Biomass and Bioenergy 148 (2021) 106001

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Wood supply chain risks and risk mitigation strategies: A systematic review focusing on the Northern hemisphere

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ARTICLE INFO

Keywords:
Wood supply
Wood supply chain risk
Supply risk mitigation
Wood supply strategy
Wood-based bioeconomy

ABSTRACT

This paper presents a systematic literature review on both the risks affecting wood supply security and risk mitigation strategies by quantitative and qualitative data analysis. It describes wood-specific supply chain risks, thereupon resulting impacts and counteracting strategies to ensure supply. Risks, impacts, and strategies are documented as basis for a comparative analysis, discussion of results, challenges and research gaps. Finally, the suitability and the limitations of the chosen methodology and the achieved results are discussed. Scanning wood supply chain risks and supply strategies, most of the reviewed papers focus on wood supply for bioenergy generation and only a few studies investigate wood supply chain risk issues for the sawing, wood panel, pulp and paper industries, or biorefineries.

This review differs significantly from other reviews in this field as it considers the entire wood value chain including recent studies on new chemical wood-based products and thus provides a more complete picture of the wood-based bioeconomy. Consequently, it contributes to the literature by providing an overarching investigation of the risks affecting wood supply security and possible side effects of a growing wood-based bioeconomy. It was found that comprehensive value chain analyses considering established wood products, large-volume bioenergy products, as well as established and new chemical wood-based products in the context of wood supply security are missing. Studies that map the entire wood value chain with its multilevel interdependences and integrating cascading use of wood are lacking.

1. Introduction

As a result of societal and political pressure to fulfil climate mitigation goals (e.g. Kyoto Agreement, Paris Agreement), the past 20 years has seen governments initiate the promotion of wood based bioenergy [1,2]. This had led to a rapidly increasing demand for wood fuels and rising competition with the paper and panel industries for logs and sawmill wood by-products in Europe [2–4]. Assessing fuel supply chain risks is vital for the successful operation of large-scale bioenergy projects [5]. Therefore, facilities are usually located close to the raw material resource [6] or harbours or terminals which facilitate economic long-distance ship or railway transport [7,8]. However, the bioenergy sector has failed to develop comprehensive supply strategies despite the rising need for such international and global strategies [9].

In Europe, the share of demand exceeding local supply is compensated by wood imports. This raises concerns about the pressure on forest resources, impacts of land availability and use changes abroad [10,11]. So, rising demand for bioenergy, as liquid biofuels or wood gasification products, disrupts established wood markets [12]. Additionally, forest management strategies promoting specific tree species can cause supply security issues for other species [13,14]. In Germany, for instance, the focus on hardwoods, as recommended by forest reconstruction guidelines, results in softwood supply risks in the long term [14]. To satisfy the demand of a bio-based economy, availability and allocation of resources have to be managed efficiently [9,15].

Established supply chain frameworks hardly cover the specific issues of biomass supply chain systems. In particular long-term strategies for mitigating wood supply chain risks and supply security issues of traditional wood supply chains (e.g. pulp and paper supply chain) are insufficiently investigated [16–18]. So, complementary investigation in related topics are needed [13]. Wood supply security, wood supply chain risks, and risk mitigation strategies are pressing topics for wood processing companies and for investors within the wood-based bioeconomy which is promoted as an essential component in mitigating

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https://doi.org/10.1016/j.biombioe.2021.106001
Received 1 April 2020; Received in revised form 21 January 2021; Accepted 7 February 2021
Available online 6 March 2021

climate change.

Therefore, this paper provides a systematic literature review addressing wood supply chain risks, risk mitigation strategies, and supply security as a basis for comparative analysis, specification of challenges, and future research needs. As a results of literature search the regional focus is on the northern hemisphere. Final conclusions on suitability and limitations of both the chosen methodology and achieved results are provided.

To this end, the proposed review will answer the following questions: (a) What are the main supply chain risks influencing wood supply security? (b) What are the impacts of supply chain risks on wood supply security? And (c) what are promising risk mitigation strategies to ensure wood supply?

2. Methodology

The proposed methodology is the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [19] consisting of two parts: literature review (search and eligibility) and meta analysis. PRISMA was adopted as the meta analysis approach for study synthesis throughout it has been widley replaced by the concept of textual narrative synthesis, as this type of analysis fits to studies which “describe the existing body of literature; identifying the scope of what has been studied […], and gaps that need to be filled” [20]. The textual narrative synthesis uses a standard data extraction format (e.g. categories), to extract parts of the reviewed literature. To compare the similarities and differences within the manuscripts the findings were clustered in subgroups facilitating quantitative analysis [20,21].

2.1. Literature search and eligibility

The search was limited by language, but not by research design or publication date. Only English papers were searched, since English is the common language for researchers worldwide. The search was carried out with the keywords wood, supply security, security of supply, supply risk, and supply strategy. In order to include the most important data sources covering the review field, the following databases and library services (in alphabetic order) were searched: Science Direct/Elsevier (http://www.sciencedirect.com), Scopus (www.scopus.com), and Web of Science (www.webofscience.com). The review focused on scientific literature describing the research’s state-of-the-art. Consequently, industry or government reports were not part of the search.

