REEEM

D5.4

Ecosystem services

CASE STUDY REPORT

January 2018

About this report

Within the framework of the REEEM project, this report constitutes deliverable D5.4 Ecosystem Services case study report. This case study of Lithuania was led by the Environmental Management and Assessment (EMA) research group, KTH Royal Institute of Technology, in cooperation with contributors from several institutions, listed below. The case study was included in REEEM Work Package 5 on Environment, Health and Resources, where multiple sustainability goals are addressed for gaining a comprehensive understanding of the system-wide implications of decarbonisation pathways. The case study of Lithuania intended to assess impacts on multiple ecosystem services of forest bioenergy options, as well as to take the first steps for model linking between an ecosystem service assessment tool, and an energy sector development model. In this way, the links between energy assessment and ecosystem services could be strengthened in a more integrated assessment, targeting to increase the sustainability of forest bioenergy strategies.

Authors

Authors: Xi Pang (KTH Royal Institute of Technology) and Ulla Mörtberg (KTH Royal Institute of Technology)

Other contributors: Vidas Lekavicius (Lithuanian Energy Institute), Arvydas Galinis (Lithuanian Energy Institute), Renats Trubins (Swedish University of Agricultural Sciences), Gintautas Mozgeris (Aleksandras Stulginskis University) and Gintaras Kulbokas (Aleksandras Stulginskis University and Lithuanian State Forest Service)

Reviewer: Ilkka Keppo (University College London)

REEEM partners

About REEEM

REEEM aims to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU energy society. This project is developed to address four main objectives: (1) to develop an integrated assessment framework (2) to define pathways towards a low-carbon society and assess their potential implications (3) to bridge the science-policy gap through a clear communication using decision support tools and (4) to ensure transparency in the process.

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Contents

Contents

Summary

Forests are important for climate change mitigation by providing bioenergy feedstock to substitute fossil fuels, as well as for carbon storage, while they are also important for other ecosystem services. The REEEM project targets to gain a comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU society. The current REEEM case study of Lithuania aims to i) analyse the forest biomass potential for Lithuania using the LEcA tool, assessing impacts on ecosystem services of alternative forest management strategies, and compare to energy pathways including forest bioenergy feedstock as a RES; and ii) develop and discuss linking between the energy assessment model that project the energy pathways, in this case the MESSAGE model, and the LEcA tool to enable iterations and information exchange.

Two alternative pathways were run with the MESSAGE model of the use of forest bioenergy feedstock in the development of the Lithuanian energy sector, Biomass Low and Biomass High. This initiated the simulation of forest growth and management of Lithuania with the LEcA tool for 2015-2050 and beyond, applying a Business-As-Usual (BAU) forest management strategy. Based on these results, a second, more intensive (INT) forest management strategy was developed and applied in order to increase the yields. From the output of the simulations of both strategies, the development of five ecosystem services was assessed: forest bioenergy feedstock, industrial wood, carbon storage in the forest, recreation area and habitat supporting biodiversity. For bioenergy feedstock, environmental restrictions and transport distances for harvest residues were considered. In addition, different assumptions about the use of forest compartments for bioenergy purposes were tested.

The estimations of bioenergy feedstock were comparable with the empirical data. However concerning logging residues, the transport distances affecting economy and climate impacts need more considerations, as those may become more pronounced in the future. It could also be concluded that the assumptions concerning the allocation of different forest compartments as bioenergy feedstock would highly influence the results. In the comparison with energy pathways, though, assumptions based on empirical data came much closer than assumptions following forestry manuals. When comparing results with the energy pathways, it was still difficult to estimate with any precision the bioenergy feedstock availability. Looking at the overall situation applying allocation assumptions based on empirical data, the results indicated that during the period up to around 2040 supply and demand may not be so far apart from each other with Strategy BAU, and the supply exceeded the demand with Strategy INT. However, closer to year 2050 when the energy pathways projected a much higher use of forest biomass, it may be more difficult to meet the demands with either of the forest management strategies.

With Strategy INT, the overall yield was around 10% higher than with Strategy BAU, with the highest yields in the beginning of the period. However, the yields were not timing well with the energy pathways, since the major increase would be needed after around year 2040. Still, these results served to illustrate that when increasing the yields above a certain threshold, the resources may be exhausted in the long run. As well, comparing strategies BAU and INT, it could be shown that there are trade-offs to be expected between bioenergy feedstock and industrial wood on the one hand, and carbon storage, recreation and habitat supporting biodiversity on the other hand.

The LEcA tool can simulate forest growth and management with modest data requirements, which allows for exploring forest management strategies across the whole landscape. The GIS-based approach to the bioenergy feedstock problem, using data that in this context has a high geographical resolution, gives more detailed and localised information than what would be possible in more lumped approaches. The possibilities to spatially allocate and as well aggregate spatially explicit information makes the LEcA tool suitable for flexible model linking. Not only impacts can be assessed, but for instance constraints can be formulated for the assessed

ecosystem services, so that they should not go below a certain value in any time period, which could also be fed back to the energy model.

For linking between the energy model and the LEcA tool, the first steps of information exchange were recognized and tested. The energy pathways created by the MESSAGE model initiated the forest management strategy BAU, from which the results concerning bioenergy feedstock yield was fed back and compared with the pathways. From this comparison, the second forest management strategy INT was developed, targeting higher yields. In future work these first steps will be further developed, preparing for full linkage between models. The results from the ecosystem service assessment will be fed back to the energy model for informed adjustments concerning a sustainable production of forest bioenergy feedstock. In this way, the links between energy assessment and ecosystem services could be strengthened in a more integrated assessment, targeting to inform energy policy and to increase the sustainability of forest bioenergy options.

Keywords

Forest bioenergy feedstock, Ecosystem services assessment, Environmental restrictions, Transport restrictions, Sustainability assessment model linking

Introduction

Forests play an important role for climate change mitigation by providing bioenergy feedstock to substitute fossil fuels, as well as for carbon storage, while they are also important for other ecosystem services. The United Nations Sustainable Development (SDG) Goal 7, Affordable and Clean Energy, aims to ensure access to affordable, reliable, sustainable and modern energy for all, and to substantially increase the share of renewable energy in the global energy mix. Still, the other United Nations Sustainable Development Goals need to be reached simultaneously, such as SDG Goal 13 Climate Action and Goal 15 Life on Land, which is why an integrated approach to sustainability is called for. Ecosystem services are the benefits people obtain from ecosystems (Millennium Ecosystem Assessment, 2005). These include *provisioning services* such as food, water, timber, and fiber; *regulating services* that affect climate, floods, disease, waste, and water quality; *cultural services* that provide recreational, aesthetic, and spiritual benefits; and *supporting services* such as soil formation, photosynthesis, and nutrient cycling. In this study, we analysed industrial wood production and bioenergy feedstock, as provisioning services; carbon storage as a regulating service that affects climate change; forest recreation evaluation as cultural service; and habitat indicators of essential biodiversity components.

To limit the increase in temperature to well below 2 degrees Celsius according to the Paris Agreement (UNFCCC, 2015), emissions of greenhouse gases worldwide need to be halved by 2050 and to be close to zero by 2100 (IPCC, 2014). Renewable energy would need to overtake fossil fuels as the largest source for energy supply and becoming the core to achieving the world's climate objectives (IEA/OECD, 2016). But there are challenges, since increasing use of renewable energy sources (RES) such as forest bioenergy feedstock also means potential conflicts with other environmental goals. This may impact on their sustainability, which is one of the three overarching policy challenges mentioned in SET-Plan Roadmap (EC, 2007).

On EU level, to combat climate change, the EU Renewable Energy Directive (2009/28/EC) aims to promote RES and to reduce greenhouse gas emissions in a sustainable way, ensuring that negative effects on ecosystem services are avoided (EC, 2001, 2010). Thus, it is essential to integrate multiple ecosystem services in assessments of policies and plans for increasing use of forest biomass as a RES. However, energy policy assessments seldom take landscape-level ecosystem services into account (Pang et al., 2014). Therefore, development of methods and tools for sustainability assessment of renewable energy options is needed, that can link energy models with ecosystem services assessment tools for integrated analyses. This will allow for balancing various ecosystem services and analysing implications of forest bioenergy options. One such tool is the Landscape simulation and Ecological Assessment (LEcA) tool (Pang et al., 2017b) where several ecosystem services can be assessed together, including a sustainable production of forest bioenergy feedstock.

Aim

The REEEM project targets to gain a comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU society. The REEEM case study of Lithuania aims to i) analyse the forest biomass potential for Lithuania using the LEcA tool, assessing impacts on ecosystem services of alternative forest management strategies, and compare to energy pathways including forest bioenergy feedstock as a RES; and ii) develop and discuss linking between the energy assessment model that project the energy pathways, in this case the MESSAGE model, and the LEcA tool to enable iterations and information exchange. This will enable the integration of relevant ecosystem services, including a sustainable production of forest bioenergy feedstock, in sustainability assessment of energy policy and related forest bioenergy options.

Methodology

Study area

The study area was the country of Lithuania (Figure 1), where around 33.5 % is covered by forest. Forest bioenergy currently accounts for 65.6% of the primary domestic energy resources in Lithuania, while 16.9% of the gross inland consumption (Statistics Lithuania, 2017). Forest biomass consumption for energy purposes has increased considerably in the Lithuanian energy sector. During 2000-2015 forest bioenergy feedstock extraction almost doubled, from 653.1 ktoe in 2000 to 1191.6 ktoe in 2015 (Statistics Lithuania, 2017). This growth was mainly associated with biomass consumption in the industry sector and for transformation to district heating and electricity in the energy sector. Forest bioenergy feedstock is seen as having a high potential to remain one of the most important local renewable energy resources in the future.

