2.68E+01	1.91E+01	2.56E+01	1.92E+01	2.00E+01	2.67E+01
Ozone depletion (kg CFC-11 eq.)	8.73E−04	1.41E−06	1.37E−06	1.83E−06	1.29E−06	1.75E−06	1.30E−06	1.35E−06	1.82E−06
Terrestrial acidification (kg SO2 eq.)	7.48E+01	1.20E−01	1.20E−01	1.52E−01	1.11E−01	1.43E−01	1.12E−01	1.18E−01	1.51E−01
Freshwater eutrophication (kg P eq.)	1.16E+00	1.86E−03	1.76E−03	2.43E−03	1.72E−03	2.39E−03	1.72E−03	1.75E−03	2.43E−03
Marine eutrophication (kg N eq.)	4.20E+00	6.76E−03	6.78E−03	8.60E−03	6.21E−03	8.03E−03	6.26E−03	6.62E−03	8.53E−03
Human toxicity (kg 1,4-DB eq.)	1.72E+03	2.76E+00	2.61E+00	3.59E+00	2.56E+00	3.54E+00	2.57E+00	2.60E+00	3.58E+00
Photochemical oxidant formation (kg NMVOC)	1.15E+02	1.86E−01	1.87E−01	2.39E−01	1.70E−01	2.22E−01	1.71E−01	1.82E−01	2.37E−01
Particulate matter formation (kg PM10 eq.)	3.61E+01	5.81E−02	5.83E−02	7.36E−02	5.34E−02	6.88E−02	5.38E−02	5.69E−02	7.31E−02
Terrestrial ecotoxicity (kg 1,4-DB eq.)	1.02E+00	1.64E−03	1.56E−03	2.08E−03	1.53E−03	2.05E−03	1.53E−03	1.55E−03	2.08E−03
Freshwater ecotoxicity	6.68E+01	1.08E−01	1.01E−01	1.43E−01	9.91E−02	1.41E−01	9.93E−02	1.00E−01	1.42E−01
Marine ecotoxicity (kg 1,4-DB eq.)	7.16E+01	1.15E−01	1.08E−01	1.53E−01	1.06E−01	1.50E−01	1.06E−01	1.08E−01	1.52E−01
Ionising radiation (kBq U235 eq.)	1.04E+03	1.67E+00	1.61E+00	2.19E+00	1.54E+00	2.12E+00	1.54E+00	1.59E+00	2.18E+00
Agricultural land occupation (m^2a)	1.02E+04	1.64E+01	1.64E+01	1.65E+01	1.64E+01	1.65E+01	1.64E+01	1.64E+01	1.65E+01
Urban land occupation (m^2)	6.22E+02	1.00E+00	9.04E−01	1.43E+00	9.03E−01	1.42E+00	9.03E−01	9.04E−01	1.43E+00
Natural land transformation (m^2)	4.32E+00	6.96E−03	6.81E−03	8.80E−03	6.46E−03	8.45E−03	6.49E−03	6.71E−03	8.76E−03
Water depletion (m^3)	8.85E+03	1.42E+01	1.35E+01	1.86E+01	1.32E+01	1.82E+01	1.32E+01	1.34E+01	1.85E+01
Metal depletion (kg Fe eq.)	7.47E+02	1.20E+00	1.14E+00	1.63E+00	1.09E+00	1.58E+00	1.10E+00	1.13E+00	1.62E+00
Fossil depletion (kg oil eq.)	4.49E+03	7.22E+00	7.06E+00	9.33E+00	6.65E+00	8.92E+00	6.68E+00	6.94E+00	9.28E+00