In this step the eligibility of each identified paper (n = 3397) was proven stepwise. To be included, a paper had (a) to belong to the topic of forestry, agriculture, environment, engineering, biochemical, energy, business, economics, logistics, or supply chain; (b) had to be a research paper, review paper, or conference paper; (c) must investigate wood supply chain risks or related issues, or (d) wood supply security in general, or (e) strategies mitigating wood supply chain risks, or (f) effects of a growing wood-based bioeconomy. Meeting concurrently (a), (b) and one of (c), (d), (e), or (f) was obligatory. Papers with a focus on renewable resources other than wood from forests were included if the applied methods provided an analysis of supply chain risks. Bioeconomy-related papers concerning food or feed resources as feedstock or, crops, plantation wood, and woody biomass, which discussed supply chain risk issues were also included.

2.2. Quantitative and qualitative data extraction and summarizing

Two different ways to analyse the identified papers were applied. First, in a quantitative analysis, a bibliographic analysis was conducted including number of manuscripts by year, database, type, source, geographical information, and keywords. In the second, a systematic narrative summary is provided as a table to summarize and to compare studies’ results. A standardized form for extracting data (i.e. authors, geographical information, methodology (technique/application), aim of the research, and research gap) from papers was developed.

The following iterative steps were conducted to search and select the literature.

1. Searching with the keywords in the databases resulting in 3397 paper.
2. Selecting review, research and conference articles written in English (2754 paper remaining).
3. Eliminating all manuscripts that are not within the field of forestry, agriculture, environment, engineering, biochemical, energy, business, economics, logistics or supply chain (management) (2509 paper remaining).
4. Checking the manuscripts for duplicates: Duplicated papers were identified by the authors’ name, the title and the abstract. Afterwards repeated documents were be removed; Screening the title and the abstract of remaining paper against the eligibility criteria and through following screening questions based on the eligibility criteria:
   a. Does the paper treat wood and wood supply issues?
   b. Does the manuscript contain issues related to wood supply chain risks or supply security?
   c. Does the manuscript contain impacts of supply chain risks on wood supply security?
   d. Does the manuscript contain strategies to ensure wood supply and mitigating supply chain risks?
   e. Does the paper treat supply security or supply chain risk issues regarding renewables other than wood?
   f. Does the manuscript contain effects or side effects of a growing wood-based bioeconomy on wood supply security? (134 paper remaining).
5. Assessing the full-length articles and prove the eligibility criteria (105 papers remaining).

3. Main definitions

[22] summarised eight types of risks in the context of supply chains: supply risks, operational risks, demand risks, security risks, macro risks, policy risks, competitive risks and resource risks. The first four risks connected strongly with internal supply chain factors, whereas the latter four risks describe external factors influencing supply chains [22] (Table 1). The eight categories serve as basis for supply chain risk categorisation in this review (see Table 2).

Risk management includes strategies to reduce risk events or mitigate the results of such events [22]. In the study at hand these strategies are called wood supply chain risk mitigation strategies since they are aiming to provide a stable and uninterrupted wood supply.

Wood supply security is “the ability to procure a certain volume of roundwood at a stable price” [23] fulfilling the demanded assortment

Table 1
Categorisation of wood supply chain risks [22].

	Risk category	Risk source
Internal risks	Supply risks	E.g. failed access to material, inventory, technology; quality or price issues
	Operational risks	E.g. breakdown of production or logistic infrastructure; missing capability; changes in processes
	Demand risk	E.g. fluctuating demands based on new products, fads; demand distortion and amplification
	Security risks	Security breaches from terrorism, vandalism, etc.
External risks	Macro risks	E.g. changes in prices, interest rates, exchanges rates
	Policy risks	E.g. governmental regulations, quotas, restrictions
	Competitive risks	Lack of historical information on competitors
	Resources risks	Unforeseen resource requirements

Table 2
Wood supply chain risks: categories and specific risks.