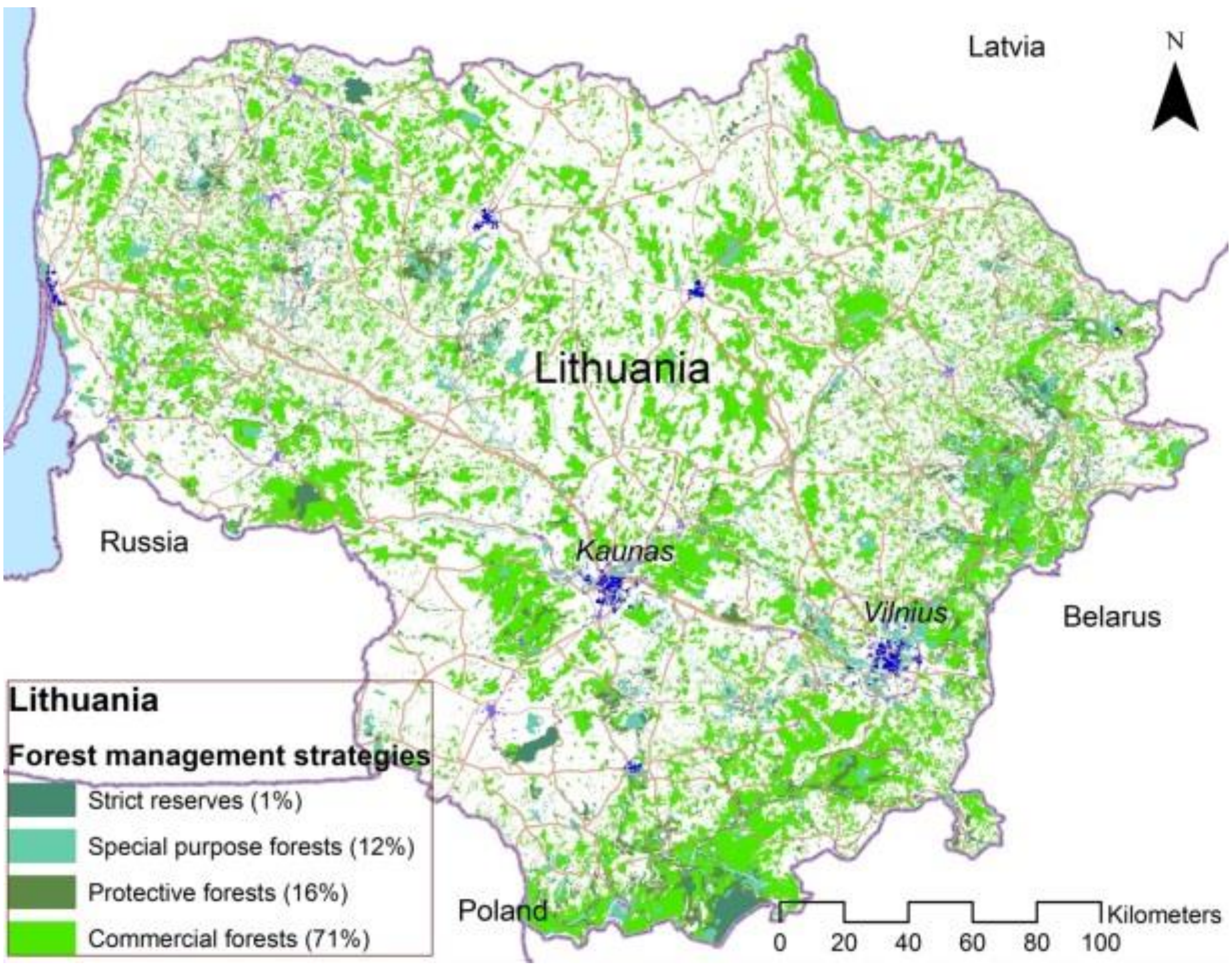

Figure 1. The study area of Lithuania, illustrating different forest management strategies that are applied in the country, see text for explanation. Coordinate system LKS_1994_Lithuania_TM, spatial data State Forest Survey Service (2016).

Within the Lithuanian forest, the dominating tree species are pine (33.2%), birch (21.1%) and spruce (19.7%) (State Forest Service, 2016). From a forest management point of view, major transformations took place after the restoration of independence in 1991, including the adoption of a new edition 2001 of the Forest Law of the Republic of Lithuania (Lietuvos Respublikos Seimas, 1994), with the strengthening of a forest management approach related to forest groups (Kuliešis et al., 2016). This is based on four functional forest groups, turning towards market economy, modernization of forestry technologies, and liberalization of international trade and acceptance of international environmental standards. The forest management strategies related to the four forest groups embrace *strict reserves*, where no active forest management is applied; *special purpose forests*, dedicated to encompass ecosystem protection and recreational use, with severe forest management restrictions; *protective forests* that are aimed at protection of soil or water, with some additional management restrictions compared to commercial forests; and *commercial forests* where timber production is prioritized (State Forest Service, 2010) (Figure 1).

The LEcA tool

The LEcA tool was constructed for integrated assessment of forest ecosystem services (Pang et al., 2017b), and consists of three modules embedded in a GIS framework (Figure 2). These modules are (i) the LandSim model that simulate forest growth and management; (ii) the storage and yield estimator, that uses the spatially distributed output from LandSim to aggregate and estimate the storage of carbon and the yield of industrial wood (sawlogs and pulpwood) and bioenergy feedstock; and (iii) the habitat assessment tool, used for localising and quantifying habitat with high value for forest biodiversity as well as for recreation. Input data for the modelling was the Lithuanian State forest cadastre (State Forest Survey Service, 2016) and land use data (GIS-Centras, 2017). The LandSim model was built in MatLab (Mathworks, 2015) and other spatial and non-spatial modelling was peformed in ArcGIS ModelBuilder (ESRI, 2011). The links between the modules of the LEcA tool are shown in Figure 2 and described in Pang et al. (2017b). Figure 2 also shows the links between the LEcA tool and the energy model MESSAGE (IAEA, 2007), which were developed and discussed in the current case study. Finally, as illustrated in Figure 2, insights from the integrated sustainability assessment can inform energy policy.

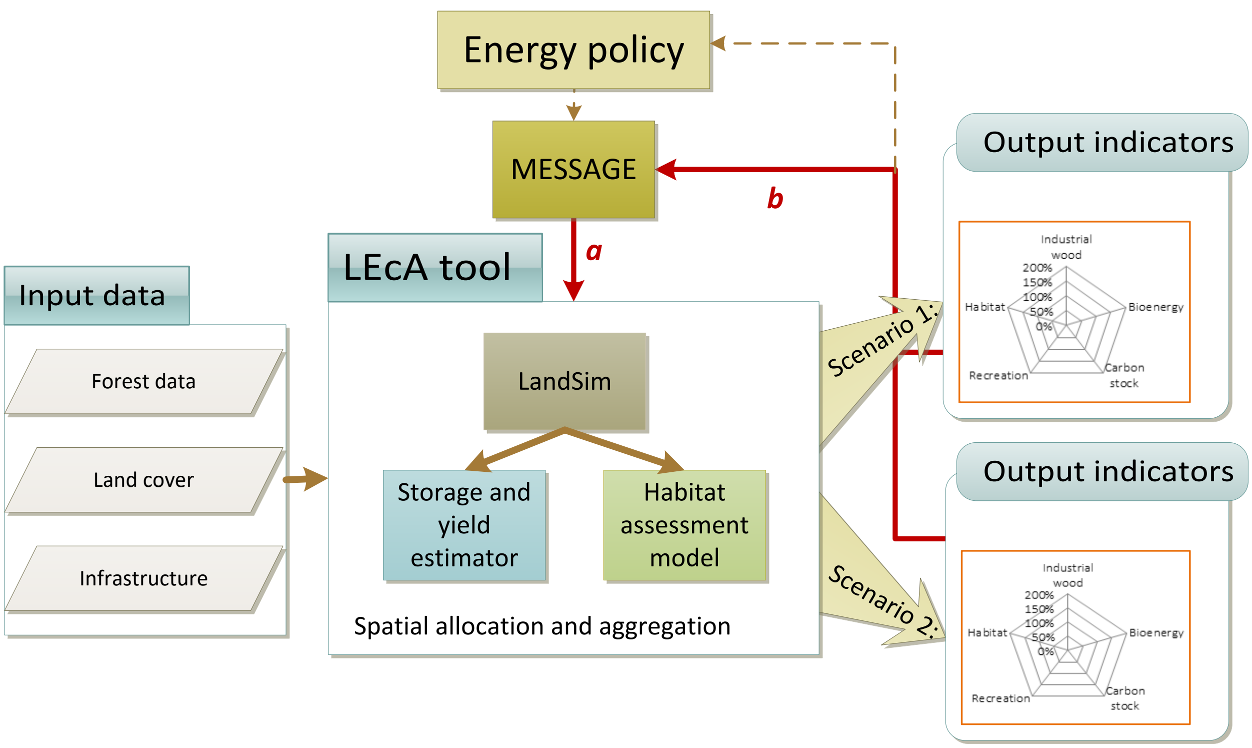

Figure 2. Overview of the LEcA tool (adapted after Pang et al. 2017b). The LEcA tool includes the landscape simulator LandSim, the storage and yield calculator, and the habitat assessment tool. The ecosystem services can be assessed together. The red lines ***a*** and ***b*** are links under development and discussion, where results can be fed back to the MESSAGE model and in the next step again influence LEcA. Eventually, the insights can inform energy policy.

Energy pathways using the MESSAGE model

A bottom up energy system model created in the MESSAGE (IAEA, 2007) environment was run to estimate the cost optimal forest biomass use for bioenergy purposes in Lithuania, in the two pathways Biomass Low and Biomass High. Both pathways represented the possible Lithuanian energy sector development which correlates well with the current European Union energy policy. The Biomass Low pathway was originally derived from the analyses that were performed in the process of preparation of the Lithuanian National Energy Strategy (Galinis, 2015), while the Biomass High pathway was derived by slightly modifying Biomass Low in order to express a more intensive utilisation of forest bioenergy for the current case study.

The pathways were based on not only the price and availability of biomass but also on requirements for the share of RES in the final energy demand. The differences between the pathways lied in the wood biomass price projections and in the assumed wood biomass availability for energy feedstock production purposes. The differences in assumptions were several. In the Biomass Low pathway, the consumption of wood chips and wood waste was bounded according to assumptions about their availability in the domestic market (Galinis, 2015). In the Biomass High pathway, it was allowed to import these products or to produce them locally if there would be enough wood. In addition, in the Biomass High pathway the price of wood chips and wood waste was considerably cheaper than in the Biomass Low pathway. In the Biomass High pathway the wood biomass prices corresponded to the current price level in Lithuania, which is in a range of 115-127 Euro/toe (2.75-3.03 Euro/GJ) depending on wood biomass type. In the Biomass Low pathway, the total wood biomass availability for centralized energy production purposes was constrained by 31.1 PJ (8638 GWh).

Both pathways reflected the country's energy policy, which is oriented towards the widest possible integration into the international energy markets and the optimal use of the country’s energy infrastructure. The GDP growth rate was expected to be 3.5% until 2030, and 2.6% after 2030 (3.0% on average over the period from 2014 to 2050). The electricity demand during the period until 2050 was expected to grow on average by 1.7% annually (2.0% per year until 2030 and 1.5% per year after 2030) (Galinis, 2015). In 2040 the Lithuanian economy would consume approximately 14.7 TWh of electricity, which means 5700 kWh per capita, corresponding to the current EU-28 countries average. The final energy demand growth rates are much slower, an average of 0.6% per year (Galinis, 2015). The RES target expressed as its share of the final energy demand would be 30% in 2030 and and 55% in 2050, which relates to the EU average in the corresponding year (EC, 2012a). Both pathways represented the same energy policy conditions regarding the RES share in the final energy demand.

