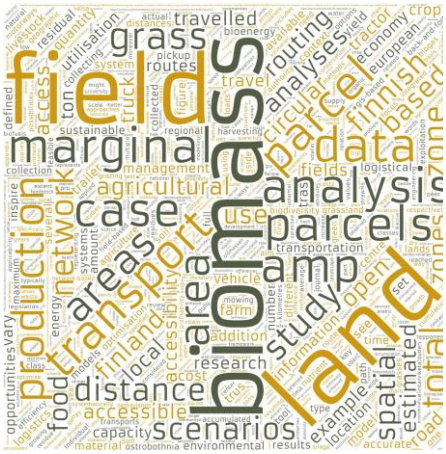
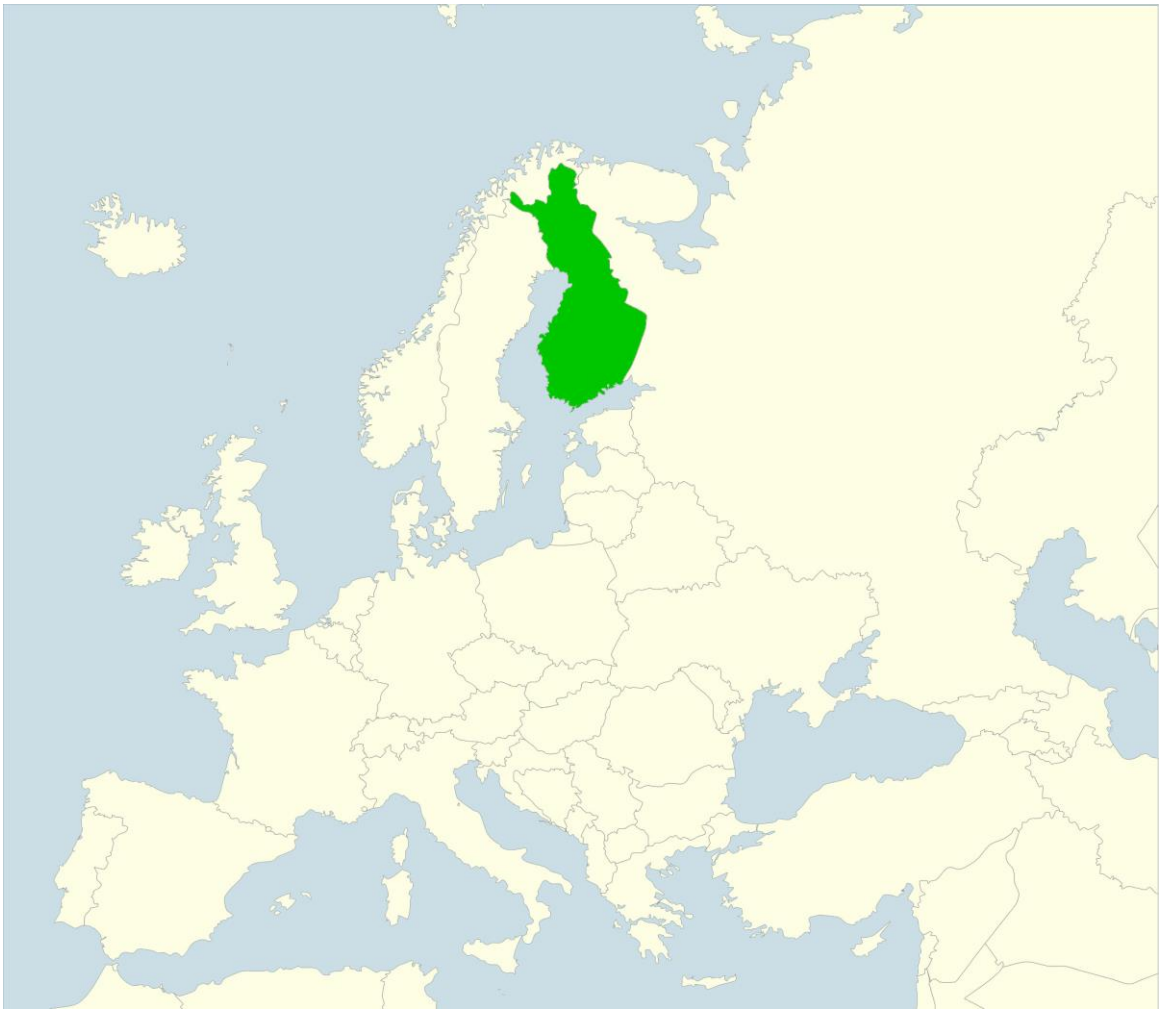
European Countryside | volume 15 | No. 4 | p. 542-562 | DOI: 10.2478/euco-2023-0029

MEASURING ACCESSIBILITY AND OPTIMISING LOGISTICS OF MARGINAL LAND GRASS BIOMASS IN THE CASE OF NORTHERN OSTROBOTHNIA, FINLAND

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Received 15 April 2023, Revised 13 July 2023, Accepted 21 July 2023

Abstract: Grass biomass originating from marginal agricultural land unsuitable for food production can be utilised in variety of bio-based productions. The key profitability constraints for such productions are regional availability and transport costs. The aim of this paper is to methodologically test open access agricultural field parcel data – enabled by the EU INSPIRE directive – integrated with the road network in measuring biomass accessibility and optimising collection and transport using geographic information system (GIS) technology in two Finnish case areas. The analytical framework applies closest facility and vehicle routing analyses for tractor and truck transport scenarios. The key finding is that the area of field parcels and the amount of biomass accumulating within an observed area are not the only important factors influencing transport efficiency: cost-effectiveness of collection routes can be equally high in regions with scarce and abundant biomass areas.

Keywords: Agricultural parcel data, INSPIRE, Accessibility, Network analyses, Geographic information systems (GIS), Marginal agricultural land, Field biomass, Circular economy, Finland

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Abstrakti: Maatalouden tuotannolle marginaalisten alojen ruohobiomassaa voitaisiin hyödyntää energian ja biopohjaisten tuotteiden tuotannossa. Keskeisiä kannattavuutta rajoittavia tekijöitä biomassan hyödyntämisessä ovat alueellinen saatavuus ja kuljetuskustannukset. Tämän tutkimuksen tavoitteena on testata avoimilla peltolohko- ja tieverkkoaineistoilla menetelmiä biomassan saavutettavuuden mittaamiseen ja kuljetusten optimointiin paikkatietojärjestelmän avulla, kahdella pohjoispohjanmaalaisella case-alueella. Analyysit pohjautuvat EU:n INSPIRE-direktiivin mahdollistamaan avoimeen peltolohkodataan. Analyyseissä sovelletaan verkostoperusteisia menetelmiä, joiden avulla mallinnetaan traktori- ja yhdistelmäajoneuvon kuljetusskenaarioita. Havaitsimme, että biomassan saavutettavuudessa voi olla suuria alueellisia eroja, mutta myös niukoilla biomassan alueilla kuljetustehokkuus voi olla hyvä.

Avainsanat: Peltolohkorekisteri, INSPIRE, Saavutettavuus, Verkostoanalyysit, Paikkatietojärjestelmä (GIS), Maatalouden ympäristönhoidolliset alueet, Peltobiomassa, Kiertotalous, Suomi

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Highlights

- The aim of marginal agricultural land grass biomass utilisation with logistical optimisation.
- EU INSPIRE directive enables open access spatial data on agricultural field parcels.
- Vehicle routing network modelling enables integrating road network and parcel data.
- Routing models result in accurate spatial comparison for accessibility and logistics.
- Parcel data improvements needed to identify the actual available biomass with no prior exploitation.