Wood supply chain risk category (based on [22])	Risk sub-category	Description of specific risk	Authors
Supply risk	Over-exploitation of forest resources	Unsustainable use of forest resources, illegal logging, delayed replantation/ regrowth, trading in uncertified wood	[10,13, 31–36]
		Deteriorating forest system functions (e.g. biodiversity), competition for forest areas based on alternative land use requirements, forest area conservation	[13,18,23, 27,31,33, 37,38]
		Uncertainty in techno-economical resource accessibility, promotion of wood harvesting, local reduction in forested areas, poor harvesting practices	[2,9,31,35, 37,39–48]
		Rising market demand	[36,43,47]
	Insufficient resource supply	Complicated organisation of supply due to fragmented forestry ownership structure	[2,31,42]
		Forest owner's willingness to harvest wood, lack of interest of forest owners in managing their forests, attitudes of stakeholders, unreliable biomass producers (in volume, quality), lack of qualified work force	[2,17,27,31, 37,39,40, 45,49,50]
		Price fluctuations, market price influences availability, price relation of both biomass price to crude oil price or of biofuels price to fossil fuels price	[2,4,31,44, 50,51]
		Limited access to harvest residues and industrial by-products	[5,50]
		Substitution between wood quality assortments	[36,43,50, 52,53]
	Resource scarcity	Certification schemes, such as PEFC, FSC, assure sustainable forest management and by its introduction reduce the supply volume	[13,35,36]
	Wood quality specific risk	Product instability and perishability (humidity, explosion risks, fungi)	[29,40, 54–57]
		High bulkiness of roundwood	[7,54]
		Limited storability	[31,58]
Operational risk		Information deficits and lack of coordination (transparency)	[31,40,59]
		Dependency on single transport mode/one supplier, lack of infrastructure, transport route risk	[8,9,23,37, 40,45,60, 61]
		Disperse biomass production, lack of significant volume, distribution density, lack of pre-treatment technologies to increase energy density	[8,49,50,52, 58,62–65]
		Technical inefficiency, lack of technology, deficient practices, special technology with limited replicability and penetration	[9,10,31, 40]
		Operational difficulties (depots, road system), on-site logistics, insufficient space (e.g. for chipping), unreliable carriers (delays, cancelled shipments, technical breakdown)	[37,40,47, 66,67]
		Lack of investment in infrastructure (e.g. harvesting, collecting and storing, transport), intermodal transport, year-round available terminals, pre-treatment	[8,17,37, 58]
Demand risk		Seasonal demand (e.g. heating season)	[38,68]
		Purchasing power of consumer	[31,48]
		Opportunistic behaviour of biomass producers	[40]
		Volatile biorefinery production volumes, biorefinery location, technology development regarding utilisation degree	[44,62,63, 69]
		Lack of civil acceptance and support for large-scale plants, food vs. fuel conflict	[40,61,70]
Macro risk	Wood trade risk	Lack/inaccuracy of production, trade and consumption statistics (national and international).	[64]
		International trade driven by the political, economic or social environment of the wood importing/ exporting countries (e.g. national incentives) with conflicting targets.	[8,44,53,60, 71,72]
		Supply dependence on other countries/foreign stakeholders, unreliable delivery, international market disruption, bilateral trade friction, reduction of domestic supply capability, exchange rate fluctuations	[37,47,51, 60,71–76]
Policy risk		Subsidies/regulations (e.g. promoting bioenergy, import/export barriers, bans, taxes)	[4,13,40,41, 47,60,64, 73,77,78]
		Wood trade restricted to limited geographic areas, communal land tenure systems	[48,79]
		Country specific legislation (e.g. mandatory certification, proof of chain of custody)	[27,37,38, 40,41,47]
		Incompatible certification systems (e.g. PEFC, FSC)	[64]
		Varying sustainability criteria	[16]
		Different perceptions of stakeholder on policy making and development	[80]
Competitive risk			

(*continued on next page*)

Table 2 (*continued*)

Wood supply chain risk category (based on [22])	Risk sub-category	Description of specific risk	Authors
		Resource competition within wood-based industries	[5,13,17,37,39,43,50,70,75,81]
		Wood theft, illegal logging, fuelwood collecting for private purpose mainly in developing countries	[13,28,30,34,48,56,82]
Resource risk	Ecosystem risk	Natural disturbances (diseases, pests, weeds, fires, storm, floods, droughts)	[13,16,18,27,31,37,40,49,56,70,83]
		Disturbances by climate change impacts	[13,37,38,45,49]
		Unfavourable weather conditions (e.g. heavy snow fall or rain hindering harvest operations and forest road accessibility)	[8,13,18,31,47,56], [84,85],
	Seasonality risk	Cyclic harvesting periods	[25,31,49,54,55,58,84,86]
		Seasonal fluctuations of yield and quality	[5,37,40,62,85,87–89]

qualities without supply disruptions. So, supply security for this study is defined as the ratio of fulfilled demand to total demand with sustainably produced wood in a given time unit.

On the basis of Roos [24] this study defines wood-based products as follows: (1) established wood products (e.g. sawmill products, building material, furniture), (2) large-volume bioenergy products, as fuels, heat and power, and (3) established and new chemical wood-based products (e.g. cellulose-based products, biomaterials, chemicals or pharmaceuticals) resulting from chemical or thermochemical processes applied to wood material. Proceeding thereupon, the identified papers were clustered by these three product types.

4. Results

4.1. Quantitative analysis

The keyword search resulted in 3397 papers (2213 Science Direct, 1167 Scopus, 17 Web of Science), whereof 105 papers (Fig. 1); 92 research papers, 11 reviews, and 2 conference papers) published between 1975 and 2019 met the inclusion criteria. Most articles were published in the journal Biomass and Bioenergy (24%) (Fig. 2).