The pathways for the future needs of forest bioenergy feedstock were run for Lithuania for the time period until 2065. Annual time steps were used in the time period 2011-2020, 5 year time steps in period until 2030, 10 year steps in period until 2050 and one additional step reaching 2065. The linear programming MESSAGE model for Lithuania is focussed on centralised heat and electricity supply, while other energy uses such as heat production in individual houses are modelled with less detail. Heat and electricity production is spatially disaggregated in the model to reflect isolated district heating systems. The model covers a wide variety of energy technologies (different types of heat plants and CHPs, technologies for electricity production, storage, etc.). Also, considerable attention is paid on the reflection of existing and prospective policy measures, electricity exchange with foreign countries and optimal allocation of reserve capacities. Availability of variable energy resources (e.g. wind) is represented using probability curves. When run stand-alone MESSAGE considers the cost optimal deployment of energy technologies, but does not consider other ecosystem services.

LandSim

The landscape simulator LandSim can simulate forest growth and management, using forest data and empirically derived functions thereof (Pang et al., 2017a). It was designed for exploring energy and land zoning policies and related forest management regimes across the whole landscape. The basic growth simulator is a matrix-based model of Markov chain type representing change by transition of areas (in this case pixels) between fixed states (in this case different states of the forest). Management programmes can be specified, differentiating between site productivity, species, age and volume. In simulations the activity probabilities can be shifted by a coefficient for the individual simulation period to meet, for example, a desired total harvest level. In the current study the landscape was represented by 25*25 m pixels. The state of each pixel of forest land was described by six variables:

i. Mean age (33 classes),
ii. Standing volume (13 classes),
iii. Dominant tree species (8 classes),
iv. Site productivity (2 classes),
v. Ownership (2 classes), and
vi. Forest group related to management strategy (4 classes).

Dynamic variables (mean age and standing volume) changed during the simulations while static variables (all other variables) remained as they were. Other land cover classes were not included in the forest simulations (but were used in other LEcA modules). For each pixel, changes of the class associations were projected in 5-year time steps across the study area, from the base year 2015 to 2115. Activities such as final felling, thinning, and regeneration were simulated. The initial forest description of the base year situation was derived from stand level data from the Lithuanian State forest cadastre (State Forest Survey Service, 2016), from which relevant attributes were used to create the LandSim variables.

In the simulations, the classes for each pixel were projected by using the probability of transitions between classes based on data from the Lithuanian National Forest Inventory (NFI) (Kuliešis et al., 2010). Activity probabilities for thinning and final felling were also estimated from the NFI permanent sample plot data using logistic models with the variables above as predictor variables. Thus the management specifications used in the simulations represented a business-as-usual (BAU) strategy, representing the forest management that has been applied in Lithuania during the period 1998-2015. As a response to the results of Strategy BAU and the higher demands of the MESSAGE pathway Biomass High a second forest management strategy was created, Strategy INT, in which a more intensive forest management applied. This was done by increasing the probabilities of harvesting which lowered the mean final harvest age for all categories of forests. Still, also in Strategy INT the mean final harvest was higher than the minimum legal final harvest age, which ultimately regulates how much wood that can be harvested. The outputs from LandSim were used for the estimation of the development of five ecosystem services.

Estimation of bioenergy feedstock

From the output of LandSim, the harvested stem volume was derived for each time step, using the storage and yield estimator of the LEcA tool (Figure 2). From these records, the forest bioenergy feedstock was estimated and summed up. For energy generation, different compartments of forest biomass can be used: firewood, primarily stemwood that has no alternative industrial uses, but secondarily it could be some fraction of industrial roundwood useful for pulpwood or sawmilling; industrial waste (sawdust and wood chips); and logging residues (tops, branches and stumps) (Kuliešis et al., 2016).

Extractable logging residues were considered to be those that could be extracted while minimising soil-related damages on forest ecosystems (Table 1), according to State Forest Service (2010). These environmental restrictions involve 1) poor soils, where the objective is to maintain the natural fertility; 2) for soils with a slope of more than 15 degrees, remaining cutting residues are supposed to make such soils stable; 3) for eroded soils, the aim is to minimize the erosion process; 4) for moist soils, the objective is to minimize the damage on the soils; and 5) for organic soils, extraction is not allowed due to both damage avoidance and maintaining the property (State Forest Service, 2010).

Table 1: Parameters for biomass estimations for Lithuania (State Forest Service 2010).

% of harvested stem volume according to Assumption Set 1	*Pine*	*Spruce*	*Birch*	*Aspen*	*Black alder*	*Grey alder*	*Oak*	*Ash*
Firewood	2%	2%	4%	29%	17%	17%	10%	8%
Industrial waste	10%	10%	10%	10%	10%	10%	10%	10%

Added share of residuals based on harvested stem volume	*Pine*	*Spruce*	*Birch*	*Aspen*	*Black alder*	*Grey alder*	*Oak*	*Ash*
Residues (branches and tops)	0-12%	0-15%	0-14%	0-12%	0-10%	0-10%	0-13%	0-15%
Residues (stumps)	0-21%	0-21%	0-15%	0-15%	0-15%	0-14%	0-17%	0-16%

Harvested stems can be used in different ways, so assumptions need to be made about how to make such allocations. From a bioenergy point of view, the allocation of the harvested stemwood into roundwood assortments affects the yield in two ways. Firstly, stemwood can be consumed for fuel directly, for example, as solid-piece firewood. Secondly, the proportion of sawlogs affects the amounts of produced industrial waste. In industrialized countries firewood is often regarded as the economically least valuable roundwood assortment. Consequently, in order to maximize the total economic value of the harvested wood, only those parts of the stem should be designated as firewood that are technically unsuited for other uses, either due to the dimensions or quality flaws. However, local economic circumstances might lead to a different allocation of the harvested stemwood, including higher proportions of designated firewood.

Following these considerations we developed two sets of assumptions regarding the use of harvested stemwood (Table 2). Assumption Set 1 was based on a "schoolbook" allocation of the stemwood aiming to maximize the total economic value with the lowest priority given to firewood (State Forest Service, 2010). Assumption Set 2 was instead based on the observed average allocation of harvested stemwood according the Lithuanian forestry statistics for 2015 (State Forest Service, 2016).

Table 2. Assumption Sets concerning the use of harvested stemwood for bioenergy purposes (State Forest Service, 2016).

	Assumption Set 1	Assumption Sets 2a and 2b
Sawlogs from harvested volume	40 %	30 %
Firewood from harvested volume	Average from the species specific use (see Table 1)	26-39 % (2a and 2b)
Industrial waste from sawlog volume	50 %	50 %
Utilization of industrial waste	50 %	100 %

The empirically derived proportion of firewood was substantially higher and the corresponding proportion of sawlogs was substantially lower compared to the "schoolbook" proportions. Moreover, in Assumption Set 2 we adopted a more optimistic assumption with regard to the utilization of the produced industrial waste. While in Assumption Set 1 we assumed that only 50 % of the industrial waste would be used for fuel, in Assumption Set 2 we assumed that it would be the entire 100% of the industrial waste. Furthermore, the amount of the harvested stem volume that was used for firewood derived from empirical data (State Forest Service, 2016), was somewhat uncertain. Therefore, the lower (Assumption Set 2a) and upper (Assumption Set 2b) ends of this range were both estimated, see Table 2.

Not only can different forest biomass compartments be used as bioenergy feedstock, but in addition, different forest management strategies can be applied to extract these. Therefore, in this study a rule-based approach was applied, starting with extracting biomass compartments that were considered most sustainable (i.e. no stumps or industrial wood), see Figure 3. If the demand for bioenergy feedstock according to the MESSAGE model was not met, then the next option was used, and so forth, until the demands were met or the options were exhausted. Firstly, options concerning biomass compartments were applied to the forest management Strategy BAU, and in the next step to Strategy INT.

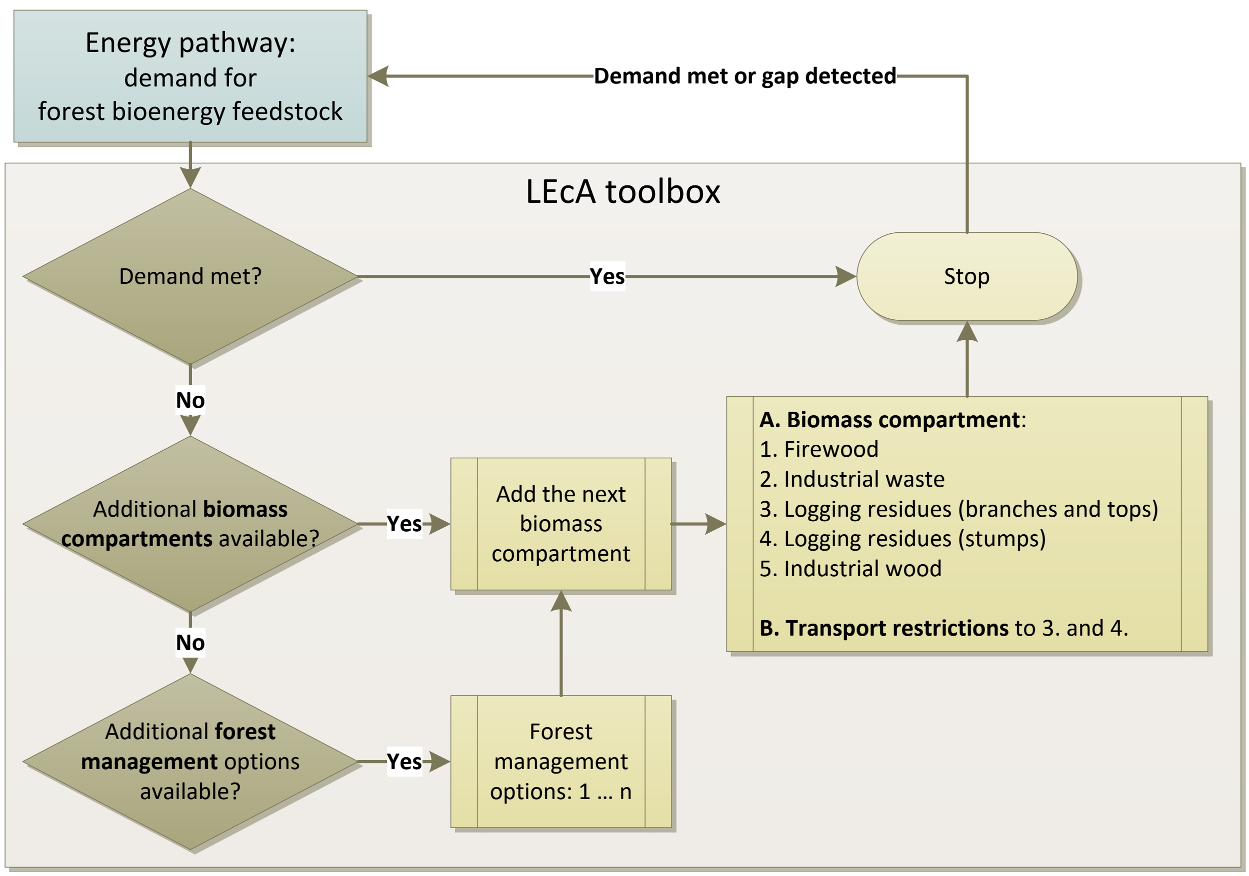

Figure 3. Linking the energy scenarios with the LEcA tool, showing iterations for adding different options within the rule-based approach.