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1. Introduction

The rural livelihood of agricultural production is facing the challenge of producing enough food for the growing world population while meeting sustainability goals and balancing land and resource use conflicts between food, energy, and other material production (e.g., European Commission, 2020b, 2021; Willett et al., 2019). It has been recognised that agriculture produces not only food but also other ecosystem services, such as energy, materials for industry, biodiversity, and cultural landscapes, to name a few. The multifaceted challenge of agricultural production varies with its nuances on different global, national, regional, and local spatial scales. However, there are some common approaches to addressing the broad picture of sustainable agricultural production.

The circular economy and circular farming have been highlighted as such promising approaches (Ellen MacArthur Foundation, 2019; European Commission, 2020a; Jurgilevich et al., 2016). Although food production is prioritised over other uses of biomass, the circular farming principle of making the best possible use of resources also acknowledges and includes residual by-products (de Boer & van Ittersum, 2018). Promoting the utilisation of such residual and side stream material can contribute to enhancing circular economy in the wider society (Kumar & Verma, 2021; Mujtaba et al., 2023; Scordia & Cosentino, 2019). Marginal agricultural lands out of active agricultural use are identified as a potential source of such residual biomass, namely herbaceous grass biomass (Bosworth, 2015; Kumar & Verma, 2021). Possibilities for integrating marginal agricultural lands into circular systems have been studied previously (Gerwin et al., 2018; Koppelmäki et al., 2021; Liu et al., 2011; Niemeläinen et al., 2014; Nilsson et al., 2015; Scordia & Cosentino, 2019; Von Cossel et al., 2019). One of the main reasons for increased interest in this aspect of agricultural side streams is that there is no conflict between food and energy production on such marginal lands.

A major challenge associated with biomass exploitation is related to unprofitable transport possibilities, as some of the marginal land areas are scattered in location, too far away from a farm centre, and are small and inconveniently shaped (Lötjönen & Niemeläinen, 2014; Nilsson et al., 2015). As the harvesting and transport costs are a major constraint to profitability (Gunnarsson et al., 2008; Niemeläinen, 2022), proper logistical planning is required for economically feasible utilisation of marginal biomass (Scordia & Cosentino, 2019). As summarised by Monti and Alexopoulou (2017), efficient biomass exploitation requires effective logistical concepts from the field to the biorefinery. Furthermore, most of the previously reviewed studies on the utilisation of marginal land biomass have been conducted at an experimental scale, while scalable case studies on replicable logistical concepts on marginal land are still needed (Scordia & Cosentino, 2019).

As a result of the EU's Infrastructure for Spatial Information in Europe Directive (INSPIRE), geographic, i.e., spatial data on agricultural fields, is increasingly available on an open access basis (for example, in Finland, France, The Netherlands, Spain, and Estonia). The availability of the data opens up new possibilities for optimising the use of field-based biomass in the circular economy context. Spatial data on agricultural fields includes the attributes of location, area, and agricultural land cover, and is therefore valuable data for a wide range of uses. In Finland, for example, the Finnish Food Authority makes available the data sets of the land parcel register, landscape features on agricultural land, agricultural land use type, and specified agricultural land use (Finnish Food Authority, 2022b). This data allows for a better scrutiny of the opportunities associated with often under-utilised residues in rural marginal areas.

A wide range of optimisation methods are applied in the analysis of biomass supply chains to increase efficiency, reduce costs, and improve sustainability (Sun & Fan, 2020). Geographic information system (GIS)-based network analyses provide an excellent tool set for analysing the geographic or 'spatial' components of logistics optimisation as a part of the supply chain with graphical network data, such as routable geographic models of route networks (Miller & Shaw, 2015). The analytical framework is largely applied to centralised delivery or collection types of study settings (see Bosona et al., 2011; Korhonen et al., 2017; Kosovac et al., 2020; Kotavaara et al., 2017; Yu et al., 2021), including also logistic optimisation of rural side stream flows (Lemire et al., 2019). There are also several studies applying location optimisation for rural cases in Finland such as accessibility of local and organic food (Kotavaara et al., 2014), bale wrapping waste from farms in North Karelia, Finland (Tepponen et al., 2020) and location optimisation for cattle and pig manure-based biogas reactors in Northern Ostrobothnia, Finland (Kotavaara et al., 2022). Logistic models for grass biomass transport have been designed and calculated previously (e.g., Gunnarsson et al., 2008), but these analyses lack the geographic, i.e., the spatial, component. Previous approaches have not included a routable and spatially accurate digital model of road networks, and there are limitations such as the assumption of no distance between fields within the same farm for simplicity.

Scattered grass biomass is an interesting study case for GIS-based network analysis because the availability and transport of biomass from small field parcels is not easily profitable due to the high mileage needed for collecting sufficient side stream masses. On the other hand, grass biomass is a bulky

material that requires massive quantity transport equipment. Therefore, network analyses and logistic optimisation are also widely applicable to agricultural residues and side streams based on agricultural land area and yield estimates. In this study, we apply an accurate GIS-based road network model and recently opened INSPIRE agricultural field parcel data to test a logistic optimisation framework for grass biomass from marginal agricultural land.

The term 'marginal' agricultural land is often used in a subjective sense for less-than-ideal land without sufficient specificity (Richards et al., 2014). However, when the term marginal land is precisely defined, it refers, for example, to land that is unsuitable for food production, to ambiguous lower-quality land or to economically marginal land (Shortall, 2013). In this study, marginal agricultural land refers to the environmental management areas related to agricultural support schemes.

2. Research aim

This paper examines the potential for the use of grass biomass harvested from marginal environmental management areas in agriculture and ways to promote it. The secondary aim is to test open access agricultural field parcel data in promoting circular economy. The spatial scale of this study is two local case areas in Northern Ostrobothnia, Finland (see Fig. 2where such agricultural land areas have been identified as potential growing sites for exploiting biomass (ProAgria Oulu, 2018). However, some field parcels are identified as being too small, inconveniently shaped, or too far from farm centres to exploit with sufficient profit (ProAgria Oulu, 2018).

Therefore, the focus of this paper is to explore the possibilities of applying open access field parcel data and GIS-based network vehicle routing analyses in observing the accessibility and logistics of marginal agricultural biomass. The aim is to seek and to compare two types of logistics models for biomass collection: 1) transport of biomass only from large-area fields accumulating full trailer loads by individual back-and-forth tractor transports (the TRA-A and TRA-B scenarios); and 2) routing via a large number of fields (including all the parcels) with a larger truck transports (the TRU-A and TRU-B scenarios). In particular, the aim is to evaluate the applicability of the vehicle routing method in this type of research framework involving collection of massive quantities. The scenarios are tested in three distance zones (15, 30, and 45 km) and in two different local case areas: case A located in the coastal area bordering the Gulf of Bothnia, and thus representing a case of scarce agri-environmental areas and residual biomass flows; and case B in the inland area, representing a case of denser agri-environmental areas and residual biomass flows. Due to differences in the case areas, they are not comparable, but the aim of having two cases is to gain a better understanding of methodological applicability. As the main focus is on methodological experimentation, the purpose of the further use of the biomass is also not considered.

The differences in the results are examined by the distances travelled per ton (1000 kg) of biomass collected between the different transport options, analysis zones, and case areas. This simple parameter can be used to indicate the efficiency and the advantage of different transporting options at varying spatial scales. For both case areas, the clear hypothesis is that large-quantity truck routing results in a shorter total distance per ton of biomass than individual back-and-forth tractor transports. The study is therefore approached through the following research questions:

1) What opportunities and limitations exist in integrating open access farm field parcel data into transport accessibility analyses according to the case of marginal field biomass?
2) How does the accessibility of marginal land grass biomass vary between the transport scenarios of back-and-forth transport (by tractor) and collection routes (by truck) in different analysis zones?
3) How does the accessibility and effectiveness of transportation differ in the context of spatially scarce versus dense biomass?

