A GIS-based site suitability assessment of harvest residue procurement during integrated first thinning operations in southern and eastern Ireland

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Abstract

The Irish forestry sector faces a wood mobilisation challenge as many forest owners do not engage in forest management. Simultaneously, demands for biomass continue to increase to meet the requirements of national and European policies regarding the use of renewable sources of energy. First thinning operations in Ireland are normally conducted through Cut to Length (CTL) practices. In this study, Integrated Thinning (INT), a practice that procures woody residues in addition to the conventional roundwood assortments, was evaluated as an alternative, leading to higher profits that may increase forest owners' engagement with management. This study was part of SIMWOOD, a European project aiming to increase the mobilisation of wood from forests and woodlands in Europe and assessed the sustainability of INT in the south and east of Ireland. Results include geographic datasets describing harvesting operations at the forest areas of interest, soil damage and nutrient loss risks, and distance to the nearest biomass end users. It was found that c. 42,000 ha of forests had reached a suitable age for first thinning, of which c. 22,000 ha were on soils where INT could be conducted. Additionally, 99% of the area where INT could be implemented was less than 50 km from the nearest biomass end user. To increase wood mobilisation INT appears to be a useful alternative to CTL; however, its sustainability depends on site- and stand-specific variables and also depends on other aspects not considered in this study, such as weather conditions or market drivers.

Keywords: *Woody residue, biomass, soil damage, nutrient loss, integrated thinning.*

Introduction

Ireland's renewable energy targets, which are part of the National Renewable Energy Action Plan, include an increase to 16% of the renewable energy share in overall energy use by 2020, with 9% coming from wind energy generation and biomass combustion. Moreover, when the Paris Agreement on climate change was signed, Ireland committed to a minimum 27% share of renewable energy by 2030 (European Commission 2017). In 2014, 8.6% of the overall energy demand was

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derived from renewable sources; 5% from wind power and biomass combustion. Among the government policy strategies to reach these targets are grants for installing biomass boilers. The main obstacle is that the biomass material needed to feed those installations, from privately owned forests (43% of total forestry area of Ireland) is not being sufficiently mobilised.

As a result, it has been forecasted that there will be a substantial shortfall in the national timber supply by 2020 (COFORD 2015, Knaggs and O'Driscoll 2015). To meet the increasing demands, the roundwood processing sector would need to expand considerably. In addition, a large proportion (36% in 2014) of Irish roundwood is already used for energy generation (mostly in the form of by-products within the wood processing sector), while additional biomass for energy is imported (DAFM 2015). Consequently, it is appropriate to assess alternative harvesting methodologies and investigate whether it is possible to extract residual biomass from the forests to help meet the bioenergy demands. At the beginning of the previous century, forest cover in Ireland was very low (i.e. 1% in 1900), and up to the 1980s, almost all afforestation was undertaken by the State (DAFM 2014). In 1980, an EU co-funded afforestation scheme providing afforestation subsidies to farmers was launched (Ní Dhubháin et al. 2006). As a result of this and later schemes, the current national forest estate is still expanding and has reached 11% of the total area of Ireland (DAFM 2018).

The main challenge wood mobilisation faces in Ireland is that many private forest owners have no previous experience with forest management. Convincing these owners to thin their stands represents the key mobilisation challenge (SIMWOOD 2015). Because in some cases traditional first thinning operations do not generate enough revenue to cover the costs, or the profit is very low, it is expected that forest owners will be more interested in thinning their forests if the operation is more profitable.

First thinning in Ireland is almost exclusively conducted using the Cut to Length (CTL) system in which the assortments produced include pulpwood, small sawlog, palletwood and stakewood, however, woody residues are generally not procured. Integrated thinning (INT), the management practice analysed in this study, as defined by Coates et al. (2016), consists of producing small sawlog, palletwood and biomass assortments in one operation. Those thinned trees that do not produce any roundwood because of size or quality limitations are included in the biomass assortment together with the tree tops and branches of the trees harvested as roundwood. Since INT thinning procures woody residues as well as the conventional assortments extracted during CTL thinning, the income from the mobilisation of those residues may improve the profitability of the operation. Research trials to study different approaches to the mobilisation of this additional wood fuel from conifer stands at first thinning have been carried out in Ireland and showed significant differences in biomass output (82% more wood mobilised through INT compared to CTL) and, consequently, in the potential income for the owner (Coates et al. 2016). However, before implementing the most promising methods at an operational scale, certain operational aspects need to be evaluated to ensure that this harvesting alternative is sustainable.