When it comes to extraction of logging residues, there may also be limitations to the distance to the demand nodes, since transportation will affect economy and climate impacts (e.g. (Höhn et al., 2014; Skruodys, 2016). Therefore, transport restrictions were taken into consideration, so that 1 km extraction distance to collection spots was applied, and transport distances from collection spots to combined heat and power (CHP) plants or equivalent were assumed to be 30 km or 60 km. Zones representing these transportation distances (Figure 4) were used as masks for the extraction of residues.

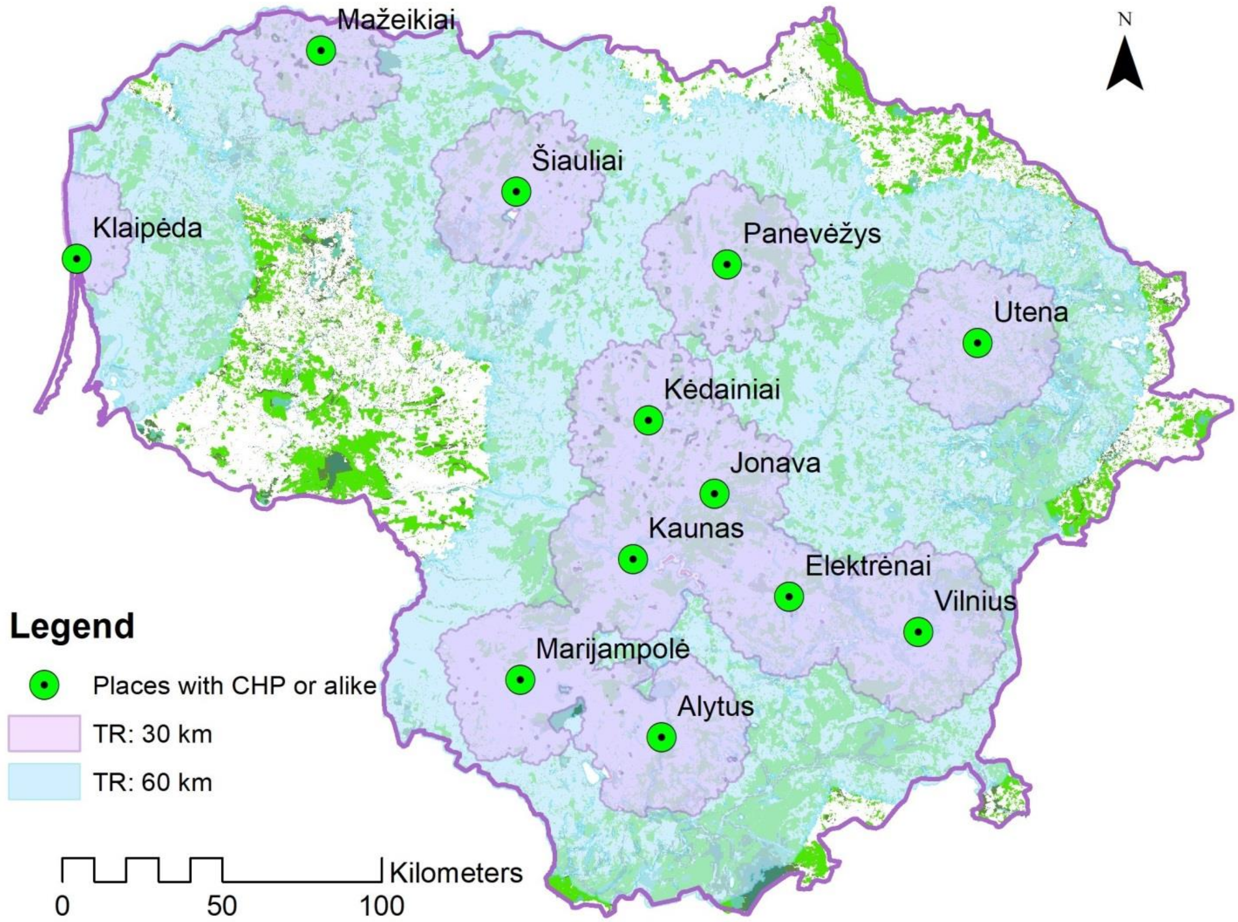

Figure 4. Forest residues extraction areas around CHP plants and alike, with transportation restrictions. Coordinate system LKS_1994_Lithuania_TM, spatial data State Forest Survey Service (2016) and GIS-Centras (2017).

Estimation of industrial wood

The harvested stem volume that was the outcome of LandSim, was also used to estimate the production of industrial wood, using the storage and yield estimator of the LEcA tool (Figure 2). For this purpose, the harvested stem volume was derived after subtracting the amount of that was used for firewood. Since this amount as mentioned was uncertain, the upper and lower ends of this range were both tested (see explanation of Assumption Sets 2a and 2b in the sub-section Estimation of bioenergy feedstock).

Estimation of carbon storage

The carbon accumulated in living trees was estimated using the storage and yield estimator (Figure 2). It was divided into the above-ground biomass (AGB) and the below ground biomass (BGB), and was then summed up to the whole tree carbon stock. The AGB was calculated as:

$$AGB = GS \times WD \times BEF$$

where GS means growing stock volume including bark (m^3), WD means wood density (ton dry matter/m^3 fresh volume) and BEF means the above ground biomass and stem biomass coefficient (Konstantinavičiūtė et al., 2017). The BGB was calculated as:

BGB = AGB x R

where R for coniferous forest is 0.26 and for deciduous forest 0.19. The carbon accumulated in living trees across the study area was then modelled with ArcGIS for each 5-years' time step in the two forest management strategies BAU and INT. The results show the change of carbon stock due to the different harvest activities following the forest management strategies.

Estimation of recreational area

In Lithuania, approximately half of the forest area is governmentally managed. Nature protection is part of the management objectives and 27% of all forest area is classified as protected areas (Ministry of Environment and State Forest Service, 2012). Designated recreational forest covers 3 % of the total forest area in the country, including forest parks, resort forests, urban forests, recreational forest sites and forests in the recreational zones of national and regional parks (Mizaras et al., 2015). However, a much wider range of forests may have high recreational value for the citizens. In order to understand the value of forest recreation in Lithuania and in general, a literature review was performed (De Vries and Goossen, 2002; Edwards et al., 2012; Filyushkina et al., 2017; Hjortsö and Straede, 2001; Hörnsten and Fredman, 2000; Mizaras et al., 2015), from which parameters for the recreation area indicator were derived.

To estimate the recreational area in this study, old and mature forest stands (>70 years) were selected. Tree species data was not differentiated, since mixed forest was so common in the country. Proximity to water was used as a measure of preferred sites with a buffer zone of 500 m. In addition forest roads were used as a measure of accessibility with a preferred zone of 500 m, while a zone of 50 m around highways was considered as noise polluted. The recreational area was modelled with ArcGIS for each 5-years' time step for the forest management strategies BAU and INT, and the results show related changes of the potential recreation area.

Habitat assessment

As indicators for prioritised biodiversity components, the total area of old and mature coniferous and deciduous forest was estimated for each forest management strategy and time step. In addition, a model species, the three-toed woodpecker (*Picoides tridactylus*) that is tied to spruce-dominated coniferous old forest combined with certain deciduous trees was selected for the assessment. Suitable habitat for the model specie across the study area was derived and a habitat network analysis was performed. In order to quantitatively assess the habitat size and connectivity for certain species within a certain landscape and time, a habitat network analysis method was used (Pascual-Hortal and Saura, 2006; Saura and Rubio, 2010). The Equivalent Connected Area (ECA) index was used since it takes into account both the amount of habitat within habitat patches and the connectivity among them. ECA builds on the probability of connectivity and relates the connectivity changes to the amount of available habitat (Saura et al., 2010). It is defined as the size of a single habitat patch, maximally connected, that would provide the same value of the probability of connectivity as the actual habitat pattern in the landscape (Saura et al., 2010). It was calculated as in Eq. 4:

$$\mathrm{ECA} = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i \, a_j p_{ij}^{*}} \qquad \text{Eq. 4}$$

where a_i and a_j are the area of the habitat patches i and j, and p*ij is the maximum product probability of all the possible paths between patches i and j. ECA has an area unit which makes it relatively easy to interpret, since it represents changes in the available habitat area.

Results and Discussion

Energy pathways

The results from the energy pathways Biomass Low and Biomass High, projecting the use of forest bioenergy feedstock as a RES, are shown in Figure 5. For the year 2015 (the starting year for the LEcA simulations), a use of 13813 GWh was projected in Biomass Low and 13873 GWh in Biomass High pathway. Later on, as can be seen in the figure, the Biomass Low pathway projected the use to reach 20786 GWh in year 2050, while 31365 GWh in the Biomass High pathway. In average for the whole projected period, the bioenergy use per year was 13966 GWh in the Biomass Low pathway and 15884 GWh in the Biomass High pathway. In the Biomass Low pathway the wood biomass prices were assumed to be 25-37% higher in 2017, compared to the Biomass High pathway. During the study period they were increasing and in 2050 exceeded the Biomass High pathway prices by 100-125%.