3. Utilisation challenges and opportunities associated with marginal land grass biomass

There are several challenging reasons why residual grass biomass is not always systematically utilised, such as lack of practical applications or unsuitability for ruminant animal feed at the local scale (e.g., ProAgria Oulu, 2018; Gaffey et al., 2023). Furthermore, due to the specialisation and spatial centralisation of agricultural production in Europe, there are areas throughout the region where livestock production does not exist (see, e.g., de Roest et al., 2018). This eliminates the possibility of utilising the unharvested biomass locally for livestock grazing. However, the use of underutilised marginal land is seen globally as a possibility to promote year-round biomass supply to replace unsustainable petroleum-based refining (Kumar & Verma, 2021).

Typically, marginal agricultural grassland is used for livestock grazing or forage harvesting where applicable. Grass biomass can also be used as chopped bedding material in livestock production (Manni, 2022). In addition to the above, there are several other ways in which grass biomass can be integrated in agricultural systems or outside of agricultural purposes. For example, the biomass can be used for energy production, such as bioethanol production (Mohapatra et al., 2019) or biogas production integrated into a sustainable circular agricultural system (e.g., Koppelmäki et al., 2021). For example, Niemeläinen et al. (2014, p. 22) estimated that in Finland, marginal agricultural land (including green fallow, natural fields, and buffer zones) could yield biomass for a significant amount of bioenergy production; by exploiting the most suitable fields for biomass harvesting, the estimated amount of energy produced is only slightly less than the annual electricity consumption of agricultural and horticultural enterprises in Finland. Moreover, using marginal land instead of primary, heavily managed land can reduce greenhouse gas emissions in bioenergy production (Rasi et al., 2019).

In addition, grasses could be an important feedstock for modern biorefineries in producing high value-added products such as biochemicals and bio-based materials (Gaffey et al., 2023; Scordia & Cosentin, 2019), which would be reasonable in the context of replacing petrochemical production (Kumar & Verma, 2021). Additionally, grass biomass can be used as a component for organic soil fertiliser or soil conditioning products (Scordia & Cosentino, 2019). Thus, the circular utilisation of residual grass biomass can be integrated into more sustainable agricultural approaches such as regenerative and carbon farming (cf., Oberč & Arroyo Schnell, 2020), as well as to enhance self-sufficiency in agricultural nutrient supply. In addition, due to the positive effects of grass cultivation on cropland conditions (e.g., restoration of soil fertility; pest, disease and weed control), it is recommended to integrate grass into arable land crop rotations (Oberč & Arroyo Schnell, 2020). For fertilisation and soil conditioning purposes, the advantage of grass biomass could be further improved and better targeted if, for example, the residual biomass is used for biogas production and the nutrient-rich by-product, digestate, is recycled by timely reallocation to the field parcels with actual nutrient demands (Möller & Müller, 2012). Therefore, especially in regions where low livestock production hinders the systematic use of such grassland biomass, the fields used for such green manuring purposes can be considered as marginal grassland providing residual biomass.

Furthermore, removal of the grass biomass after mowing is important for water and nature conservation, as the removal on some of the marginal land areas, such as buffer zones close to water systems, reduce nutrient leaching into water bodies (e.g., Hyvönen et al., 2020, p. 24; Lätti et al., 2014; Uusi-Kämppä & Kilpinen, 2000). Managing marginal grasslands by removing the biomass also enhances biodiversity by balancing appropriate soil nutrient level (Cole et al., 2020). In Finland, for example, mowing the vegetation on some of the agri-environmental management areas is mandatory (Finnish Food Authority, 2022a), but removal and further economical utilisation of the biomass is optional, and not always done systematically.

4. Data and methods

The spatial data used in the analysis consists of 1) existing land use on agricultural parcels (see Figure 1), supplemented with estimated biomass quantity; and 2) routable road network (see Figure 2) with speed limit attributes and restricted road sections. The open access data are available for download as follows: '*Paikkatietoa sisältävä kasvulohko'*, i.e., land use on agricultural parcels from the INSPIRE Geoportal (2023) and '*Digiroad'* for road network at the Finnish Transport Infrastructure Agency (2023) download

service. In addition, the potential locations for the biomass collecting hubs were used. In case A, a local projected circular economy centre (HUB-A) was used, and in case B, a potential location for a biorefinery under consideration (HUB-B) was selected.

4.1 Open access farm field parcel data

The area-based biomass quantities are based on the dataset of existing specified land use on agricultural parcels (in the year 2021). The spatial information is based on the Land Parcel Identification System (LPIS), which is a reference database of agricultural parcels used as a basis for area-related payments to farmers under the Common Agricultural Policy (CAP) (European Commission, 2020c). The spatial dimensions of the polygon-shaped parcels were derived as centre points. The attributes of the dataset being used in this study are the parcel area (hectare, ha) and the specified agricultural land use (the agricultural plant species defining the land use class). The classification including the environmental management area classes used in this study is specified in Appendix A. Some of the land use classes are permanent grassland and some are a part of a crop rotation, in which the grass phase lasts only some years and other years, the land is typically used for agricultural production, such as crop cultivation. The area of the field parcels varies between 0.02–24.60 ha in case area A, and 0.01–89.8 ha in case area B.

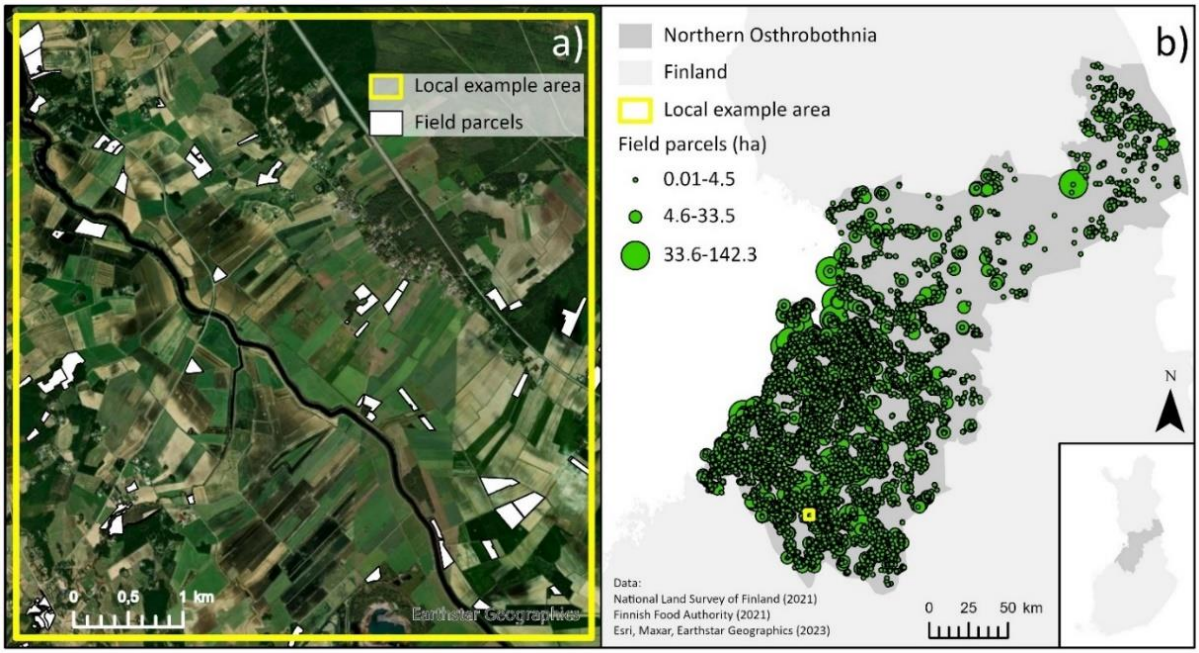


Fig 1. Open access field parcel data based on the Land Parcel Identification System (LPIS) presented on an example spatial scale of a) a local area with satellite imagery; and b) the region of Northern Ostrobothnia, Finland. The field parcels under environmental management selected for this study are classified and represented (in hectares, ha) in the map b) with natural breaks, i.e., the classes are created in a way that best groups similar values together and maximises the differences between classes. Source: own elaboration