Fig. 3 shows the regions and countries that were investigated in the reviewed papers. 16% of the papers had a global perspective, compared

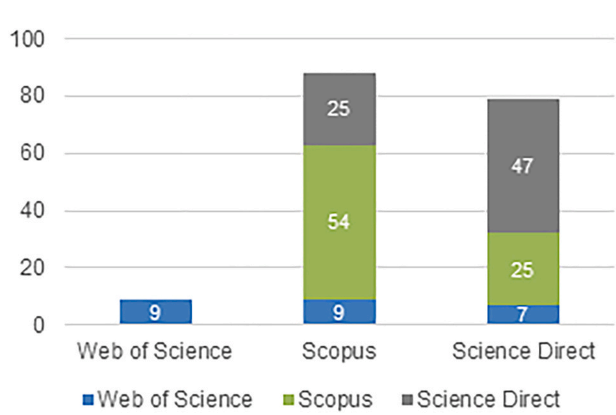

Fig. 1. Number of papers by database.

to 10% for each of Europe and the United States of America. Papers with a global perspective mostly focussed on bioenergy supply chain related issues, e.g. international trade, securing biomass supply, certification systems, sustainability and optimisation of biomass supply chain chains. 10 out of 11 Europe-concerning papers deal with trade and allocation of biomass for bioenergy purposes mostly driven by political directives. All of the papers covering the United States of America are shown in a biorefinery context, whereof 10 out of the 11 discussed examine biofuel production.

Nearly 80% (81 papers) of the total papers were published between 2010 und 2019. Only six papers were published before 2001, one per year in 1975 [25], 1978 [26], 1993 [27], 1999 [28] and two in 1995 [29,30]. Wood use for bioenergy production was discussed for the first time by the last four [27–30]. Since 2006, biomass supply chain risks and related topics have been, in the context of bioenergy, frequently investigated (Fig. 4). Biomass and wood supply chain risks and risk mitigation strategies were in focus in the last years. Similarly, the chemical conversion of wood has recently become an upcoming topic (see Fig. 5).

Of the papers reviewed, 88% investigated risk mitigation strategies, making it the most common topic. Supply chain risks, the impacts of supply chain risks and supply security were less frequently addressed with 71%, 43%, and 12%, respectively (Fig. 4).

4.2. Qualitative analysis

4.2.1. Categorisation of wood supply chain risks

Based on the eight categories of supply chain risks from Manuj and Mentzer [22] seven wood supply chain risk categories were defined. As no paper mentioned security risks (e.g. terrorism or vandalism) this risk category was excluded. Table 1 summarises the results.

Table 3 lists wood supply chain risks and briefly summarises their impact on supply security, following the previously introduced wood supply chain risk categories. For five out of seven wood supply chain risk categories, supply chain impacts were identified. Supply chain risks impacts of demand risk and competitive risk were not discussed.

4.2.2. Wood supply chain risk mitigation strategies

Mapped risk mitigation strategies (92 papers) were grouped into the categories: production optimisation, feedstock and source diversification, long-term contracts, supply chain integration, logistics strategies, process/technology innovation, increasing shelf-life, and policy strategies. The reviewed papers show different time horizons of mitigation strategies: strategic (long-term), tactical (medium-term) and operational (short-term) (Table 4).

4.2.3. Reviewed research methods

Supply chain risks and risk mitigation strategies were most frequently examined with policy analysis and literature reviews were the most often chosen method (20 times), of which 15 papers were written in the bioenergy context. Supply risk mitigation strategies were mostly investigated by applied methods such as supply chain analysis/design, optimisation or criticality assessment (20 times). With 16 supply chain risk mitigation strategy papers the bioenergy sector was again the most investigated one.

Raw material supply for established wood products was mostly investigated with methods, such as policy analysis and literature reviews as well as methods of supply chain analysis/design, optimisation or criticality assessment (both each four times).

Comprehensive investigations considering the entire wood supply chain with all the three types of wood-based products are lacking. First approaches catching a more completely picture of the wood supply chain are, for instance Refs. [53,72] focusing primarily on the bioenergy sector. Ghafghazi et al. [43] and Chitawo et al. [10] enlarged investigations through consideration of the entire wood supply chain looking at interdependencies by applying Material Flow Analysis or

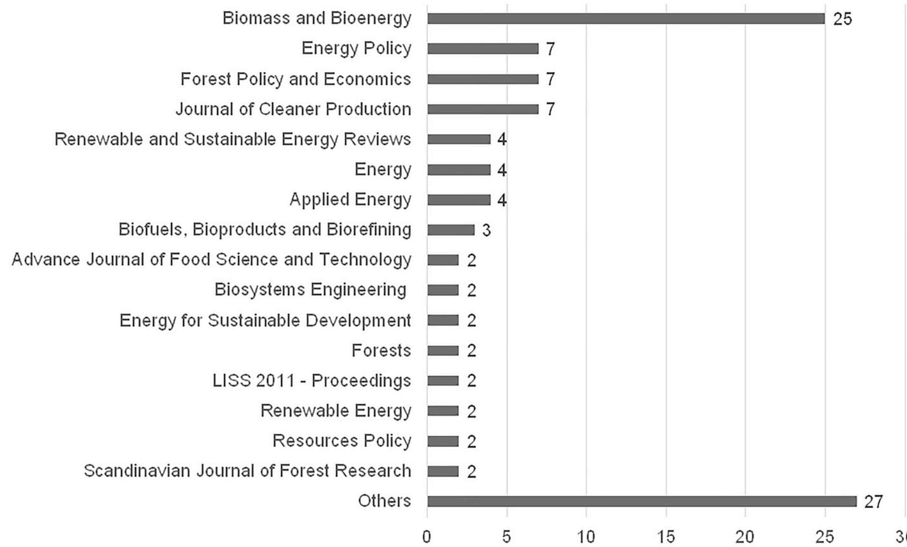

Fig. 2. Number of papers by journal.