Fox (2000) highlights that not all soil types are suitable for intensive management practices. Machines' transit as well as soil properties can be affected by harvesting woody residues. When woody residues are extracted from a forest, soil physical disruptions such as soil compaction or soil erosion might occur. At the same time, brash material contains relatively large amounts of nutrients in comparison to stumps and stem-wood (Iwald et al. 2013) and its extraction can result in reduced forest production (Vanguelova et al. 2010). Hence, to prevent soil degradation, forest management should be adapted to specific soil characteristics. A highly recommended protective measure is to leave brash mats made from (a proportion of) the harvested woody residues on the forest floor in the racks where the harvester and forwarder travel, leaving them thicker when soils are soft (e.g. peats) or when large volumes of wood will be carried over key routes. To prevent nutrient losses, Egnell and Leijon (1999) recommend leaving most of the nutrient-rich foliage in the forest as they have a relatively higher nutrient content than the rest of the aboveground biomass.

This study was part of SIMWOOD, a European project that emerged to address some of the climate protection objectives of the European Union and aimed at ensuring that the increasing demand for biomass for energy generation in Europe could be met by helping to mobilise timber and by promoting collaborative forest management while ensuring the sustainability of forest functions are kept (SIMWOOD 2016). The research question addressed in this study is whether woody residues can be sustainably extracted as biomass during first thinning operations from any given forest in a study region? In this paper, the biophysical aspects of this sustainability assessment are presented. The economic aspects of the assessment have been evaluated by Ardao Rivera (2017).

The study region is the IE02, southern and eastern Ireland, of the NUTS 2 region of Ireland (European Commission 2013) (Figure 1) and consists of an area of 36,414 km^2 or 53% of the total surface of the country. The total forest area in the region is 348,233 ha, which represents 9% of the model region and 47% of the forests are in private ownership (Ní Dhubháin et al. 2015).

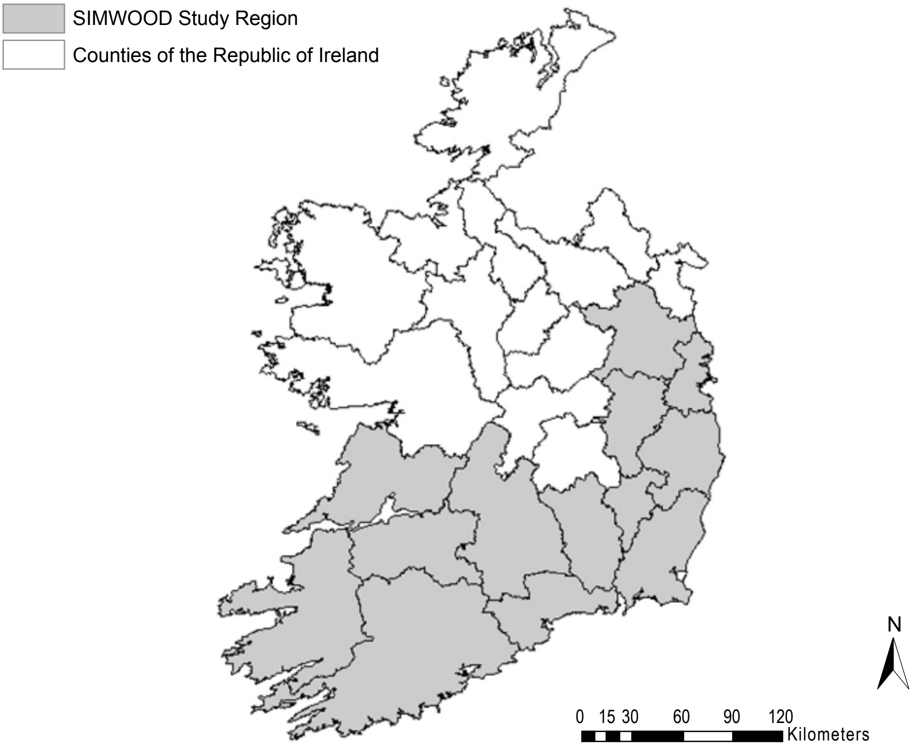

Figure 1: *The study area of this SIMWOOD pilot project in Ireland.*

Materials and methods

The main software employed was ArcGIS 10.1 (ESRI). Through Model Builder, a visual programming language for building geoprocessing workflows in ArcGIS, a spatial model was developed to generate the outputs needed to address the objectives of the study. Since the model was developed using Model Builder, the script could be modified at any stage, providing flexibility in the generation of outputs, meaning for example that if data were updated the model would automatically run using the new data and generate new outputs.

Plantation age and tree size

This research focused on those forests whose development stage made them suitable for first thinning. Information on forests' locations and their stand characteristics were retrieved from a national forest cover GIS layer developed by the Forest Service (2015). Date of establishment was used to calculate the age of the plantations, through a model that selected forests that were established between 15 and 20 years before current date.

The species that were included in the study were: ash (*Fraxinus excelsior* L.) Douglas fir (*Pseudotsuga menziesii* D. Don), hybrid larch (*Larix* × *eurolepus*), Japanese larch (Larix kaempferi (Lamb.) Carr.), lodgepole pine (*Pinus contorta* subsp. latifolia (Engelm.) Critchfield)), Norway spruce (*Picea abies* L.), Scots pine (*Pinus sylvestri*s L.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.).