There are no statistical data on biomass yields for different marginal agricultural fields observed in this study (Niemeläinen, 2022). To calculate the biomass estimation (for one mowing), average values based on previous literature are used. The fresh matter yield is calculated as:

$$FM = \frac{DM}{DMC}$$

where FM is the fresh matter yield, DM is the dry matter yield, which is estimated to be 4.00 $t \cdot ha^{-1}$ (Niemeläinen et al., 2014, p. 11) as the average yield for managed uncultivated field, and the DMC is the dry matter concentration, which is determined to be 32.10% and is estimated based on silage grass statistics (Salo et al., 2014, p. 11). Therefore, the estimated average FM yield is 12.46 $t \cdot ha^{-1}$. It is difficult

to make a precise estimate of the average FM, as the actual biomass amounts can vary considerably between field parcels (Niemeläinen et al., 2014, p. 24). However, the estimate here is in line with the average grass biomass FM of 12.50 t·ha^{-1} collected from road verges in the county of Lincolnshire, UK (Brown et al., 2020, p. 6), which corresponds to marginal areas with limited management. The estimate of 12.46 t·ha^{-1} is also comparable to the larger average quantity of 19.80 t·ha^{-1} for silage grass fresh yield on more intensively managed grasslands reported in Finland (Kurki & Valo, 2013, p. 2).

3.2 Transport network data

The accessibility and routing analyses were based on the openly available Digiroad 2018 model of the Finnish road network (Figure 2), which includes all drivable roads in Finland. For the tractor scenarios, the motorways and motor-traffic ways were set as restricted road sections based on Finnish legislation (Finlex, 2020). For the road network, driving speed estimates were formulated based on the speed limit data and 20–30 km/h was used for missing information. For the tractor scenario analyses, the speed limit of 45 km/h was set as an average based on the maximum allowed speeds of 40 km/h and 50 km/h for different tractor types in Finnish legislation (Finlex, 2020). In Northern Finland, travel time estimates based on speed limits are accurate under typical circumstances, as the impact of traffic congestion in this area is low. However, travel times in built-up areas are increased by 25% (Kotavaara et al., 2017, p. 85). Travel time estimates are therefore accurate.

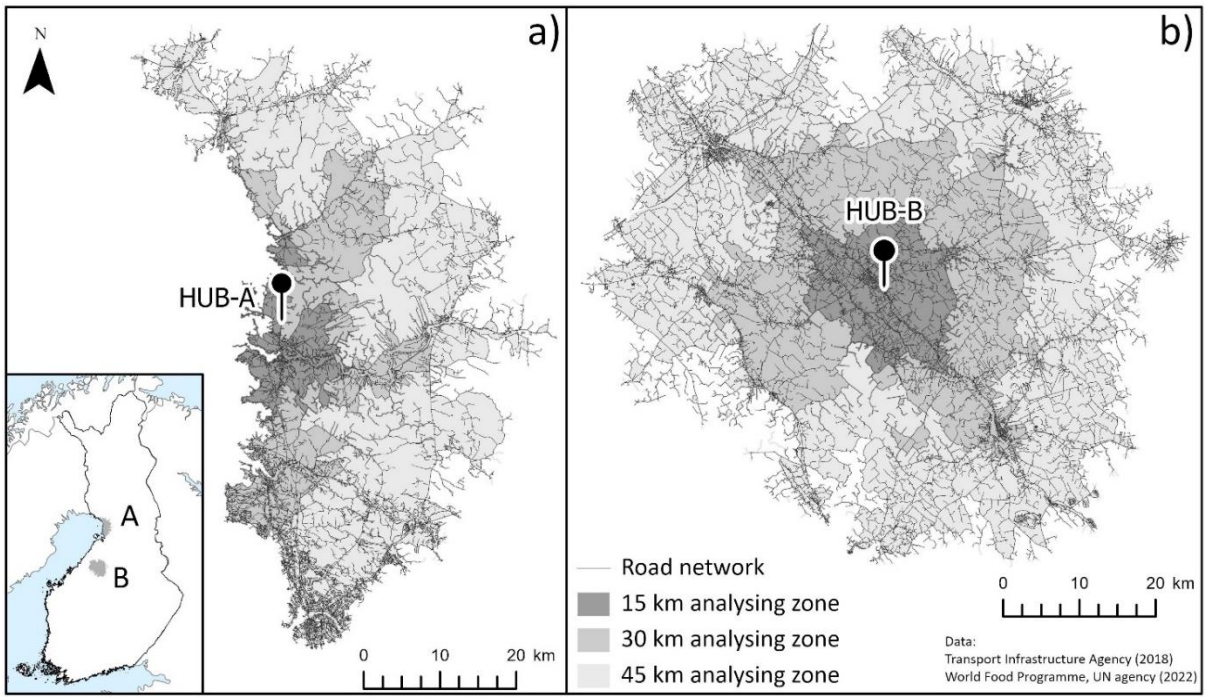


Fig 2. The road network used within the analysis zones of 15, 30, and 45 km in a) the case area A, and b) the case area B in Northern Ostrobothnia, Finland. The zone extents are based on the travel distances on tractor-drivable roads excluding motorways and motor-traffic ways. Source: own elaboration

3.3 Transport accessibility and network analysis framework

Accessibility as a scientific concept is typically defined by a combination of two basic components: the transport cost to certain destinations and the quality or quantity of opportunities reached (see Páez et al., 2012; Rodrigue, 2020). Accessibility can also be defined as the ease of reaching opportunities and can be used to assess the performance of a transport system (Chen et al., 2007), or more specifically, Geurs and Ritsema van Eck (2001, p. 19) express accessibility as "…the extent to which the land-use transport system enables (groups of) individuals or goods to reach activities or destinations by means of a (combination of) transport mode(s)". The analyses in this study used an approach based on the cumulative opportunities index (Kelobonye et al., 2020; Owen & Murphy, 2020; Páez et al., 2012),

which measures access to opportunities within a given transport threshold. Thus, the cumulative opportunity index summarises, for example, the number, value, or volume of opportunities (i.e., the biomass quantity in the field parcels in this study) that are reachable within transport cost-distance thresholds. The study uses the approaches based on back-and-forth transportation and collection routes for cumulated opportunities and also applies kilometres travelled per biomass collected as a measure of cost-effectiveness.

The analyses were implemented in the commercial Esri ArcGIS Pro software (version 2.9.0) and applied the Closest Facility (CF) and Vehicle Routing Problem (VRP) accessibility analysis tools. The CF analysis seeks to identify the nearest service facility to each incident location (Esri, n.d.-a). The CF tool is used to call for the shortest paths within a specified cut-off distance by using a multiple-origin, multiple-destination algorithm based on Dijkstra's algorithm (see, e.g., Javaid, 2013). The VRP analysis tool is designed to optimise routing for a fleet of multiple vehicles serving multiple destinations with different nodal weights (Esri, n.d.-a). More specifically, the VRP analysis results in a solution for a set of routes, each performed by a single vehicle which starts and ends at its own location, fulfilling all pickup requirements and minimising transport costs (Baldacci et al., 2010). The VRP is a superset of the classical travelling salesman problem, which is a combinatorial problem using heuristic algorithms (Esri, n.d.-a).