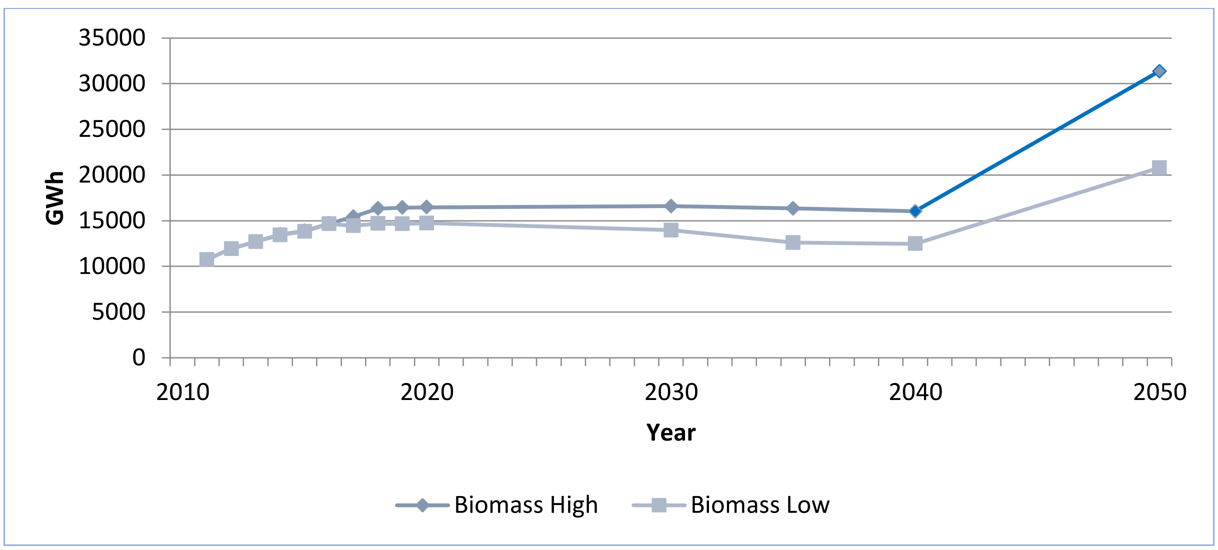

Figure 5. Forest biomass demand for bioenergy feedstock as modelled by the MESSAGE energy model, from 2011 up to 2050, in the Biomass High and Biomass Low pathways.

The biomass consumption in Lithuania for the Biomass Low and Biomass High pathways was estimated by an energy sector development model created in the MESSAGE environment, as mentioned. The RES target in this model was set as the RES share in the final energy demand. This share was the same for both pathways and was growing from the current level up to 55% in 2050. However, the exogenously assumed RES target in final energy, from the optimisation results converted into RES shares of primary energy, in the Biomass Low and Biomass High pathways were slightly different. These differences were caused by the different technological structure of the energy sector in the analysed pathways, and consequently by the different overall efficiency of the energy conversion from primary to final energy. In 2050, the RES target as its share of primary energy in Biomass Low pathway would be 56.8%, which however was not achieved. In order to achieve this target it would be necessary to consume an additional 5245.2 GWh of RES. In the Biomass High pathway the RES share target in 2050 would be 59.7% (in primary energy). It was achieved in the calculations because the upper limit on the forest biomass quantity that is available for energy feedstock production purposes (Galinis, 2015) was not applied.

Forest bioenergy feedstock

The total forest bioenergy feedstock that could be extracted according to the LEcA simulation of the two forest management strategies is illustrated in Figure 6. As can be seen, there were substantial differences in the outcome depending not only on strategy but to a large extent on the assumptions that were made concerning use of forest biomass compartments for bioenergy purposes. The outcome applying Strategy BAU could be compared to empirical data for year 2015 (State Forest Service, 2016), when 2.1 mill. m^3 *firewood* was used. In relation to this, the LEcA yield estimation for 2020, representing the period 2016-2020, with Assumption Set 1 and Strategy BAU was 0.61 mill. m^3/year which equals to 29% of the record from 2015. With Assumption Set 2a it was 2.45 mill. m^3 which is 117 % of the record from 2015. With Assumption Set 2b it was 3.82 mill. m^3 which is 182 % of the record from 2015. Furthermore, in year 2015, 1.45 mill. m^3 bioenergy feedstock came from *industrial waste* (State Forest Service, 2016). The LEcA estimation of industrial waste for the period 2016-2020 with Assumption Set 1 and Strategy BAU was 0.98 mill. m^3/year which is 68% of the record from 2015. With Assumption Set 2 (a and b) it was 1.47 mill. m^3 which equals to 101 % of the record from 2015. Assumption Set 2 matched better with empirical data, which is logic since the allocated shares for the use of biomass compartments were derived from this data. Thus, not only the total estimated harvested stem volume, but also the allocation of biomass compartments and the assumed utilization of industrial waste for bioenergy had a strong influence on the results.

As a response to the results of Strategy BAU and the higher demands of the MESSAGE pathway Biomass High, Strategy INT was created, aiming for around 10% higher overall yield. The strategies differed in that Strategy INT implied a more intensive forestry, with higher probabilities of harvesting and a lower mean age of harvested stands, in order to increase the yields. However, the simulations did not allow for harvesting stands below a certain age, in agreement with the forestry legislation. As a result, the harvest was very high in the beginning of the simulation period, but stabilised and even decreased after around year 2040 (Figure 6). This was due to the initial state of the forest, combined with the effect that with time, many stands suitable for harvest were already used. The total increase in overall yield with Strategy INT was 9.5%.

Figure 7 shows the *logging residues* that could be extracted according to the LEcA simulations of the two forest management strategies. The extraction of all logging residues (tops, branches and stumps) in the first simulated period 2016-2020 was estimated to be 2.42 mill. m^3/year with Strategy BAU, while 3.40 mill. m^3/year with Strategy INT. The available residues per year with Strategy BAU would increase so that by 2050 it would be 133 % of that of the first period, and end up in 3.22 mill. m^3 by 2050. With Strategy INT it would instead start on a high level and then slightly decrease so that by 2050 it would be 89 % of that of the first period, and end up in 3.03 mill. m^3 by 2050. The average extraction of residues of the whole period would with Strategy BAU be 2.96 mill. m^3 per year, while with Strategy INT it would be 3.25 mill. m^3 per year. When applying transport restrictions of 60 km to Strategy BAU and Strategy INT, in average 2.34 and 2.56 mill. m^3 per year would be available. However, when considering transport restrictions of 30 km, only in average 0.83 and 0.91 mill. m^3 per year would be available, respectively.

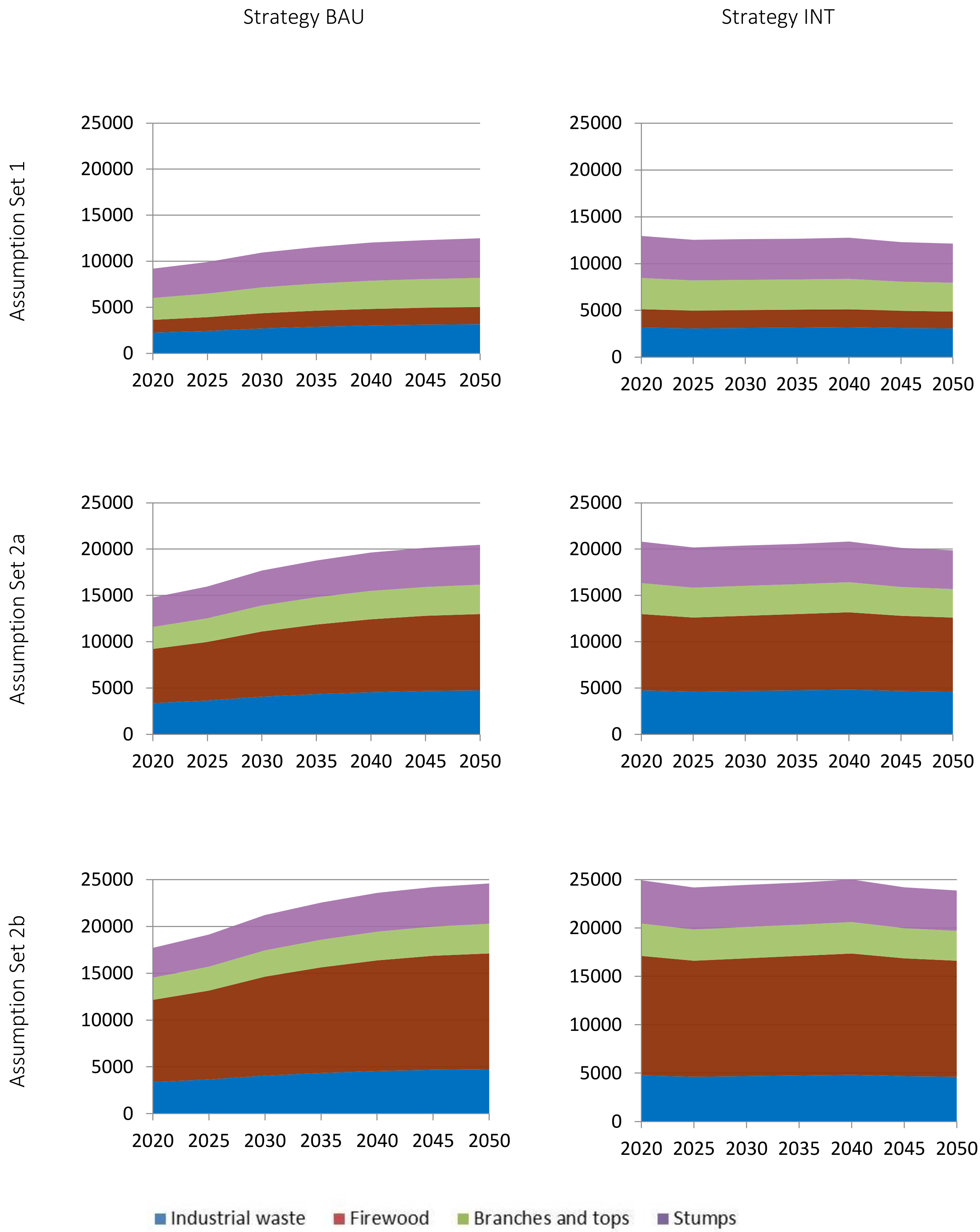

Figure 6. The total forest bioenergy feedstock (GWh/y) that could be extracted according to the LEcA estimations, applying the forest management strategies BAU and INT, under the Assumption Sets 1 and 2 (a and b).

In order to compare these estimates with empirical data, only tops and branches can be considered since stumps are currently not extracted in Lithuania. According to State Forest Service (2016), bioenergy feedstock from logging residues (tops and branches) accounted for 0.4 mill. m^3 in year 2015. In comparison, the corresponding LEcA estimates with Strategy BAU for 2016-2020 were 1.03 mill. m^3, which is 258 % of the empirical record for 2015. With Strategy INT it was 1.45 mill. m^3, which is 363% of the record for 2015. However, with transport restrictions of 60 km, the estimate for Strategy BAU was 0.85 mill. m^3, which is 213 % of the record for 2015 (1.2 mill. m^3 and 300 % for INT). With transport restrictions of 30 km, the LEcA estimate for Strategy BAU was 0.31 mill. m^3, which is 78 % of the record for 2015 (0.44 mill. m^3 and 110 % for INT).