Soil suitability – Soil Damage Risk and Nutrient Loss Risk
To generate the Soil Damage Risk and Nutrient Loss Risk maps, a soil classification and a map of that classification were needed. Since the Irish Soil Information System (Teagasc 2014) does not use soil groups or soil series as the basis of soil mapping units, data on soil associations were used. The predominant soil series of each soil association was used to assign a soil group to each polygon and then a map of soil groups was created for the study region. The soil classification used in this study was composed of soil groups: alluvial, brown earth, brown podzolic, groundwater gley, lithosol, luvisol, podzol, rendzina and surface water gley (based on the classification by Gardiner and Radford (1980)). The various soil groups naturally have different soil characteristics and, hence, different soil damage and nutrient loss risks.

Soil damage risk
For soil damage risk, the data used needed to reflect the most important terrain factors affecting machine movement, which according to the Forestry Commission (1974) are ground conditions, ground roughness, and slope. Ground conditions covers the bearing capacity of the soil, determined by soil type and moisture regime, ground roughness is concerned with the presence of obstacles to movement across the land surface, and slope influences the choice and efficiency of machines. The data required to characterise those three aspects were sourced from the second report of the National Forest Inventory (NFI) (DAFM 2012). It compiles detailed data at plot level for 1,680 plots, of which 987 plots were located within the SIMWOOD region. Considering the NFI data, it was decided that slope was not required to characterise machine movement and soil damage risk in the study region as 55% of the plots were located on slopes of less than 5°, 77% on slopes of less than 10°, and only circa 4% were located on slopes over 20°.

Relationships between soil groups and the above characteristics were analysed for the NFI plot data (DAFM 2012). All the soil groups were classified according to the three relevant terrain characteristics (soil conditions, ground conditions and ground roughness). Each soil group was assigned a range of categories for each of the terrain characteristics, e.g. brown earth soils have rough-to-even ground roughness. Each range of categories was then given a score out of 5, e.g. rough-to-even ground roughness has a score of 2 (with 1 being the best and 5 the worst). The ranges were created so that a minimum of 95% of the plots in each soil group fell within those ranges. After the ranges were determined, a total soil damage risk was assigned to each soil group by accumulating the scores of soil conditions, ground conditions and ground roughness (Table 1).

Table 1: *The range of soil conditions, ground conditions and ground roughness for each soil group and their associated scores. The predominant score is given first, followed by the range of scores in brackets. The Soil Damage Risk score for each soil group consists of the scores for the three soil characteristics.*

	Soil		Ground				
Soil Group	**Conditions[a]**	**Score**	**Conditions[b]**	**Score**	**Roughness[c]**	**Score**	**Soil Damage Risk**
Luvisol	NP	1	≤VG	1 (1 - 5)	VR - E	2 (1 - 5)	Very low risk - 1.1.2.
Alluvial	NP	1	≤G	2 (2 - 5)	R - E	2 (1 - 4)	Low risk - 1.2.2.
Brown earth	NP	1	≥VG	2 (1 - 3)	R - E	2 (1 - 4)	Low risk - 1.2.2.
Brown podzolic	NP	1	≥VG	2 (1 - 3)	R - E	2 (1 - 4)	Low risk - 1.2.2.
Ground-water gley	NP or <30 cm P	1 (1 - 2)	P - G	3 (2 - 4)	U - AE	2 (2 - 3)	Low-moderate risk - 1.3.2.
Surface-water gley	NP or <30 cm P	1 (1 - 2)	P - G	3 (2 - 4)	U - AE	2 (2 - 3)	Low-moderate risk - 1.3.2.
Rendzina	NP	1	P - G	3 (2 - 4)	VR - AE	3 (2 - 5)	Low-moderate risk - 1.3.3.
Podzol	NP or <30 cm P	2 (1 - 2)	P - G	3 (2 - 4)	R - AE	3 (2 - 4)	Moderate risk - 2.3.3.
Lithosol	<20 cm MS or <30 cm P	3 (3 - 4)	P - G	2 (2 - 4)	VR - AE	4 (2 - 5)	Moderate risk - 3.2.4.
Minerotrophic peat	>30 cm P	5	≤A	4 (3 - 5)	R - E	2 (1 - 4)	High risk - 5.4.2.
Ombrotrophic peat	>30 cm P	5	≤A	4 (3 - 5)	R - AE	3 (2 - 4)	Very high risk - 5.4.3.

[a] NP is no peat, P is peat and MS is mineral soil.
[b] P is poor, A is average, G is good and VG is very good.
[c] VR is very rough, R is rough, U in uneven, AE is almost even and E is even.