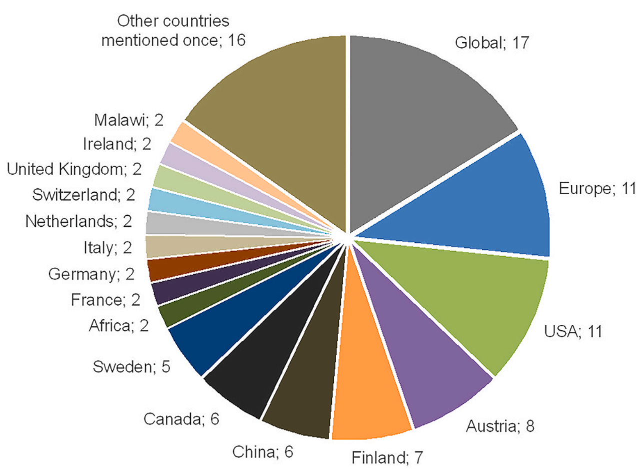

Fig. 3. Region/country of investigation and number of publications.

System Dynamics.

To sum up, the lack of studies on wood supply security and the conjoint analyses of wood supply for established wood products (e.g. sawnwood, veneer, panels) and established and new chemical wood-based products (e.g. chemicals, cellulose fibres, pulp and paper) becomes obvious (Fig. 6).

5. Comparative analysis and discussions

Reviewed papers mostly considered bioenergy (biofuels, heat, power) topics (75%, 85 papers). Infrequently studied were the two topics of established and new chemical wood-based products (8%, 9 papers) and established wood products (19%, 20 papers). There is also a strong connection between the country of investigation and the research focus. Considering bioenergy, Austria (8 papers), Finland, and Sweden (5 papers each) are the leading countries. Additionally, 10 papers focusing on supply for bioenergy production considered Europe and the United States of America. Thus, there seems to be a strong interest in optimising biomass supply chain for bioenergy production in Europe

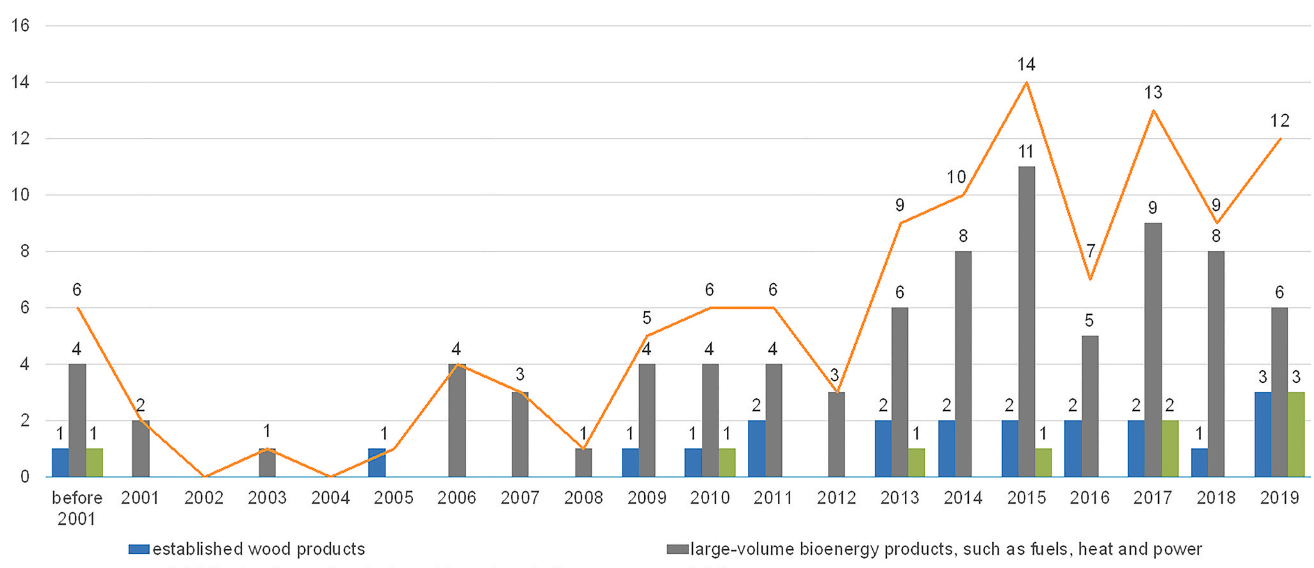

Fig. 4. Type of wood-based product examined by the reviewed papers (multiple answers possible).