4. Transport scenarios modelled by Closest Facility and Vehicle Routing Problem

Two transport scenarios were created: 1) the tractor scenarios TRA-A in case area A and TRA-B in case area B; and 2) the truck scenarios TRU-A in case area A and TRU-B in case area B. All the analyses (TRA-A, TRU-A, TRA-B, and TRU-B) were performed on 15, 30, and 45 km zones from the HUBs. The zones are defined by the distance cut-offs for tractor-drivable routes, as the distances along tractor allowed routes (excluding motorways and motor-traffic ways) are longer.

In the tractor scenarios (TRA-A and TRA-B), the grass biomass is only transported (presumably by a local farmer) from those field parcels that yield at least a full trailer of 7 t (based on Lätti et al., 2014, p. 12). The trailer is assumed to have a harvesting mechanism. The vast majority of the biomass accumulating from the marginal field parcels comes from the largest parcels (Niemeläinen et al., 2014), which supports the exclusion of the smallest fields in tractor transport. From some of the largest fields, there are several back-and-forth transports due to the accumulation of multiple full loads, nevertheless, the restriction of only full trailer load transports is considered. The origins were set as the marginal field parcels and the destinations were set as the HUB-A and the HUB-B in case area A and B, respectively. Thus, in the TRA scenarios, the analyses do not consider the distance travelled by a tractor from a farm centre to a field parcel and vice versa from the field parcel to the farm centre on the return trip. Total travel distances were calculated based on the CF-derived shortest path distance between an individual parcel and a HUB and the number of journeys travelled between the parcel and the HUB in order to collect the maximum amount of biomass by means of full trailer loads. The distance travelled per ton collected was calculated based on the total distance travelled and the total number of full trailer loads of 7 t.

In the truck transport scenarios (TRU-A and TRU-B), a combined vehicle truck (composed of a truck bed and a trailer) with a capacity of 22.5 t (based on Lätti et al., 2014, p. 5) was used for routing via all the marginal field parcels. Trucks were set to depart from and return to HUB-A and HUB-B in case A and B, respectively. The harvest is assumed to be carried out with a separate forage harvester. The amount of biomass transported from a single field parcel is massive, and thus the individual parcel points that exceeds the specified truck loading capacity (22.5 t) were multiplied so that each pickup point had the biomass quantity of the maximum capacity. The remaining biomass in the original parcel data that exceeds the maximum transport capacity is collected and transported on a different collection route. Thus, no maximum number of pickup routes was set as the aim was to find the number of routes required to collect all the estimated biomass available within a given zone of analysis. In this way, it was possible to create a VRP analysis model in which multiple pickups were carried out from a single field parcel.

The VRP analyses consider the total time capacity of a route. In this study, the maximum time for each route, i.e., the maximum length of a working day (9 hours) includes four variables: 1) working breaks in

accordance with the Finnish legislation and the collective agreement of the truck transporting trade, resulting in a total travel time of 7.5 hours; 2) 5 minutes for preparatory duties for departure; 3) loading time of 1 minute per ton (Lätti et al., 2014, p. 15); and 4) unloading time of 5 minutes (based on Lätti et al., 2014, p. 15 with a slight increase). For very small parcels, the estimated pickup time may be unrealistically short. For this reason, 10 min were added to the pickup time for each parcel, which is assumed to be used for duties such as turning around the transport equipment and other pickup-related duties.

The total distance travelled in TRUs was calculated based on the number and total distance of the VRP-derived routes. The distance travelled per ton collected was calculated based on the total distance travelled and the total quantity of estimated biomass tons in an analysis zone.

5. Results

The focus of this paper has been to build transport models applying open access field parcel data and GIS-based network analyses to observe the accessibility and logistics of grass biomass transported from marginal agricultural land. The VRP and CF-derived optimised routing results for the TRA-A, TRU-A, TRA-B, and TRU-B transport scenarios in the largest analysis zone of 45 km are shown in Figure 3. The parcels of marginal agricultural land selected for the analyses as well as the variation in the estimated biomass per parcel (i.e., the variation in parcel area), and the spatial distribution within the maximum zones in both case areas, are also presented in Figure 3.

The accessibility metrics defining 1) the number of accessible field parcels; 2) the total area of accessible field parcels; 3) the cumulative distance (with the least distance cost path); 4) the cumulative accumulation of the estimated biomass; and 5) the total travel distance per total biomass collected for each zone of analysis are represented in Tables 1 and 2 for case areas A and B, respectively. In both case areas and all the analysis zones, the number of accessible field parcels represents the parcels accessed within the set distance cut-off of 15, 30, or 45 km modelled by the tractor-drivable routes excluding the motorways and motor-traffic ways. In addition, the restriction of half-empty trailer loads in the TRA scenarios decreases the number of accessible field parcels. In practice, according to the area-based estimation, the field parcels smaller than 0.56 ha yield less than 7 t and are therefore not accessible in the TRA results. Thus, in both case areas and in each analysis zone, the number of accessible field parcels in TRAs is lower than in TRUs.

Tab 1. Comparison of results of cumulative accessibility analyses based on grass biomass in 15, 30, and 45 km zones for tractor (TRA-A) and truck (TRU-A) transport scenarios in case area A. The number of accessible field parcels represents the parcels accessed by the tractor-drivable routes within the set distance cut-off of 15, 30, or 45 km, and the number is smaller in TRAs compared to TRUs as the restriction of half-empty trailer loads excludes parcels smaller than 0.56 ha. Source: own elaboration

	Transport scenarios in 15 km zone		Transport scenarios in 30 km zone		Transport scenarios in 45 km zone	
	TRA-A	TRU-A	TRA-A	TRU-A	TRA-A	TRU-A
The number of accessible field parcels	22	37	118	192	265	433
The total area of accessible field parcels (ha)	50.6	62.3	215.2	241.6	578.7	697.2
The estimated biomass amount collected from accessible parcels (t)	630	776.7	2 317	3 009.8	7 210.0	8 686.5
Total travel distance (km)	1 175.4	568.2	13 985.0	6 362.0	64 856.4	26 082.2
Total travel distance per biomass ton collected ($km \cdot t^{-1}$)	1.9	0.7	6.0	2.1	9.0	3.0