Nutrient loss risk

Farrelly (2011) analysed how forest soils influence productivity of Sitka spruce in Ireland. Since productivity is largely dependent on soil fertility (Farrelly 2012) and the nutrient availability in less fertile soils is more likely to go below sustainable levels as result of residue removal in the short-term, linkages between soil groups and nutrient loss risk categories (categorised as 1 to 5, least risk to greatest) were made to generate a nutrient loss risk classification. To create the Nutrient Loss Risk map, linkages were created between data from Farrelly (2011) and the geographic data on soil groups from the Irish Soil Information System.

Recommended proportion of woody residue removal

Different soils have different characteristics and, hence, different susceptibilities to being affected by residue removal. Using field data from forests in which INT had already taken place, a matrix that depicted the recommended proportions of woody residue removal suitable for each soil group was created. Relevant data of the visited forest stands included: soil variables (slope, soil conditions, ground conditions, ground roughness and visual effect of soil conditions on harvesting operations) and volumes of the extracted assortments. Relationships between the soil variables and the volumes allow for recommendations on extraction rates. The matrix has the nutrient loss and soil damage risks as rows and columns and each of the cells indicates the proportion of woody residues that is recommended be left on site.

Distance to biomass end users

The proximity of the forests to the user of the harvest residue will determine whether it is economical to bring the material to the market. Hence, the distance to the end user needs to be taken into account. Data from the Bioenergy Installations Map Ireland 2015 (Irish BioEnergy Association 2015) on the location of biomass end users were used. The biomass end users considered in this analysis are those that require large quantities of biomass: CHP plants and those end users that require a minimum of 5,000 tonnes per year (c. 3 MW). A GIS layer including the locations of the large biomass end users was created. Using Euclidean distances was found to be the most appropriate methodology (Zhang et al. 2011) as they represent the distance from every cell in the map to the nearest source, which in this case was the end user. Other studies (Noon and Daly 1996, Voivontas et al. 2001, Carr and Zwick 2005) have shown that using more complex methods (e.g. Least Cost Path Analysis) did not improve results sufficiently to justify the added data requirements. Thus, the forest areas already categorised by soil damage risk class and residue removal proportion were also quantified according to their distance to biomass end users.

Results

Age of forests

The commercial forests in the study region that were of suitable age for first thinning (between 15 and 20 years) were spatially identified (Figure 2) and the number of forests and the areas planted with each species were calculated, based on the predominant species in each forest (Table 2). Results indicated a large proportion of forests of interest in the western area of the study region.

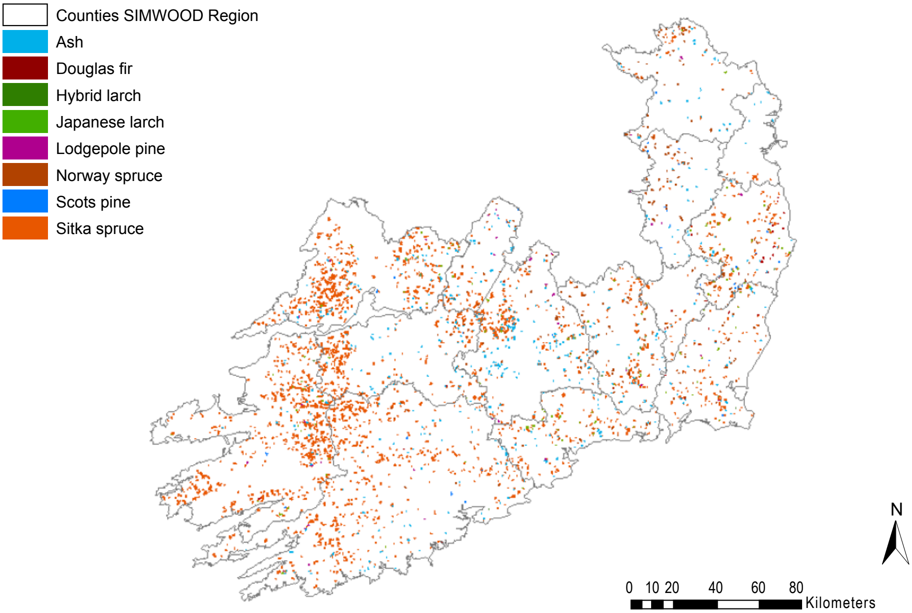

Figure 2: *Location of the forest plantations of the main commercial species suitable for first thinning based on age criteria.*

Table 2: *Number of forest stands and forest area of suitable age for thinning per species.*

Main species	**Number of forest stands**	**Average area** (ha)	**Total area** (ha)
Sitka spruce	5,556	6.25	34,748
Ash	1,060	2.71	2,870
Norway spruce	641	4.71	3,022
Japanese larch	240	3.19	766
Scots pine	86	3.33	287
Lodgepole pine	84	3.76	316
Douglas fir	76	4.06	308
Hybrid larch	29	5.11	148
Total	**7,772**	**5.46**	**42,463**
Percentage of the total forest area[a] (%)			34.1

[a] The total forest area refers only to the area of private (grant-aided) forests of commercial species (of any age) considered in this study.