Strategy BAU

Strategy INT

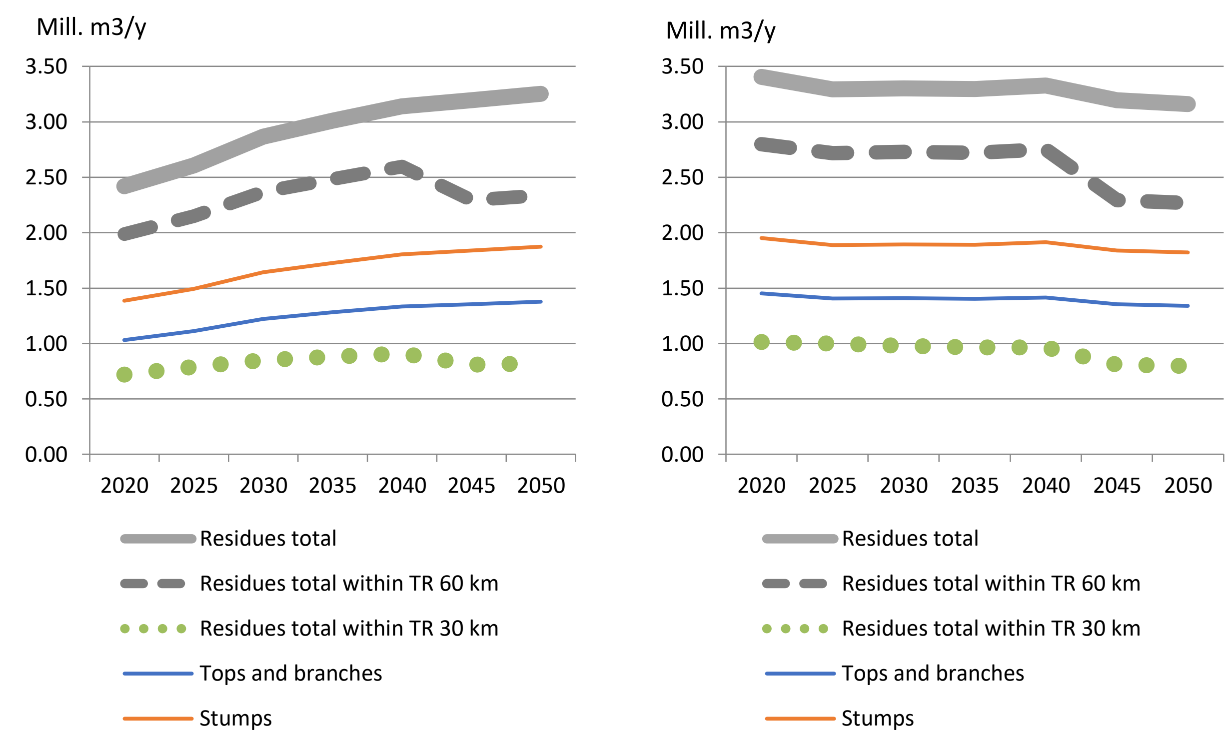

Figure 7. The extraction of logging residues with and without transport restrictions, for the forest management strategies BAU and INT.

When it comes to logging residues, applying transport restrictions in the LEcA tool resulted in a lower potential for bioenergy feedstock, especially when comparing 30 km transportation distance with the empirical data. When applying 60 km transportation distance, a large share of the country's forest area was covered (Figure 4) and the yields were considerably higher. The transport restrictions were only very rough assumptions which should be further investigated. However it may be that transport distances of logging residues, affecting economy and climate impacts (Gustavsson et al., 2011; Lindholm et al., 2010; Ranta, 2005), will be an issue in the future that needs to be addressed. In addition, the extent to which the environmental restrictions related to soils are considered in reality is a question that could be looked into. For Lithuania, the environmental restrictions on extraction of logging residuals related to moist soils may be the most significant when it comes to the amount that would be available for harvest.

The application of environmental restrictions could be discussed, since increased extraction of logging residues can be expected to have environmental impacts. For instance, for Sweden estimated thresholds for how much extraction of logging residues could increase while avoiding conflicts between different national environmental objectives were estimated (de Jong et al., 2017). According to these authors, the extraction of branches and tops should not reach over 80% of the total final felling area in order to keep forest productivity and avoid leakage of toxic substances, and not reach over 50% of the total final felling area to avoid acidification and conflicts with biodiversity targets. Stumps should only be harvested on less than 30% of the total final felling area to keep forest productivity and to avoid leakage of toxic substances, and only on up to 20% of the final felling area to avoid conflicts with biodiversity targets. From a biodiversity point of view, extraction of logging residues should be restricted to coniferous forest, avoiding deciduous trees (de Jong et al., 2017; de Jong and Dahlberg, 2017). Thus, there are several ways of taking environmental considerations into account when using logging residues, which could be further looked into.

Comparison of the results from both models

The projected forest biomass use in the energy pathways Biomass Low and Biomass High (2015-2050) exceeded by large the total resource availability that was estimated by the LEcA tool, according to the BAU forest management strategy, environmental restrictions related to soils, and Assumption Set 1 concerning the allocation of harvested stemwood (Figure 8). In average the total available forest biomass resource covered 76% and 60% of the projected use in Biomass Low and Biomass High, respectively. If stumps were excluded from the estimates, the gap became even larger with only 50% and 39% of the projected use secured by the estimated resource. Applying transport restrictions resulted in further reductions of the projected biomass use coverage, see Table 3.

By contrast, the total resource availability estimated by the LEcA tool, according to the BAU forest management strategy and the Assumption Set 2 for the allocation of harvested stemwood covered as much as 121% and 96% of the Biomass Low and Biomass High pathways, respectively. If stumps were excluded, the corresponding percentages were 95% and 75%, not reaching the projected use levels. The resource availability under the transport restrictions resulted in reductions of the biomass use coverage, as shown in Table 3. So, also when the extraction options were exhausted, apart from using industrial wood, the projected biomass use of the energy pathways would not be covered. However, when applying Assumption Set 2a the resource estimates came relatively close, and the transport restrictions could be discussed and perhaps re-considered. When applying Assumption Set 2b, the situation looked different and the projected use of the Biomass Low pathway was exceeded by the resource availability projected by the LEcA tool. However, the Biomass High pathway was not equally well covered (Table 3) so an extraction of an additional 10% harvest was desired, and implemented in Strategy INT.

When applying Strategy INT, the yields were considerably higher in the earlier periods, but by the end of the period the yields were on the same or declining level while the Biomass Low and Biomass High pathways increased. Therefore, this forest management strategy did not seem to be very useful for meeting the demands, since the timing for the increased demands after 2040 was missing. The forest management strategy could though be further iterated in order to respond more closely to the timing of the demands of the energy pathways. Still, the major differences were again between assumptions, the relevance of which would need careful consideration. Furthermore, Strategy INT could serve as an illustration of what could be projected if high levels of forest bioenergy feedstock would be expected to be kept up for a long period, for instance after 2050 (such long-term projections should though benefit from taking into account impacts of climatic changes on the forest ecosystem). For both pathways, looking at the overall situation applying Assumption Set 2, the results indicate that during the period up to around 2040 supply and demand may not be so far apart from each other with Strategy BAU, and the supply exceeding the demand with Strategy INT. However, closer to year 2050, it may be more difficult to meet the demands with both forest management strategies, especially if these will continue for a long time period.

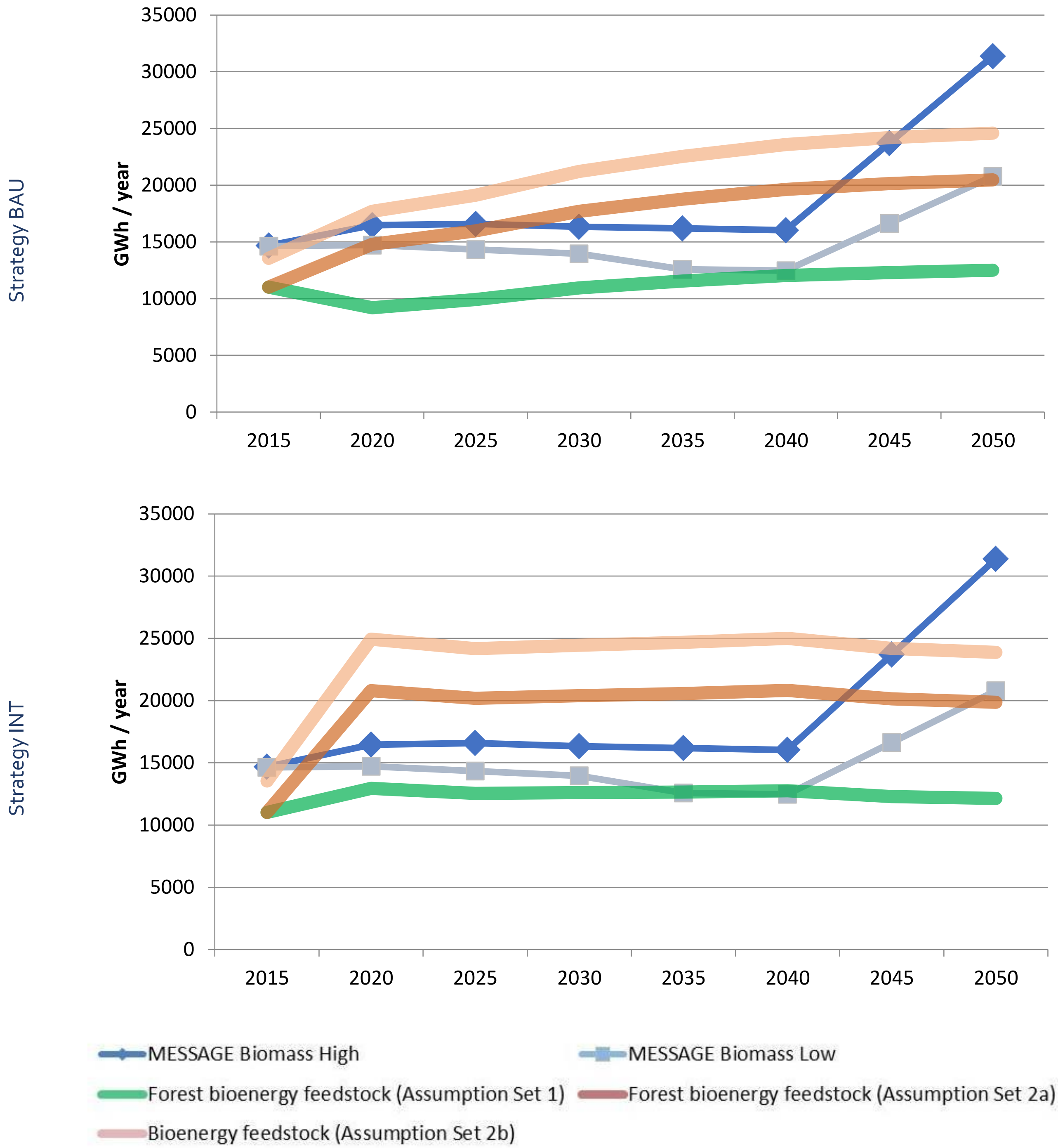

Figure 8. Comparison of the projected use of forest bioenergy feedstock according to the MESSAGE scenarios, versus the supply according to the LEcA tool estimations. The Assumption Sets were applied for estimating the share of industrial waste and firewood. However, the logging residues (tops, branches and stumps) were the same in both Assumption Sets.