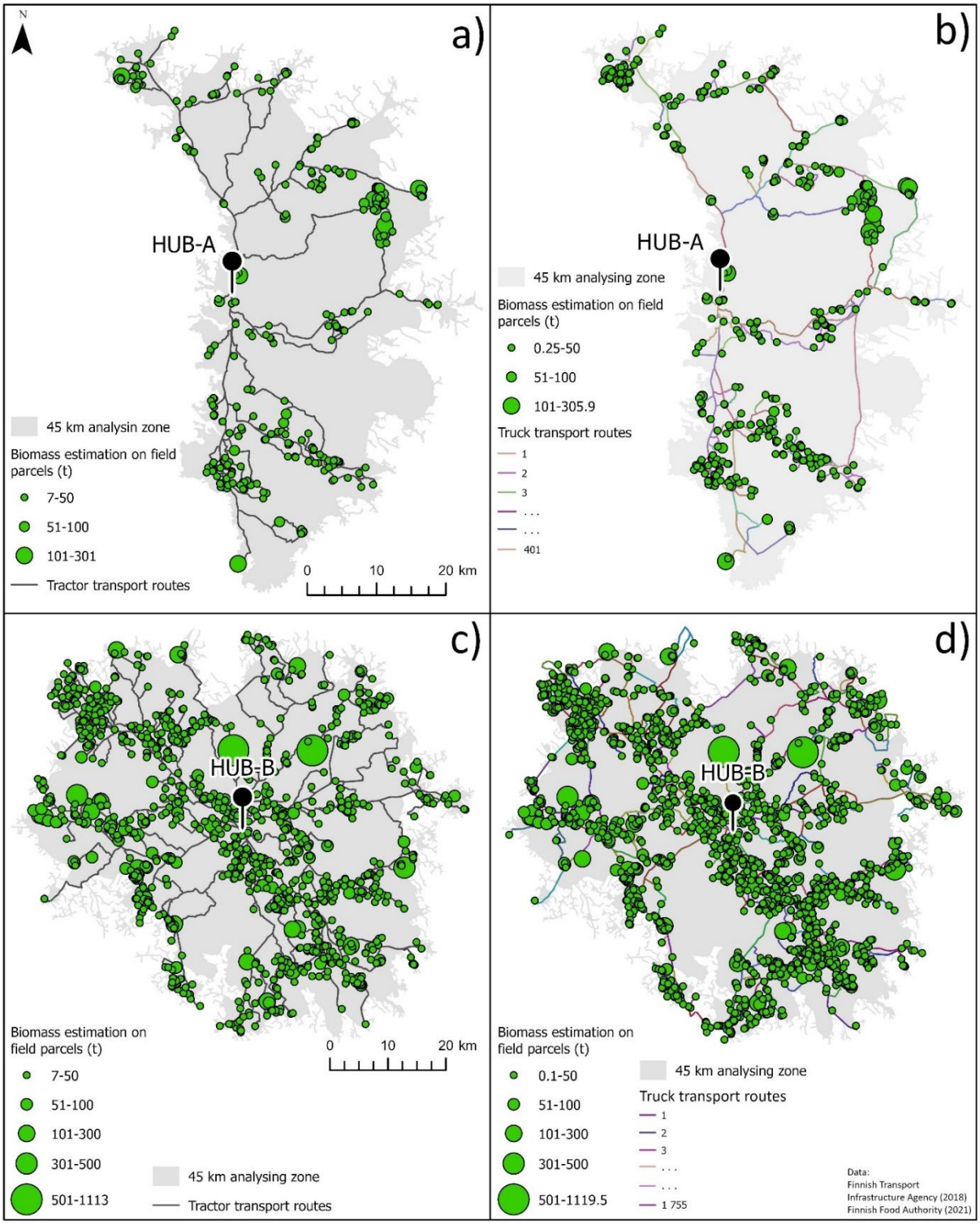


Fig 3. Network model results for a) the tractor transporting routes (n=1 030) from field parcels (n=265) to the biomass collecting location HUB-A within the 45 km analysis zones in case area A; b) the truck transporting routes (n=401) from field parcels (n=433) to the biomass collecting location HUB-A within the 45 km analysis zones in case area A; c) the tractor transporting routes (n=4 351) from field parcels (n=1 212) to the biomass collecting location HUB-B within the 45 km analysis zones in case area B; and d) the truck transporting routes (n=1 755) from field parcels (n=2 057) to the biomass collecting location HUB-B within the 45 km analysis zones in case area B. Each line colour in the maps b) and d) represents an individual trucking route. The biomass estimation is based on the field parcel area of the selected parcels under environmental management. Source: own elaboration

Tab 2. Comparison of results of cumulative accessibility analyses based on grass biomass in 15, 30, and 45 km zones for tractor (TRA-B) and truck (TRU-B) transport scenarios in case area B. The number of accessible field parcels represents the parcels accessed by the tractor-drivable routes within the set distance cut-off of 15, 30, or 45 km, and the number is smaller in TRAs compared to TRUs as the restriction of half-empty trailer loads excludes the parcels smaller than 0.56 ha. Source: own elaboration

	Transport scenarios in 15 km zone		Transport scenarios in 30 km zone		Transport scenarios in 45 km zone	
	TRA-B	TRU-B	TRA-B	TRU-B	TRA-B	TRU-B
The number of accessible field parcels	210	353	645	1044	1212	2057
The total area of accessible field parcels (ha)	374.9	411.9	1 490.9	1 532.4	2 756.5	3 016.4
Estimated biomass amount collected from accessible parcels (t)	3 976.0	5 133.1	15 631.0	19 096.1	30 457.0	37 589.2
Total travel distance (km)	10 564.0	5061.0	88 788.4	38 370.8	244 163.4	104 866.6
Total travel distance per biomass ton collected ($km \cdot t^{-1}$)	2.7	1.0	5.7	2.0	8.0	2.8

Due to the greater number of accessible parcels in TRUs compared to TRAs, the total estimated biomass amount collected – based on the parcel area – is also greater for TRUs than TRAs in each analysis zone. However, the differences in estimated biomass amount between TRUs and TRAs in each analysis zone and in both the case areas do not appear to be as substantial as for total travel distances. That is to say, even though the small field parcels accumulating less than a full trailer were excluded in the TRAs, the total back-and-forth distances travelled in the TRAs were substantially longer for each analysis zone in both case areas. Moreover, as the TRA scenarios do not consider the distance travelled from a farm centre to a field parcel and vice versa from the parcel to the farm centre on the return trip, the calculated total distances travelled in TRAs are underestimations. Therefore, the actual difference between total distances in TRAs and TRUs in different analysis zones is likely to be even greater in reality.

The values for the total distance travelled per ton of biomass collected vary between 0.7 and 9.0 $km \cdot t^{-1}$. Further, the lowest values in both the case areas are in the 15 km zone by trucking transport (TRUs), 0.7 $km \cdot t^{-1}$ and 1.0 $km \cdot t^{-1}$ in the case A and B, respectively. Overall, in each comparable zone in both the case areas, fewer kilometres accumulated per biomass ton collected in TRUs than in TRAs. Furthermore, the smallest difference between TRA and TRU appears in the 15 km zone in both case areas.

Regarding the TRU models as more feasible modes of transport, if the estimated biomass amount is observed as a percentage of the biomass tons reached in each zone in relation to the total biomass within the 45 km zones of the whole research areas, only minor portions exist in the smallest 15 km zones, 8.9% and 13.7% in the cases A and B, respectively. In the 30 km analysis zones, the corresponding shares are 34.6% and 50.8%. Therefore, the major portion of estimated biomass is not reached until considering the largest analysis zone of 45 km, i.e., outside the 30 km zone, with values of 65.4% and 49.2% for TRU- A and TRU-B, respectively. However, the number of kilometres travelled per biomass ton reached increases as the extent of analysis zone and the total amount of biomass accumulated increase.

Overall, as the coastal case area A represents the case of scarce residual biomass flows, the number of accessible field parcels, the total area of accessible field parcels, and the estimated amount of biomass collected are greater in case area B than A in each analysis zone. Regardless of this considerable difference in the biomass flow quantities between the case areas, a similar pattern can be seen in the parameter of total travelled distance per biomass ton collected. The values are lowest in the 15 km analysis zones, and they increase with expanding zones in both the case areas. It is also noteworthy that the values are remarkably similar for comparable transport modes and comparable analysis zones between the case areas. For example, when taking a closer look at the TRUs, the distances per biomass ton are 0.7 $km \cdot t^{-1}$ in case A and 1.0 $km \cdot t^{-1}$in case B in the 15 km zone; 2.1 $km \cdot t^{-1}$ in case A and 2.0 $km \cdot t^{-1}$ in case B in in the 30 km zone; and 3.0 $km \cdot t^{-1}$ in case A and 2.8 $km \cdot t^{-1}$ in case B, in the 45 km zone. Thus, between the case areas of A with scarce and B with dense biomass flows, the difference is only 0.3 $km \cdot t^{-1}$, 0.1 $km \cdot t^{-1}$, and 0.2 $km \cdot t^{-1}$

in the analysis zones of 15, 30, and 45 km, respectively. It can be concluded that, for example, in the 30 km analysis zone, a nearly equal travel cost (with the difference of 0.1 km·t^{-1}) is realised even though the amount of accessible biomass differs notably between TRU-A (3 009.8 t) and the TRU-B (19 096.1 t).