Soil suitability - soil damage risk and nutrient loss risk

Soil Damage Risk

Each soil group was assigned a range of categories for soil conditions, ground conditions and ground roughness to generate the resulting soil damage risk categories and Soil Damage Risk map (Figure 3). The area for each risk category was obtained (Table 3). It was observed that a large proportion of the forest areas of high and very high soil damage risk were located in the west of the study region, where the density of forests of interest was also the highest.

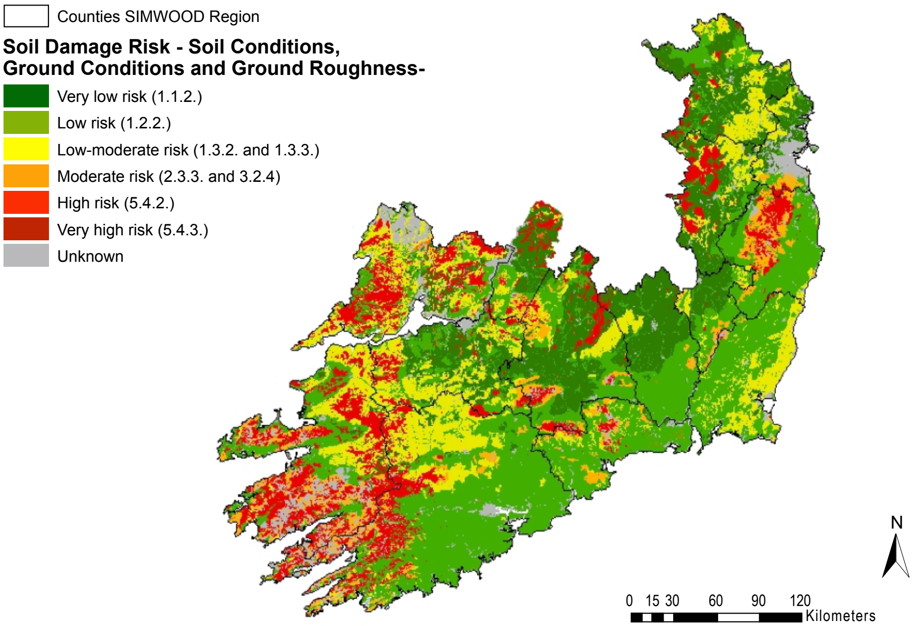

Figure 3: *Geographic representation of the soil damage risk for each soil group. The numbers in brackets refer to the scores of soil conditions, ground conditions, and ground roughness of each soil damage risk category.*

Table 3: *Area of forests of interest in each soil damage risk category.*

Soil damage risk category	**Total area** (ha)	**Relative area** (%)
Very low	2,858	6.7
Low	11,450	27.0
Low-moderate	8,820	20.8
Moderate	2,382	5.6
High	107	0.2
Very high	16,018	37.7
Unknown[a]	828	1.9

[a] Unknown soil damage risk corresponds to polygons for which soil data were not available.

Nutrient Loss Risk

The Nutrient Loss Risk map (Figure 4) and the areas per risk category were collated (Table 4). As for soil damage risk, there was a higher density of soils with high and very high nutrient loss risks in the western part of the study region, the area where the density of forests of interest was also highest.

Subsequently, the soil damage and soil nutrient risks were considered simultaneously for each forest of interest (Table 5) and results indicated that 60.8% of the area of forests of interest were located on soils where at least one of the risks was either high or very high.

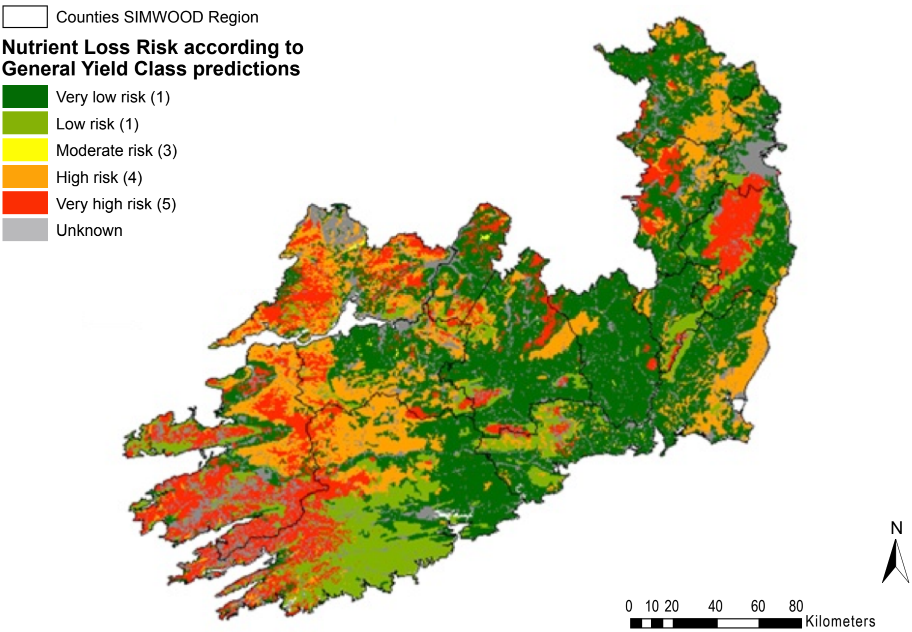

Figure 4: *Geographic representation of the nutrient loss risk of each soil group. The numbers in brackets represent the nutrient loss risk scores.*