Table 3. The overall coverage of forest bioenergy feedstock estimated by the LEcA tool, compared to the use projected by the energy scenarios Biomass Low and Biomass High, for the period 2015-2050. The two forest management strategies BAU and INT were run.

Strategy BAU	**Assumption Set 1**		**Assumption Set 2a**		**Assumption Set 2b**	
Energy scenario	Biomass Low	Biomass High	Biomass Low	Biomass High	Biomass Low	Biomass High
Use of logging residues and transport restrictions						
Full use	76%	60%	121%	96%	148%	117%
Full use without stumps	50%	39%	95%	75%	122%	97%
Full use – transport restrictions 30 and 60 km	43-66%	34-52%	88-113%	70-90%	115-138%	91-109%
Full use without stumps – transport restrictions 30 and 60 km	36-46%	28-36%	81-93%	65-74%	108-118%	86-93%

Strategy INT	**Assumption Set 1**		**Assumption Set 2a**		**Assumption Set 2b**	
Energy scenario	Biomass Low	Biomass High	Biomass Low	Biomass High	Biomass Low	Biomass High
Use of logging residues and transport restrictions						
Full use	83%	66%	133%	105%	162%	128%
Full use without stumps	54%	43%	104%	83%	133%	106%
Full use – transport restrictions 30 and 60 km	47-83%	37-66%	97-124%	77-99%	126-151%	100-120%
Full use without stumps – transport restrictions 30 and 60 km	39-50%	31-40%	89-102%	71-81%	118-129%	94-102%

Industrial wood

The results of the simulated yields of industrial wood are shown in Figure 9a. Corresponding to the bioenergy yield, the assumptions highly affected the results, so that Assumption Set 1 meant a much higher yield than Assumption Sets 2a and 2b. In Assumption Sets 2a and 2b, a higher portion of stemwood was used as firewood, affecting mainly pulpwood. In a similar pattern as for bioenergy feedstock, the forest management strategy INT gave a much higher yield in the beginning of the simulation period. However, after around 2040, the resources would be somewhat exhausted and a decrease would follow.

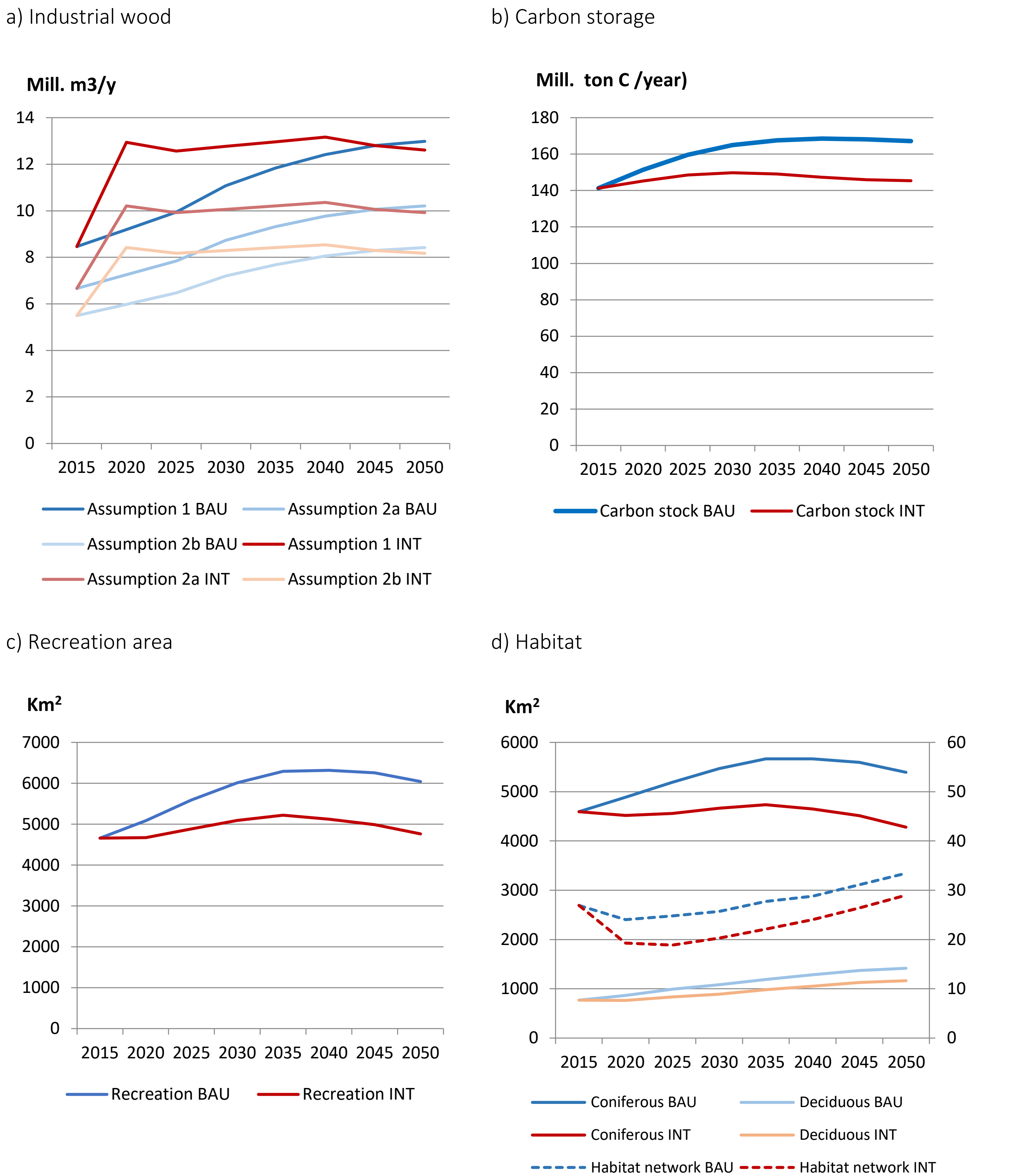

Figure 9. Development of the ecosystem services industrial wood, carbon storage, recreation area, and habitat networks under the forest management strategies BAU and INT. In d) habitat network values are shown on the right-hand axis.

Carbon storage

The results of the estimation of carbon storage in the remaining living trees after harvest are shown in Figure 9b. In Strategy BAU, the carbon stock would steadily increase from the start of the simulation, and then slightly decrease in the end of the period. In average each year, the carbon stock would be 161 million tons. In Strategy INT, the carbon stock would first increase but then decrease again. In average, the carbon stock would be 147 million ton/year. For comparison, a current estimation from (Global Forest Watch, 2018) implies a current forest carbon stock of 167 mill. tons for Lithuania.

The different patterns of carbon stock changes were closely related to the forest management and harvest activities in the two forest management strategies. In Strategy BAU, the forests were managed with the strategy that has been applied in Lithuania since year 2000. However, in Strategy INT a relatively shorter rotation period was applied, which means trees were harvested in average at a younger age compared with that in BAU, so the higher harvest levels resulted in a lower carbon stock in Strategy INT. This trade-off should be considered when using forest biomass as a renewable energy source. It should furthermore be noted that carbon stored in dead wood and litter in the forest was not accounted for, which may be as much as around 40% of the living forest biomass carbon in Lithuania (FAO, 2010). A more detailed analysis of this part of the total forest carbon stock can be added to the assessment in the future.

Recreation areas and habitat supporting biodiversity

The results of the estimation of forest with high *recreational value* after harvest in each 5-year time period are shown in Figure 9c. In this study, recreational forest was defined as old and mature forest accessible through roads and around water bodies. Recreation areas would increase at the beginning of the simulation period and drop after year 2035. The average size of the recreation area over the years was 5784 km^2 in Strategy BAU. Due to higher yields in Strategy INT, it resulted in a smaller average recreation area over the years, 4926 km^2. This was a consequence mainly of the smaller area of old and mature forest with Strategy INT than that with Strategy BAU during the same period of time. The model of areas with high recreation value will be further developed, taking additional forest variables into account in order to create a more realistic representation of this ecosystem service. However, the current model will suffice for demonstration purposes.

For forest habitat supporting biodiversity, the *total habitat area* for mature and old coniferous and deciduous forest, respectively, is illustrated in Figure 9d. The average total habitat area with Strategy BAU was 5309 for the coniferous and 1120 km^2 for the deciduous forest habitat. When applying Strategy INT, it was 4565 and 948 km^2, respectively. With Strategy BAU, the coniferous forest habitat increased up to around 2035 where it started declining somewhat. The deciduous forest habitat increased continuously throughout the simulation period. With Strategy INT, the coniferous forest habitat showed a small increase, at a lower level than with BAU, and then declined by the end of the period. The deciduous forest habitat showed an increasing trend but at a lower level than with BAU.

When comparing the *habitat network area* between the forest management strategies, Strategy BAU lead to a larger ECA value than Strategy INT, since a combination of mature coniferous and deciduous trees was defined as suitable habitat for the model species (see Figure 9d, right y-axis). The average ECA of the habitat networks over the years in Strategy BAU was 27 km^2, which is higher than the corresponding value of 23 km^2 in Strategy INT. The habitat network declined somewhat in the beginning of the period but later on increased substantially. However, in Strategy INT the initial decline was more drastic which can have detrimental impacts on the persistence of populations in the landscape that depend on the targeted habitat.

The different development patterns between the total habitat areas for coniferous and deciduous forest, respectively, and the habitat network ECA, can be explained by the original state of the forest (stand age, tree species, etc) and possible development paths of these, together with the spatial dimension of the habitat demands for a combination of coniferous and deciduous forest, of the model species. The habitat network ECA takes into account larger concentrations of suitable habitat with high connectivity, irrespective of other parameters. In general, mature and old forest can be seen as a good overall indicator for forest biodiversity, while in particular woodpeckers has been seen as having high indicative value for forest biodiversity (Roberge and Angelstam, 2006). However, additional indicators could be added for a more complete study.