6. Discussion

6.1 Network-based modelling in the context of field-based biomass transportation

In this study, the GIS-based network analysing tools of VRP and CF were tested in the building of optimised transport models for grass biomass from marginal agricultural land. Two transport scenarios in two different case areas with three zones of analysis (15, 30, and 45 km) were modelled and compared in terms of distance travelled per biomass ton collected. In both case areas and in each analysis zone, it proved to be more feasible to transport the biomass by pickup transportation with a larger truck fleet routing via a large number of fields (TRU scenarios) than by individual back-and-forth tractor transports only from large-area fields accumulating full trailers (TRA scenarios). Although the major proportion of estimated biomass in both case areas is reached in the largest analysis zone of 45 km, the kilometres travelled per biomass ton reached increases as the analysis zone extent and the total amount of biomass accumulated increases.

In light of the results, it is not only the amount of accessible field parcel area or the derived estimated amount of biomass within a defined spatial extent that determines the profitability of field-based biomass utilisation. In other words, regardless of the quantity of accessible field parcel area or the area-based biomass estimate, the travel cost, i.e., the distance travelled for each biomass quantity collected, can turn out to be remarkably similar within different analysing extents or in different areas. It can therefore be concluded that not only the amount of accessible field parcel area and the spatial distribution of the parcels affect the total kilometres per accumulated biomass ton, but also the spatial coverage of the local road network, and further the locations of the parcels in relation to the road network.

In the sense of the monetary cost of transportation, the distance-based travel cost – framed in this study as the total travel distance per biomass ton collected – can be used to estimate the kilometre-based monetary transport cost. In other words, it is a simple parameter to indicate the efficiency and the precedence of different transporting options at different spatial scales. Therefore, as the monetary cost of transportation is a key profitability constraint in marginal biomass utilisation (Gunnarsson et al., 2008; Niemeläinen, 2022), the key finding of this study is that not only the field parcel area and accumulating biomass amount within an observed region determine the feasibility of biomass utilisation, but also the routing possibilities enabled by the local road network remarkably affect profitability.

However, it is essential to bear in mind that not only the distance-based travel cost affects the feasibility of biomass utilisation, but also the absolute amount of biomass that accumulates in relation to the demand for a particular type of biomass usage. Thus, the resulting absolute quantity of the estimated biomass can be further discussed in relation to the refining possibilities of certain biomass quantities. For example, in the truck transport analyses in this study, the estimated total amount of biomass increases substantially as the zone of analysis expands, for both the case areas, yet the resulting kilometres accumulated per biomass ton do not appear to increase substantially. Therefore, the resulting accumulated kilometres per biomass ton and the absolute estimated total biomass in different analysis zones should be observed simultaneously in relation to the possible local demand for biomass. For example, according to Kotavaara et al. (2022, p. 11) in the region of Northern Ostrobothnia, there are biogas reactors with a total annual feedstock input capacity varying between 14 000–130 000 tons, and in part of the reactors, grass biomass is being used in the feedstock mixture.

Besides the accessibility metrics, conclusions were drawn on the use of the CF and VRP network analysis tools. The pre-editing work of the original open access field parcel data for biomass estimation is effective. So is the calculation of the model of back-and-forth distances between field parcels and the HUBs derived from the CF model and further the total distance travelled per biomass ton collected. However, the VRP data pre-editing requires more iterative editing as the individual parcel points that exceed the defined loading capacity in TRU scenarios need to be multiplied so that each pickup point has a biomass quantity

equal to the maximum transport capacity, at most. The VRP method has been developed for delivery or pickup sets of multiple orders, i.e., stops, (Esri, n.d.-a), and is thus more feasible for low-volume pickup freight, allowing routing via a large number of pickup stops. According to this study, the VRP tool can be applied for analysing truck pickup routing for a large volume of freight against the transport capacity, but as the data preparation and iterative analyses require laborious pre-editing, automated workflow management is required for larger studies.

In addition, the GIS-based VRP model is capable of increasing the accuracy of transport optimisation in terms of location and travel distance (cf., Gunnarsson et al., 2008), particularly when the number of deliveries included in the analysis is high. However, the VRP model created in this study has shortcomings, and the transport scenarios involve assumptions and uncertainties. Firstly, although the trucks in the TRU- A and TRU-B were set to route via all the marginal field parcels, in practice it can be challenging for a truck to enter and drive on the smallest and most inconveniently shaped fields. In addition, the VRP solver is not designed to account for the use of the same vehicle across workday shifts in a single routing solution, or for driver changes within a workday (Esri, n.d.-b). Therefore, the routes calculated (representing the traversal between the HUB locations and the marginal field parcels) may represent temporally sequential, partially overlapping transports. The number of vehicles is therefore assumed to be unlimited.

6.2 Further development for the modelling approach

Overall, this study applies specifically to transportation part in the context of the entire machinery use chain in grass biomass exploitation. However, it should be noted that a matching harvest and transport capacity is essential in minimising the time required for harvesting and the resulting costs (Gunnarsson et al., 2008). More specifically, this study excludes the capacity of all operations as a whole in the machinery chain (harvesting including mowing, chopping, and/or collection, transport, and storage). In other words, the VRP model does not consider both the time and machinery quantity capacities in each (partly simultaneous) phase of the chain, nor the timing of mowing. For example, if the total biomass amount for one transport load on a TRU route is harvested from several small parcels (requiring several stops), it may take more time for the forage harvester to move from one parcel to another than it does for the truck.

In addition to the analysis approach used in this research, there are further possibilities. For example, the different transport scenarios and resulting routing solutions could be compared with a wider range of accessibility metrics such as a precise monetary cost or carbon dioxide (CO^2) emissions. The monetary cost could be applied by a fixed hourl- based transport vehicle cost or by a more precise cost model including several detailed vehicle cost factors (see, e.g., Tepponen et al., 2020).

In addition, as mentioned previously for the TRA scenarios, the analyses do not consider the distance travelled by tractors from the farm centres to the fields and vice versa from the field parcel to the farm centre on the return trip. Furthermore, in reality, the least distance cost path from a HUB to a farm centre is likely to be a 'straight' path from a HUB to a farm centre, rather than the HUB-parcel-farm centre path assumed in the TRA model in this study.

It should also be borne in mind, that the area-based fresh yield biomass amount is only an estimation, and the actual amount can vary greatly between field parcels (Niemeläinen et al., 2014, p. 24). Overall, the biomass yield can vary significantly across locations and is strongly influenced by land characteristics: latitude, temperature, plant species, soil fertility, and harvest management. Yield can also vary from year to year depending on growing conditions. Thus, as the biomass productivity can vary between different types of land use on marginal land, actual biomass quantities could be more accurately assessed.

In addition, for both transport methods (TRAs and TRUs), the loading capacity of the biomass are estimates as the capacity depends on the characteristics of the biomass and the trailer mechanisms (Lätti et al., 2014, p. 11). The density of the chopped material depends not only on the dry matter content, but also on the composition of different types of grass, and the length of the cut material (Gunnarsson et al., 2008). It should also be noted that, in reality, mechanical mowing and harvesting may not be possible in

all areas due to challenging geomorphological characteristics of the field parcels. However, as the main purpose of this paper is to discuss the methodological solutions for vehicle routing, the uncertainties in the biomass quantity and transport capacity assumptions are of minor importance.