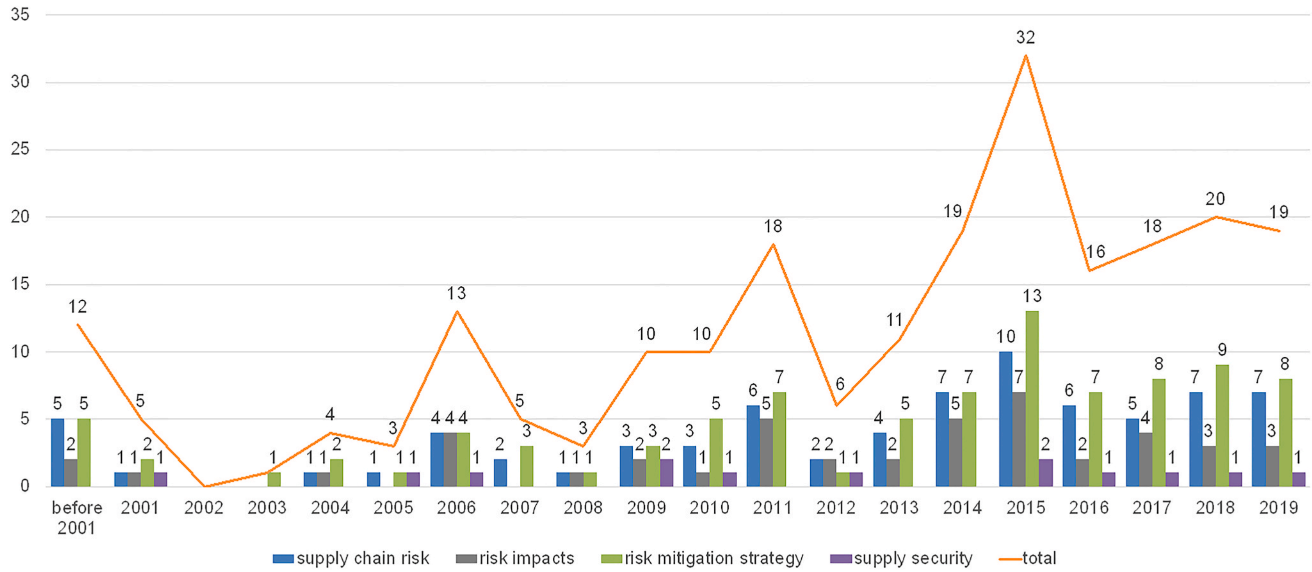

Fig. 5. Number of papers by publication year and research topic (multiple answers possible).

and the United States of America. That is in line with Santos et al. [16], who found bioenergy supply chains to be mostly investigated in Europe and North America, whereas in the United States of America biofuel production and in Europe heat and power production have a higher priority.

Contrarily, supply chain risk issues within established wood products were mostly investigated in China (4 papers), mainly dealing with import dependencies, followed by Canada (3 papers), mostly considering availability and distribution of by-products. Established and new chemical wood-based products were themed in 9 papers with no regional focus.

Unsurprisingly, since year-round supply in terms of volume, quality, and price is critical for large-scale projects [4], large-volume bioenergy products are the most investigated. For bioenergy, the most commonly applied investigative methods are interviews, workshops, (Delphi-) surveys, and case studies. Economic analyses are the most applied method within biofuel production studies [63,95,101] considering almost exclusively the feedstock crops, annuals, and waste [18,62,63].

Among the 75 papers dealing with supply chain risks, limited resources are considered the most (41 papers), followed by supply and operational risks (22 papers). Risk impacts were less discussed, but "impacts" were also not explicitly searched among the keywords. Nonetheless, it shows that multilevel interdependencies are only rarely considered. Additionally, risks tend to be investigated separately and rarely in the context of the entire wood supply chain, therefore level interdependencies are mainly excluded (cf. [18]). Generally, buyers have to accept trade-offs between cost reduction and supply chain risk reduction through supply splitting [40,87] and storage [25]. Comparing the previously mentioned supply chain risks with supply chain risks addressed in general supply chain literature it is noticeable that generic risks such as strikes [116,117], or infringement of traffic regulations [116] (e.g. permissible load restriction) [118] are not mentioned within the reviewed papers.

The most mentioned wood supply chain risk mitigation strategy is resource and feedstock diversification (92 papers, 41%; cf. also [55]). For bioenergy production multilevel redundancies (e.g. multi boiler systems) and diversification are key risk management strategies [45,87]. Within biofuel production diversification is a common strategy, since supply risks are mitigated through perennial woody biomass, logging residues, import of feedstock [63], and blending [62]. Supply chain integration (28 papers, 30%) and increasing shelf-life (25 papers, 27%) are the next most frequently discussed risk mitigation strategies. The former is often used in large-scale bioenergy projects [31,61], whereas increasing shelf-life by pre-treatment is strongly connected to the import of biomass [3,40,51,65]. Papers with a practical context applied different combinations of risk mitigation strategies [39,61,66,94]. For instance, a German case study dealing with a power plant's wood supply chain shows that diversifying suppliers reduces wood supply chain risks and that investors claim for long-term contracts [39].