Table 4: *Area of forest in each nutrient loss risk category.*

Nutrient loss risk category	**Area of forests** (ha)	**Relative area** (%)
Very low	8,884	20.9
Low	4,542	10.7
Moderate	107	0.2
High	8,820	20.8
Very high	16,892	39.8
Unknown[a]	3,218	7.6

[a] Unknown nutrient loss risk corresponds to polygons from which soil data were not available and to the alluvial soil group (for which nutrient loss risk could not be assessed through the methodology used).

Table 5: *Area (ha) of forests of interest classified simultaneously by soil damage risk and nutrient loss risk categories. In brackets, the percentage of the total area of forests of interest in the region.*

		Nutrient Loss Risk					
		Very high	High	Moderate	Low	Very low	Unknown
Soil Damage Risk	Very high	16,018 (*37.7*)					
	High			107 (*0.3*)			
	Moderate	874 (*2.1*)	16 (*< 0.1*)		1,508 (*3.5*)		
	Low-moderate		8,804 (*20.7*)				
	Low				3,034 (*7.1*)	6,026 (*14.2*)	2,390 (*5.6*)
	Very low					2,858 (*6.7*)	
	Unknown[a]						828 (*1.9*)

[a] Unknown risk corresponds to polygons for which soil group data were not available and to the alluvial soil group (for which it was not possible to assess nutrient loss risk based on the methodology used).

Recommended proportion of woody residue removal

Due to soil damage and nutrient loss risks, woody residue extraction volumes were adapted to the soil characteristics of each site (Table 6). Data collected from cases in which INT had already taken place showed that on sites where soil characteristics were the most favourable for woody residue extraction, an estimated 30% of the woody residues were left in the forest. Hence, that value was used as the minimum proportion of woody residues recommended to leave on site to protect the soil in the machine racks. At the other end of the scale, woody residues were not extracted on sites that showed the lowest suitability for woody residue removal. Hence, recommended woody residue extraction rates were approximated with a linear trend, from 0% in the worst case to 70% in the best case.

Table 6: *Recommended proportions (%) of total woody residues for extraction during INT operations, for all soil damage risk and nutrient loss risk combinations.*

		Soil Damage Risk					
		Very high	High	Moderate	Low-moderate	Low	Very low
Nutrient Loss Risk	Very high	0	0	0	0	0	0
	High	0	0	20	20	20	20
	Moderate	0	20	20	30	30	40
	Low	0	20	20	30	40	60
	Very low	0	20	30	40	60	70

In addition, the recommended proportions of woody residues to extract through INT were applied to the areas of each classification of soil damage and nutrient loss risk (Table 4). If the thinning yield (49 m^3 ha^{-1}) for a 5-year thinning cycle in YC 20 Sitka spruce is assumed as an average (Edwards and Christie 1981), results indicate that the increase in the extracted wood volume would range from c. 5.12 m^3 ha^{-1} (average DBH before thinning 16 cm) to c. 15.49 m^3 ha^{-1} (average DBH before thinning 14 cm) for the whole area of forests, considering that woody residue extraction varied from 0% to 70%. When only the low and/or very low risk categories were considered (c. 12,000 ha), the increase in extraction volumes resulting from first thinnings ranged from c. 164,000 m^3 (average DBH before thinning: 16 cm) to c. 495,000 m^3 (average DBH before thinning: 14 cm).

Transport from forest to biomass end user

To obtain the distance from the forests to the closest end user, linear distance categories were established around each end user (Figure 5) so that haulage distances from the forests of interest could be obtained. None of the forests of interest were located more than 75 km from the closest end user and almost all of the forest area (99.2%) was located less than 50 km from the nearest biomass end user.

In addition, soil damage and nutrient loss risks were overlaid on the map containing the distances to the closest biomass end users. Results indicate that of the forest area where INT could take place (≥20% of woody residue removal), 99.5% was located less than 50 km from the nearest end user and 72.7% less than 25 km.