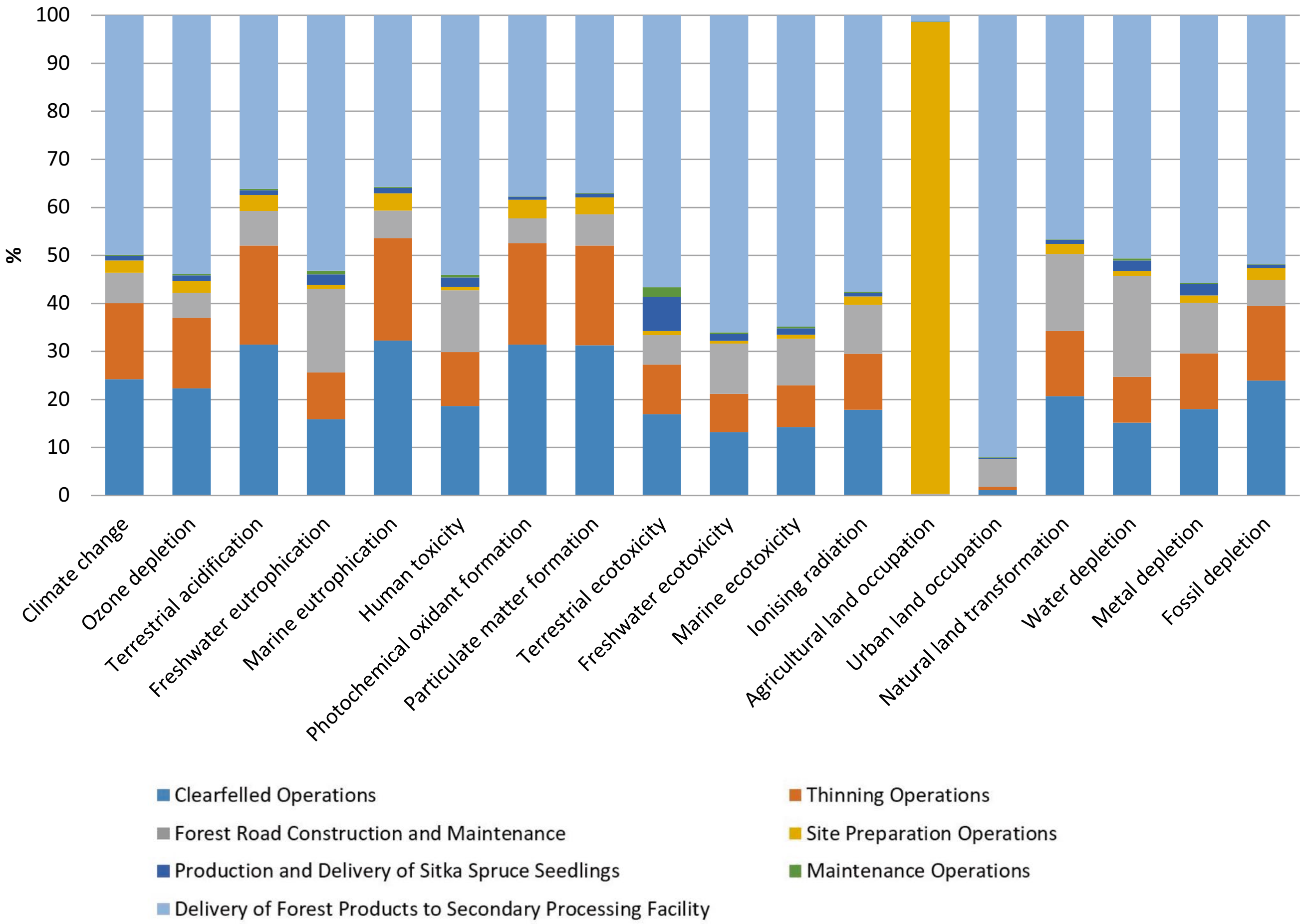


Fig. 6 Process contribution of average roundwood log (incl. Delivery)

the remaining operations in descending order of magnitude are thinning operation, forest road construction and maintenance, site preparation options, seedling production and finally forest maintenance operations.

Figure 5 highlights the contribution of each of the primary forest products, namely pulp log, pallet log and saw log toward each of the ReCiPe impact categories. It can be seen that the contribution of different operations varies significantly dependent on the log type. For example, the contribution of clearfell operations is a significant contributor to saw logs but has less influence on the impact categories associated with pulp logs. While these differences and observations may be obvious in most cases, it is important to distinguish based on log type for downstream applications in future LCA studies.

While the 'cradle-to-forest road' model is presented, the expanded 'cradle-to-factory gate' model was developed to incorporate additional transportation or delivery impacts associated with the average forest product produced and the individual log types. The ReCiPe LCIA results for the expanded cradle-to-factory gate model are shown in Table 11 for each of the functional units considered here and the results are graphically presented in Fig. 6 for the average forest product produced. The cradle-to-factory gate model, which includes transport or delivery, separates thinned and clearfelled products into separate saw or pallet logs and pulp logs. This separates forest products destined for sawmills (saw and pallet) and OSB boardmills (pulp) in Ireland which have different average transport distances and therefore, different impacts.

The results presented in Fig. 6 highlight the significant contribution of the delivery of forest products to processing facilities across all impact categories (excluding 'Agricultural land occupation'). The total contribution of the delivery process towards each of the ReCiPe impact categories is shown in Table 12 and where it was found to be responsible for, on average, 50% of each impact category presented (excluding land occupation) highlighting its significance. The contribution is also presented for the different log types in Table 12.

When reflecting on the results of this study, it is important to note that this study has certain limitations directly

Table 12 Percentage contribution to ReCiPe results of the delivery component per m^3 of product produced