6.3 Replicability of the research frame and applicability of the open access field parcel data

In the research context of biomass utilisation on marginal agricultural land, this research contributes as an example of a replicable and scalable logistical analysing concept for which there has been prior demand (Scordia & Cosentino, 2019). The research frame presented and GIS-based modelling carried out in this study are replicable and easily applicable to other regions or specific circular economy cases. Further, according to this study, the open access spatial data on agricultural land use – enabled by the INSPIRE Directive of the EU – and on the road network, are well adapted for the analysis of logistical solutions. As the agricultural field parcel data is available at least in Finland, France, The Netherlands, Spain, and Estonia (European Commission-Joint Research Center, 2022), there are opportunities to apply the analyses in numerous local and regional areas. Also, there are other open digital road network models available in addition to Digiroad, such as the globally available Open Street Map, which has excellent availability but some limitations in the topological quality needed for routing (Sehra et al., 2016) and NASA gROADS, which is globally available but has limited local roads data (Center for International Earth Science Information Network (CIESIN), 2013). Regarding the open access field parcel spatial data and the context of marginal agricultural land, the national procedure for field parcel classification needs to be assessed in order to identify the relevant marginal land classes.

In addition, some shortcomings revealed in this study – based on the Finnish national open access data – need to be considered. Firstly, the data does not include ownership and lease information of the field parcels (due to personal data security). Thus, the transports in TRAs are done only from the fields yielding at least full loads, even though in reality a single farmer may have several small parcels in close proximity making up a profitable full trailer, but this cannot be considered due to data inadequacy. Secondly, the data does not include attributes specifying whether the field parcel has been used for livestock grazing, or for collecting forage or bedding for livestock. Therefore, in reality, part of the biomass on analysed fields might be under exploitation (Kokko, 2022; ProAgria Oulu, 2018). Hence, the analyses implemented indicate a need for improvements in the extent of field parcel data attributes to identify the actual amount of available biomass with no prior form of exploitation. In addition, the coverage of open access field parcel data within the EU member states could be further extended for wider use in local, regional, and national assessments.

Despite the limitations, the open farm field data enable analysing accessibility and optimise logistics for numerous other agricultural land-related residues and side streams. For example, in the context of circular agriculture, the accessibility of the massive quantity residue of crop straw could be analysed for several production purposes, such as biochar (see, e.g., Chen et al., 2022). However, the open access data does not include information on whether the straw has been used for, e.g., as livestock bedding, and the usage rate might vary substantially when the agricultural production sectors of crop and livestock are greatly centralised (e.g., as in Finland, see Koppelmäki et al., 2021a). Therefore, the data attribute drawback in actual exploitation volume would weaken the analysis accuracy. Another field-based residue for network-based accessibility and logistical analysis could be the yet unexploited residual biomasses in vegetable production (Franke et al., 2016; Lehto et al., 2018; Pahkala et al., 2009).

As a conclusion, the same kinds of limitations are associated with several field-based residues and side streams in the open access field parcel data. Thus, as a development suggestion, such information on whether a field-based residue in question has been utilised or not could be collected for statistical data production through the LPIS. In Finland, field parcel-specific notes (about, e.g., yields, cultivation measures, and soil nutrient contents) collected on farms are proposed to be systematically assembled in a digital data resource (Valve et al., 2022). Apart from other benefits, such digitalised record-keeping including notes on the use of residues, would enhance the utilisation of residual biomasses available. In that way, the local and regional circular economy, as well as cooperation between agricultural and other businesses, could be supported and enhanced.

6.4 Sustainable circular use of marginal grass biomass

Even though the more efficient logistics sought in this study is intended to increase the utilisation rate of residual biomass from the perspective of circularity – even with low biomass productivity typical in marginal areas – other environmental boundaries should also be considered. For example, Koppelmäki et al. (2021b) excluded fields under the field class of fallow when observing marginal field biomass utilisation in biogas production due to the significant farmland biodiversity on such lands (Toivonen et al., 2015). Accordingly, Niemeläinen et al. (2014) suggested allocating the smallest marginal parcels for biodiversity enhancement and exploiting the biomass only from larger parcels. Moreover, Niemeläinen et al. (2014) concluded that in Finland, the majority of grass biomass on marginal agricultural land under environmental management is accumulated from the largest parcels. According to this study, the same observation can be seen as the difference in the accumulated biomass amount between TRUs and TRAs does not seem substantial. Therefore, even if using large-capacity truck transport routing to gather biomass from several field parcels, it would be reasonable to leave the smallest and most inconveniently shaped parcels out of biomass collecting. However, regarding biodiversity, the field class is not the only influencing character as also the landscape structure, such as surrounding forest versus open landscape, affects biodiversity (Toivonen et al., 2015).

Furthermore, some of the field parcels under the agri-environmental contract area (see Appendix A) can be classified as semi-natural grasslands (Raatikainen et al., 2017), referring to agricultural land under long-term extensive ruminant grazing or mowing without added fertilisers or other inputs. Utilising such lands in extensive livestock grazing can support sustainable livestock production by minimising arable land occupation, reducing nutrient losses, increasing carbon storage, and maintaining biodiversity (see, e.g., Torres-Miralles et al., 2022). In addition, some of the field parcels, for instance, in coastal areas (see the close proximity in Figure 2a), might be more suitable for grazing than machine mowing. The frequency of harvest can also be advanced to support the local environment (Carlsson et al., 2017).

Therefore, although a wide range of marginal agricultural lands were selected for the analysis in this study, more specific assessment on biomass harvesting from different kinds of lands is needed. Afterall, it is difficult to generalise only one type of management for several different kinds of marginal lands. All in all, when biomass exploitation is integrated into circular and sustainable agriculture, biomass use practices (i.e., grazing versus biomass harvesting) need to be assessed at the whole system level, in the local or regional context.

7. Conclusions

According to this study, the INSPIRE open access spatial data on agricultural land use, integrated with road network data, is well adapted for the analysis of accessibility and logistical solutions. Further, as the results reveal that the spatial data of field parcels alone is not sufficient in assessing the optimality and cost-efficiency of biomass utilisation, it can be concluded that the network-based analysis is a remarkable method, as it connects the spatial data of field parcels and road networks. This enables accurate accessibility models and precise comparison in seeking the most profitable logistical outcome. Specifically, GIS-based network analysing methods are considerably useful when modelling and seeking the optimised and most profitable logistical alternatives in the context of optimised maximum spatial extent (i.e., collecting zone as in this study) for transport routing, and optimised collecting locations in relation to the accumulating field parcel area in the surrounding area.

In addition to the context of marginal agricultural land grass biomass, the network-based accessibility analyses and logistical transport models demonstrated in this study could be used for numerous agricultural field-based residues and side streams in enhancing circular economy and the production of energy and high-added value products. Furthermore, the analyses produce information for estimating options among methods of transportation, and thus serve as valuable information also for transportation service providers. The accessibility metrics analysed in this study are useful in planning for local collecting and production facilities to enhance agricultural land-based circularity. The network-based accessibility results can introduce opportunities for co-operating with regional and local enterprises within

the processing industry and agriculture, as well as local and regional initiatives that elaborate functional and spatial practices to promote circular economy. However, the practical functioning of the transport scenarios used for the logistical model could be discussed with specialists in agriculture, logistics, and biorefinery engineering, and further developed for certain actual cases.

Acknowledgements

The study was carried out in the project "Growth from the circulation with green techniques (KASKI)", which is funded by the European Regional Development Fund (ERDF) for the period 1.6.2021–31.10.2023.

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Appendix A

*Tab 1. The marginal agricultural land classes based on the agricultural covering of soil (i.e., environmental management areas related to agricultural support schemes) used in this research (*Finnish Food Authority*, 2018;* Finnish Food Authority*, 2022a).*

Marginal agricultural land class
Biodiversity field (landscape)
Biodiversity field (meadow 1st and 2nd year)
Buffer zone (agri-environmental contract from 2015)
Environmental contract area (other area)
Environmental contract area (permanent grassland)
Green fallow (grassland and meadow)
Green manure grassland
Natural field (grassland, min. 2 years)
Natural pasture and meadow
Open fallow
Perennial environmental grassland
Permanent uncultivated field