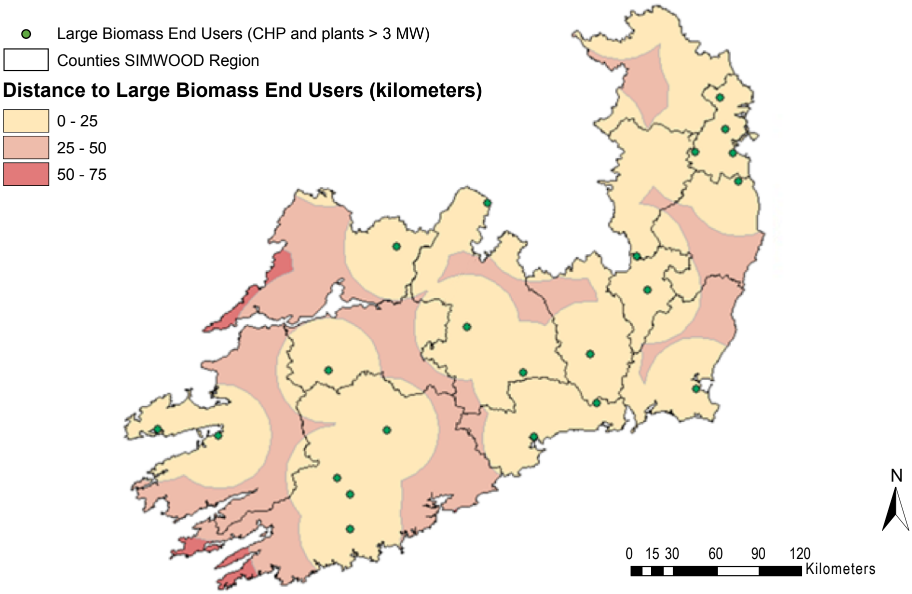

Figure 5: *The linear distance class map for all large biomass end users (CHP plants and plants that generate more than 3 MW).*

Discussion

This study set out to assess the sustainability of conducting INT as a first thinning operation in southern and eastern Ireland. The results show that the feasibility of conducting INT sustainably was highly site-specific.

To evaluate the risks of soil damage and nutrient loss, a number of assumptions had to be made due to the unavailability of appropriate data, as outlined previously. Since not every soil series of each soil association belongs to the same soil group, the accuracy of the resulting soil group dataset was compromised by this approach.

When all forests suitable for thinning were mapped it was observed that a higher density of such forests occurred in the western part of the study region; 61% of the forest area was located in counties Clare, Cork, Kerry and Limerick which comprised 51% of the study region. According to results from this study, c. 42,000 ha, or just over 34% of the total area of private (grant aided) forests of the main commercial species in the study region (amounting to 53% of the total area of this category in the Republic of Ireland (Ní Dhubháin 2015)) were of suitable age to undergo the first thinning. The geographic distribution of the different risk levels of soil damage and nutrient loss showed that soils groups at higher risk were located on the western side of the study region, where the highest density of forests of interest were found. Namely, nearly 40% of this forest area was on soils with a very high soil damage risk and/or a very high nutrient loss risk, and another 21% of the forest area was on soils with a high nutrient loss risk and a low-moderate soil damage risk or a high soil damage risk and a moderate nutrient loss risk. The high-risk classifications corresponded with peat soil occurrence. The second NFI (DAFM 2012) found that 44% of the total forest estate was located on peat soils but since 1990, there has been a gradual decrease in the afforestation of peatland and more forests have been established on mineral soils, such as gleys, grey brown podzolics and brown earths (Black et al. 2008). Therefore, the future situation for the emerging biomass wood sector is expected to improve, as those soils present lower risks of soil damage and nutrient loss while also supporting generally higher YC forests (Farrelly 2011) resulting in faster growth rates, earlier first thinnings, higher thinning yields and higher sustainable harvest residue removal rates.

The potential nutrient loss risk of each soil group was estimated by assuming that less fertile soils were more likely to reach a state in which critical nutrients are missing in the short-term. However, according to Egnell and Leijon (1999) and Fleming et al. (2014), the linkages between site quality and vulnerability to nutrient losses resulting from harvesting practices are not very strong. Therefore, a more in-depth assessment of the potential impacts of harvesting woody residues on soil nutrient balances is needed. According to an on-going study by Cummins (2016), increased harvesting of forest biomass may limit nutrient availability, although more biomass removal than the amount extracted through CTL operations can probably be allowed from most Irish forest sites while sustaining nutrient supplies for subsequent forest growth. However, because INT extracts more biomass than CTL, additional fertilising could be needed to maintain growth rates on some soil types and in some specific locations, causing the ecological footprint of the thinning operation to increase.

The assessment of soil characteristics in the study region identified the high variability in risk ratings of soil damage and nutrient loss. This resulted in a wide range of recommended extraction rates of woody residues. Depending on the average tree size and the recommended woody residue extraction rates, results ranged from a volume increase of 9.8% to 103.6% when INT was applied instead of CTL, agreeing with the results obtained by Coates et al. (2016). The use of additional data from actual extraction rates from sites where INT has been implemented is required to confirm the recommended extraction rates.