Trade-offs

Forests provide a multitude of ecosystem services, however it is often not possible to substantially increase the use of one of these without trade-offs with other ecosystem services. This is illustrated in Figure 10, where the development of 5 ecosystem services between the forest management strategies is shown for 2015-2050. The red line represents the state of the forest in the starting year 2015, while industrial wood and bioenergy yield for that year was derived from empirical data. The allocation of the total harvest between industrial wood and bioenergy feedstock followed Assumption Set 2a. In both strategies, bioenergy showed the highest increase, followed by industrial wood. In Strategy BAU, the bioenergy yield increased gradually while in Strategy INT it directly reached a high level that was more or less kept during the simulation period up to 2050. The yield of industrial wood followed a similar pattern. The difference resulted in overall lower carbon storage in Strategy INT, compared to BAU. The recreation area was overall larger in Strategy BAU. For the habitat networks, Strategy BAU led to a decline in the beginning of the period while it ended with an increase. In comparison, Strategy INT showed a similar pattern but the decrease in the first time steps was substantial. The trade-off diagrams thus point at the consequences of the higher extraction levels of industrial wood and bioenergy feedstock in Strategy INT, with impacts on the other three ecosystem services.

Strategy BAU

Strategy INT

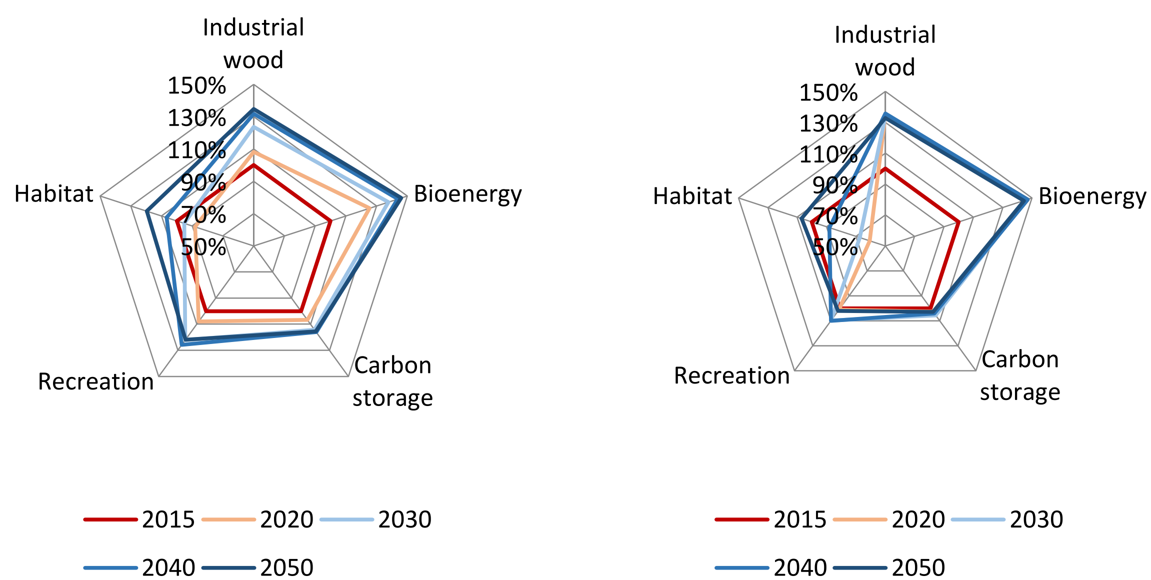

Figure 10. Illustration of trade-offs between ecosystem services, applying Assumption Set 2a to the allocation of the total harvest into industrial wood and bioenergy feedstock.

Linkages between energy pathways and ecosystem services

The assessment of impacts of forest bioenergy options on the selected ecosystem services was initiated by the Biomass Low and Biomass High pathways. For linking between the energy model and the LEcA tool, a rule-based approach was applied (Figure 3). As described, it was based on an initial BAU forest management strategy, a set of options using different biomass compartments as bioenergy feedstock, environmental and transport restrictions, and the option of changing the forest management strategy. We focused primarily on firewood consumed by individual households, industrial waste, and logging residues including tops, branches and stumps. However, stump wood and to some extent industrial wood would only be considered as alternative sources when the other sources were exhausted. An increased demand for forest bioenergy feedstock could initially be expected to increase the extraction of harvest residues, possibly also stumps. However, at higher levels of demand, competition for raw material might occur between the bioenergy sector and the pulp and paper producers as well as the wood board industry (Carlsson, 2012; Jonsson, 2012, 2013; Lauri et al., 2014). The overall demand for wood can also be foreseen to increase in a transition to a green economy where wood is a renewable material used on large scale to substitute, e.g., fossil-based products (EC, 2012b). However, the extent to which industrial wood might be used for bioenergy purposes is very difficult to predict, and it may require quite strong price increases to divert wood flows from industrial uses to energy use (e.g. (Solberg et al., 2014).

A crucial linkage between forest biomass extraction and other ecosystem services is the forest management. The same level of biomass supply can often be obtained using a multitude of different forest management configurations, both with regard to the character of activities and with regard to their geographic allocation. The search for options for meeting demands for forest bioenergy feedstock (Figure 3) start with extraction of different biomass compartments, in this case first applying Strategy BAU, and in the next step, an alternative forest management strategy can be formulated, in this case Strategy INT. Thus we can test possible options for increased biomass supply until the demand would be met or the list of options would be exhausted, in which case a gap would remain. The list of options could be further developed to a wider set of options, such as considering black liquor which is a by-product of the paper industry, however not applicable for Lithuania which has no such industry.

When comparing the LEcA results with the energy pathways, the different applied allocation assumptions would play a major role for the results. In the Biomass Low pathway, the consumption of industrial waste was limited according to assumptions about their availability in the domestic market, at the same time as the price for biomass was assumed to gradually increase. According to the LEcA estimations, the Lithuanian forest could to different degrees cover the use of forest biomass in this pathway (Table 3), depending on allocation assumptions, if stumps would be used or not, and transport restrictions. The Biomass High pathway had no upper limit for the biomass supply, it was allowed to import these products or to produce them locally if there would be enough wood, and the prices remained constant at the initial level. The LEcA tool estimated that the Lithuanian forest could to less extent cover the use of forest biomass in this pathway (Table 3). In this pathway, an increased import of bioenergy feedstock could be expected to fill the gap. However, these figures are currently very preliminary and should be taken as examples only. In further development of the link between models, this information could be fed back to the MESSAGE model, advising an adjustment of the domestic availability (Figures 2 and 3).

The availability of forest biomass for bioenergy feedstock is a crucial part of the energy policy of a forest-rich country, in view of the climate goals and targets for renewable energy. Several ways to reach these goals can be assessed, where the options and their sustainability can be highlighted. The LEcA module LandSim can simulate forest growth and management using a minimum of forest data compared to conventional tools used for forest management planning (Pang et al., 2017a). Due to the modest data requirements, it allows for exploring forest management strategies across the whole landscape.

The GIS-based approach to the bioenergy feedstock problem, using data that in this context has a high geographical resolution, gives more detailed and localised information than what would be possible in more aggregated approaches. Other studies that use GIS-based approaches take into account the spatial variability of biomass resources as well as transport networks to find suitable siting of biomass power plants (e.g. (Hiloidhari et al., 2017; Höhn et al., 2014; Rodríguez et al., 2017; Shu et al., 2017; Sultana and Kumar, 2012). By contrast, the LEcA tool can assess the sustainability of using existing or planned demand nodes and the current forest state, simulating future development of this resource under alternative policies and management strategies. The possibilities to spatially allocate and as well aggregate spatially explicit information makes the LEcA tool suitable for flexible model linking. Not only impacts can be assessed, but for instance constraints can be formulated for the assessed ecosystem services, so that they should not go below a certain value in any time period, which could also be fed back to the energy model.

For linking between the energy model and the LEcA tool, the forest management strategy BAU was initiated by the pathways created by the MESSAGE model, which can be seen as a first step for linking between models, a first use of link ***a*** in Figure 2. When the first results were analysed and compared with the MESSAGE model results, it can be seen as a first use of link ***b*** in Figure 2. Based on this comparison, a decision was taken to create the second forest management strategy INT, again using link ***a***. In future work these first steps will be further developed, preparing for full linkage between models. The LandSim model was built in MatLab (Mathworks, 2015) and other modelling was peformed in ArcGIS ModelBuilder (ESRI, 2011). In order to strengthen the linking between energy models and ecosystem assessment tools, possibilities to turn to open source models will be looked into. The results from ecosystem service assessment will be fed back to the energy model for informed adjustments concerning a sustainable production of forest bioenergy feedstock. When a set of suitable forest management strategies is found, the implications for the full set of ecosystem services can be assessed. The output can then be used to inform energy policy about the sustainability of alternative bioenergy options.

Conclusions

The estimations of bioenergy feedstock were comparable with the empirical data. However concerning logging residues, the transport distances affecting economy and climate impacts need more considerations, as those may become more pronounced in the future. It could also be concluded that the assumptions concerning the allocation of different forest compartments as bioenergy feedstock would highly influence the results. In the comparison with energy pathways, though, assumptions based on empirical data came much closer than assumptions following forestry manuals. When comparing results with the energy pathways, it was still difficult to estimate with any precision the bioenergy feedstock availability. Looking at the overall situation applying allocation assumptions based on empirical data, the results indicated that during the period up to around 2040 supply and demand may not be so far apart from each other with Strategy BAU, and the supply exceeded the demand with Strategy INT. However, closer to year 2050 when the energy pathways projected a much higher use of forest biomass, it may be more difficult to meet the demands with either of the forest management strategies.

With Strategy INT, the overall yield was around 10% higher than with Strategy BAU, with the highest yields in the beginning of the period. However, the yields were not timing well with the energy pathways, since the major increase would be needed after around year 2040. Still, these results served to illustrate that when increasing the yields above a certain threshold, the resources may be exhausted in the long run. As well, comparing strategies BAU and INT, it could be shown that there are trade-offs to be expected between bioenergy feedstock and industrial wood on the one hand, and carbon storage, recreation and habitat supporting biodiversity on the other hand.

The LEcA tool can simulate forest growth and management with modest data requirements, which allows for exploring forest management strategies across the whole landscape. The GIS-based approach to the bioenergy feedstock problem, using data that in this context has a high geographical resolution, gives more detailed and localised information than what would be possible in more lumped approaches. The possibilities to spatially allocate and as well aggregate spatially explicit information makes the LEcA tool suitable for flexible model linking. Not only impacts can be assessed, but for instance constraints can be formulated for the assessed ecosystem services, so that they should not go below a certain value in any time period, which could also be fed back to the energy model.

For linking between the energy model and the LEcA tool, the first steps of information exchange were recognized and tested. The energy pathways created by the MESSAGE model initiated the forest management strategy BAU, from which the results concerning bioenergy feedstock yield was fed back and compared with the pathways. From this comparison, the second forest management strategy INT was developed, targeting higher yields. In future work these first steps will be further developed, preparing for full linkage between models. The results from the ecosystem service assessment will be fed back to the energy model for informed adjustments concerning a sustainable production of forest bioenergy feedstock. In this way, the links between energy assessment and ecosystem services could be strengthened in a more integrated assessment, targeting to inform energy policy and to increase the sustainability of forest bioenergy options.

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