Wood supply security is a topic which is seldom addressed and the implicit definition of supply security differs between both region and the specifically addressed wood-based product. Only one paper explicitly defines the term "supply security" within the context of wood supply: "Supply security, that is, the ability to procure a certain volume of roundwood at a stable price, is an important factor in roundwood procurement planning." [23]. A detailed investigation of strategies to ensure fuel wood supply security in Austria was carried out by Ref. [37] using portfolio and risk analyses. For a large energy plant in Vienna fuel wood supply security was one important topic due to its suboptimal urban location [61]. Generally, supply security in the Austrian bioenergy sector has strong interdependencies with roundwood imports for the wood processing industry, since the feedstock self-sufficiency rate of the Austrian bioenergy sector is low. Roundwood importing and sawn wood exporting countries such as Germany, Austria, Sweden, and Finland often use sawing industry by-products for energy production. Thus, in these countries, bioenergy sector supply security is partly dependent on imports [72].

Internationalisation of wood and biomass trading offers an opportunity to ensure supply [35,60,74,76,100] as resource sources can be diversified [41,88]. Imports from countries with large resources [60] reduce domestic supply-side uncertainties [55] and trading with different import countries diminishes the risk of import dependencies [78].

An efficient logistic is essential to ensure competitive wood supply [4,37,57]. There are two ways to achieve this: First, locating facilities near the raw material resource [6] to shorten transport distances and second, locating facilities near harbours or terminals to enable economic long-distance ship or railway transport and enlarge the supply radius to increase feedstock availability and to reduce supply risk [7,8]. Long-distance transportation and storage at transhipment points allow the supply of large volumes by a single operator so that a stable quality of delivered fuelwood resource can be achieved [89].

Ghafghazi et al. [43] stated that limited availability of surplus sawmill by-products underlines the importance of developing wood

Table 3
Impacts of wood supply chain risks on wood supply security.

Wood supply chain risk category (based on [22])	Risk subcategory	Supply chain risk impact	Authors
Supply risk	Overexploitation of forest resources	Long-term degradation of soil leads to unproductive land, stricter sustainability criteria affects both volume and costs of wood supply, inefficient use of wood resource risks the overuse of the sustainable resource and depletion of mature stands	[4,10,32,34,36]
		Forest degradation, lower fuel production, reduced land productivity	[34,82]
		Increasing pressure on forests and agricultural land, wood imports shifting the pressure on foreign forests	[2,82]
		Expanding rotation lengths decrease future harvest volumes	[33]
	Insufficient resource supply	Higher prices, spot market supply, low self-sufficient rate, import dependency	[31,36,70,73]
	Resource scarcity	Competition between bioenergy plants	[81]
		Reduction in sawlog demand diminishes also the availability of pulpwood and sawmill by-products	[27]
		Scarcity within sawmill by-products boosts competition between energy production and pulp/panel production	[43,53,72,77]
	Wood quality specific risks	Quality deterioration, need of phytosanitary treatments, lack of international standards	[29,31,56–58,64]
Operational risk		Logistic complexity in wood supply networks	[5,17,49,58,66,85]
		Reduced efficiency through long transport distances to cover the demand for large scale plants	[47,70,90]
		Capacity constraints, long lead-times, varying transportation time, overall operational difficulties	[9,40,45,54,55,58]
		Failing wood supply commitments affects the local industry and employment	[27]
Macro risk	Wood trade risk	Reduced job opportunities and income	[76]
		Limiting investment decisions and capital flow, decrease production	[64]
		Overexploitation of local/regional resources	[34,82]
		International timber supply fluctuations, legal uncertainty in foreign countries, dependency from other countries, decreasing wood import potentials	[37,60,71,72,75]
Policy risks		Influencing wood trade (positively and negatively)	[64,77]
		Regulations regarding standardisation/certification exclude smaller stakeholders	[41]
		Resource availability and investment uncertainty	[65]
Resource risk	Ecosystem risks	Fluctuations in wood availability: sudden oversupply for a short period of time followed by a significant supply shortage (afforestation, regrowth of next tree generation)	[13,31,37,49,55,70,72]
		Geographic shifts in growing conditions, reduction of available wood volumes of specific species (e.g. spruce in lowlands and low mountain range)	[33,70]
	Seasonality risks	Long-term damages in wet areas, fluctuations in market price/harvest and transport capacity	[8,29,58,70,84]
		Forest accessibility (e.g. steep terrain), forest road accessibility (poor infrastructure condition)	[8,9,31,39,45–48]

supply risk mitigation strategies for the emerging wood-based bioeconomy, taking into account the impact on regional fibre flows and fibre availability for the existing secondary industry (e.g. pulp and panel industry, pellets production). For example, the Canadian bioeconomy largely depends on having direct access to primary wood from forests, as sawmills usually supply in-plant facilities (e.g. combined heat and power plant, pellets production) with a higher priority than third parties due to benefits of co-production and economies of scale [50].

Large-scale storage increases supply security and absorbs supply and demand shocks and smooths operations of large plants (e.g. biorefinery, bioenergy) [84]. Karhunen et al. [47] show that only 8 out of 24 Finnish CHPs are developing or have established supply security plans. Furthermore, bioenergy producers lack contingency plans for the consequences of climate change as forecasts mainly rely on historical data and experience [45]. Process resilience can be increased by resource diversification [25], by the raising availability of wood in the market place [31], or developing contingency plans to reduce time-to-recovery. The latter is strongly needed in times of supply disruptions [55].