The end users considered in this study were those that required large amounts of woody residues, at least 5,000 tonnes per year. There are also likely to be a large number of smaller end users with a demand for woody residues (Irish Bioenergy Association 2015). Selling biomass to these users might enable certain INT operations to further optimise supply chain costs; for example, when biomass quantities procured from any one thinning operation are insufficient to satisfy large end users, or when the distance to small end users is shorter than to large end users. Based on cases where INT has already taken place (Ardao Rivera 2017), it was observed that large end users tend to be less demanding with regard to specifications for the biomass than the smaller end users. Because this study focused on procuring biomass from woody residues as well as roundwood, it was felt that the resulting heterogeneous material was more suitable for the less demanding large end users. However, the total biomass demand is expected to increase substantially in the near future (Phillips et al. 2016) and technological development will make small biomass boilers more suitable for a wider range of inputs, which could lead to smaller end users adapting their requirements for any biomass they might purchase. Notwithstanding these predictions, de Miguel et al. (2016, 2017) found that the wood energy sector, and particularly the woodchip suppliers, are convinced that demand in Ireland would only increase if adequate support measures, such as grants for the establishment of firewood or woodchip boilers, or the creation of producer groups or cooperatives, were provided. It should also be kept in mind that the predicted increase in demand for biomass (Clancy and Scheer 2011) will result in longer haulage distance (and higher costs), as the forest units in Ireland tend to be small and geographically scattered (Farrelly et al. 2008, Sosa et al. 2015).

It should be noted that the distance estimations were based on Euclidean distance calculations, and hence, in some cases, especially when trucks cannot follow the shortest distance routes because of weight or size restrictions, the effective distances might be significantly longer. In any case, when soil damage and nutrient loss risks were considered simultaneously with the distance to biomass end users, it was observed that almost the total area (99.5%) of the forests where soil damage and nutrient loss risks were low or very low were less than 50 km from the closest end user. Therefore, distance to potential biomass end users was found not to be an obstacle for conducting INT on sites with low damage risks, assuming that local road infrastructure and forest access are adequate. However, in areas where soil damage risk and nutrient loss risk are predominantly high, as in the west of the study region, biomass end users may experience difficulties in procuring sufficient biomass material from forest areas that are located within an economically viable distance.

Based on site visits, tree characteristics were found to be another essential factor in the process of deciding whether INT should be carried out. Since INT implies higher supply chain costs, it would be logical to only procure woody residues as biomass when there is enough material to make a significantly higher profit in comparison to CTL. It was observed that in cases where enough roundwood material to procure high-value assortments (e.g. sawlog, palletwood and/or stakewood) was available, procuring woody residues as biomass did not make a significant difference in the total profit (Ardao Rivera 2017). On the other hand, it was observed that where tree characteristics were not suitable for procuring a marketable quantity of roundwood as high value assortments, procuring pulpwood as biomass in addition to a volume of woody residues could result in a more sustainable and profitable operation, assuming no other variables prevented such an operation from being carried out. Additionally, because INT provides more end products than CTL, it may prove a more flexible harvesting practice that is more resilient to the fluctuations of individual assortment prices.

Even though INT can potentially increase wood mobilisation in comparison to CTL, its sustainability depends on site- and stand-specific characteristics and is dependent on other variables not considered in this study, such as weather conditions or market drivers. Demand for biomass wood for energy generation grows alongside the development of renewable energy policies and the realisation that fossil fuel-derived energy has an end date. At the same time, the profitability of INT is highly dependent on the price of fossil fuel as it relies on machines for harvesting and transporting the produce to end users. Finally, it should be highlighted that biomass wood as an energy source can be considered carbon neutral, but this depends greatly on the type of management carried out in the forests from which the biomass is extracted (Naudts et al. 2016).

Conclusions

This study assessed the potential sustainability of INT, which is a more intensive thinning practice than the conventional CTL system. Because site suitability for INT had not been assessed in Ireland prior to this study, the results presented here are very relevant for the Irish forest biomass sector. To ensure a sustainable INT operation, both bio-physical and economic variables needed to be analysed. This paper dealt with the main sustainability concerns regarding the implementation of INT. However, evaluating the potential profitability of INT is also necessary to identify potential limitations of this harvesting practice (Ardao Rivera 2017). Soil characteristics are the main biophysical determinant of the sustainability of INT and results show that nearly 40% (or c. 17,000 ha) of the area of the forests presented very high risks of soil damage and nutrient loss. Hence, woody residue extraction in those forests would not be recommended. On the other hand, 53% (or c. 22,000 ha) of the area of forests were located on soils where INT could take place with varying rates of residue removal. Distance to the biomass end users was not found to be an obstacle to conducting INT, as almost all (99.5%) of the area of the forests where INT could take place were located less than 50 km from the nearest end user. Finally, it was found that an assessment of certain tree characteristics is necessary prior to conducting an INT, since the higher the proportion of residual biomass in a forest stand, the more likely it is that INT will generate higher profits than CTL.

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