Environmental Impact Category	Saw log Products	Pallet Log Products	Pulp Log Products	Average Product Produced
Climate change (kg CO2 eq.)	47%	45%	58%	49%
Ozone depletion (kg CFC-11 eq.)	51%	49%	62%	53%
Terrestrial acidification (kg SO2 eq.)	34%	32%	46%	36%
Freshwater eutrophication (kg P eq.)	50%	49%	63%	53%
Marine eutrophication (kg N eq.)	33%	31%	46%	36%
Human toxicity (kg 1,4-DB eq.)	51%	50%	64%	54%
Photochemical oxidant formation (kg NMVOC)	35%	33%	48%	38%
Particulate matter formation (kg PM10 eq.)	34%	33%	47%	37%
Terrestrial ecotoxicity (kg 1,4-DB eq.)	53%	53%	64%	56%
Freshwater ecotoxicity	63%	62%	73%	65%
Marine ecotoxicity (kg 1,4-DB eq.)	62%	61%	72%	64%
Ionising radiation (kBq U235 eq.)	55%	53%	65%	57%
Agricultural land occupation (m^2a)	1%	1%	2%	1%
Urban land occupation (m^2)	91%	91%	94%	92%
Natural land transformation (m^2)	44%	42%	55%	46%
Water depletion (m^3)	47%	47%	61%	51%
Metal depletion (kg Fe eq.)	53%	51%	66%	56%
Fossil depletion (kg oil eq.)	49%	47%	60%	51%

linked to the LCI data collection phase be it the primary data and associated uncertainty and the use of secondary data to complete the LCI. The following limitations are noted in addition to those presented in Section 3.4: (a) The development of this model is based on a 'steady state' assumption, which is used extensively in forestry-based studies given the exceedingly long production period of forest products (relative to other manufactured goods). As such, many limitations occur when assuming an unchanged forest production system with respect to carbon stock, land use, availability of nutrients and water and also forestry management systems over time and the developments and changes that can occur over such a time period.

(b) The primary data collected as part of this study was gathered from industry experts within public and private forest operators, and also local forest managers and forestry contractors. The sources of data were chosen to establish representative data for the forest industry, however, the diverse quality of data records from different sources resulted in inherent variability. This is previously discussed in Section 3.4 under the following headings: 1) Seedling Production, 2) Site Preparation, 3) Seedling Planting and Stand Maintenance, 4) Road Construction and Maintenance, 5) Harvesting Operations and 6) Timber Haulage.

(c) The use of secondary data may not be fully representative of the process, where products and emissions can, for instance, be missing or misrepresented. (d) This secondary data may not entirely represent the temporal and geographical boundaries of this study but such data derived from published studies and databases was required in the absence of country-specific data.

5 Summary and conclusions

In this study, a model of the forestry industry in Ireland was assessed using the ReCiPe LCIA methodology. The model analysed was the default 'cradle-to-forest road' model developed using a mass-allocation approach but was also further expanded to develop a 'cradle-to-factory gate' model which includes the delivery of logs for further processing of downstream products at sawmills and boardmills.

Given the reliance of the Irish forest industry on Sitka spruce, this species was the focus of this study and country-specific data has now been provided which can be used in further studies. Until this study, the Irish forest and forest products industry has had to utilise alternative sources of data to quantify the environmental impacts of its forest products. Given the natural variability of timber, it is typically recommended to avoid using data from other counties when considering the production of wood-based products where climatic changes may have a significant impact. The data presented in this study now addresses the environmental impacts specifically for Sitka spruce grown in Ireland.

The results of the ReCiPe impact categories are presented based on the production of 1 m^3 of forest product for 1 rotation but the results are also presented for 1 ha of forest area. The results are presented for the average roundwood product produced but also, the average roundwood products are further categorised by thinned and clearfell products, and by log type, namely, saw log, pallet log and pulp log. It can be seen that the contribution of different operations varies significantly dependent on the log type which provides important data for further downstream products such as sawn timber and OSB to accurately determine the environmental impacts. It was a primary goal to establish these values for the Irish forest industry and it is difficult to compare the results to other studies due to the influence of country-specific data, forestry practices, species mix and rotation length, however, it is possible to compare to typical values for softwood forestry in available LCI databases. For example, the GWP results for 1m^3 of sustainably managed spruce sawlog from Germany and Sweden available within the Ecoinvent LCI database (V.3.3) are 11.3 kgCO2eq. and 9.7 kgCO2eq., respectively. These values are comparable to the values for the average sawlog of 10.2 kgCO2eq. observed in this study and also highlights the variation between regions. If the GWP per hectare is also examined, values of 7568 kgCO2eq and 6073 kgCO2eq for Germany and Sweden are obtained, respectively which compare well to the GWP value per hectare of Irish-grown Sitka spruce of 6530 kgCO2eq. These values determined for Irish-grown Sitka spruce were also shown to be comparable to the global mean data available in the Ecoinvent database but also highlights the importance of country-specific data and the influence it may have on all impact categories in addition to the GWP presented in this comparison.

Furthermore, it was shown that the contribution of delivery or transportation of the harvested logs to their place of processing, determined from the expanded 'cradle-to-factory gate' model, resulted in an increase in all impact categories ranging from 1% in Agricultural land occupation to 91% in Urban land occupation. When examining GWP emissions, a significant increase of 49% was observed for the average forest product produced. The values are also presented for individual forest products as they have different destinations for further processing and these values will be used in the future to determine the impacts associated with the manufacture of further downstream wood products.

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Data availability All data generated or analysed during this study are included in this published article and supplementary information may be provided on request.

Declarations

Conflict of interest The authors declare no competing interests.

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