One limitation of this review arises from the methodology applied referring to the fact that not all studies concerning wood supply chain risks, risk impacts, wood supply security, and wood supply risk mitigation strategies have been considered due to the selected keywords and databases. Furthermore, as wood supply chain risks and risk mitigation strategies are often discussed in general, managerial implications of risks and strategy implementation issues are not examined in detail. Nevertheless, this review provides valuable insights and a good overview of wood supply chain risks such as resource risk, operational risk, supply risk, competition for resources, and policy issues.

6. Challenges and research gaps

Since future biomass supply is highly uncertain [51], but a key success factor of wood-based bioenergy and biorefinery plants, sustainable biomass supply in large volumes [4,44], and over several decades [32] is crucial. The imperfect understanding of the complex global biomass supply chain network [9] and the not fully traceable international trade flows [64] require further research on wood supply security and wood supply chain integration on a global level. As supply of

Table 4
Wood supply chain risk mitigation strategies; strategic (s), tactical (t), operational (o).

t	Harvest	Genetic improvements, reforestation, increasing harvesting quantities through the use of more forest areas, shortening the rotation period, using new assortments	[26,31,48,70,91]
		Limitation of annual cut for sustainable forest management, strengthen the social licence to operate	[10,13,92]
		Transforming produced, but unavailable potential to available biomass (e.g. collecting cultivated brushwood or cleaning material in plantations).	[81]
o		Logging residues management minimising nutrient losses	[93]
		Soil protection (brush mats, lighter harvesting machines)	[29,82,93]
t	Resource/ feedstock diversification	Resource diversification	[4,25,40,57,58, 70,75,88,94–97]
		Multiple feedstock/substitution strategy	[5,27,28,31,42, 55,70,81,82,93, 98–100]
		Mixed biomass feedstock blending	[62,69,101]
		Interchangeable technology/ equipment	[45,47,53]
		Internationalisation	[35,55,60,74,76, 100], [78]
		Domestic mobilisation	[102,103]
s	Supply chain integration	Cooperative supply	[4,6,9,31,37,39, 45,47,54,60,70, 73,80,82,102, 104]
		New business models, new organisational structures, integration of traders	[31,54]
		Co-location strategy	[6,86]
		Horizontal integration and cooperation (e.g. private forest owner network)	[8,9,26,31,37,38, 40,47,60,61,66, 73,102,103]
		Vertical integration	[42,99]
t	Long term contracts	Fixed price quantity-inflexible contract strategy at early stage	[87]
		Price index coupling contract strategy	[66]
		Flexibility within long-term contracts by option contracts or hedging	[40,88]
		Supplier commitment for long-term contracts strategy	[31,58,66]
		Combination of long-term contracts with supplier integration	[23,39,105]
		Mixed strategy of long-, medium- and short-term contracts with different suppliers	[106]
s	Logistics strategy	Contingency plans: reduced time-to-recovery	[45,55]
		Supply chain optimisation: process reengineering, transport of more assortments, optimising information flow, implementing RFID, using real-time information	[31,37,40,56,59, 83,107]
		Multimodal transport strategy: transhipment points, terminals, train/vessel/container systems, integration of harbours	[7,8,42,50,67,69, 70,89,90,98,100]
t		Matching infrastructure regarding demand and supply patterns, asynchronous supply and demand curves	[58,83]
o		Regional supply strategy considering (forest) roads, road network, regional terminals or railway-loadings	[6,46,47,71,108]
		Spot market supply	[45]
t	Storing strategy	Inventory-based strategy	[17,25,46,49,55, 62,84,85, 109–112]
		Third party logistics, consignment stocks	[89]
		External storage	[37,45,47,50,71, 88,89]
o		On-site storage, short-term storage	[26,40,45]
s	Process innovation	Standards for biomass pre-processing	[64,70]
t		Technology capable of processing/ converting multiple feedstock	[65,70,95,96,101, 113,114]
		Flexibility in operation and technology	[70,106]
o		Pre-treatment: drying, chipping, pelleting, debarking, etc.	[3,29,31,37,40, 58,62,70,84,86, 87,95,108,111]
		Pile covering	[3,112]
s	Policy strategies	Regulatory frameworks: production and use of biomass, replacing inefficient technologies, engage substitutes' attractiveness, funding of forest development, governmental control, minimising bureaucracy and interorganisational transactions	[9,31,34,48,115]
		Political stability: predictable taxation and subsidies, continuity of labour availability	[47]
		Reliable international wood flows: regular data, consistency in supply, chain of custody, certification, due diligence	[38,52]
		Incentives to meet bioenergy and bioeconomy requirements	[37,50]
		Cascading use of wood: political incentives, stable framework, improvement of recycling	[26,52,65]
		Regulations for a sustainable forest management, certification systems	[13,26,29,35,65, 103]

biomass and biofuels from Central and East Europe to the European markets is competitive [110], and large biomass potential exists for bioenergy production are located in Latin America, Sub-Saharan Africa and Eastern Europe [8], a year-round sustainable and secured supply has to be carefully investigated. For instance, biomass-based chemical production is forecast to result in an 80% import rate of biomass for the Netherlands by 2030, with South America as the largest supplier [44].

Sustainable resource management on a global level is the main challenge as limited natural resources face increasing demand in several areas, so strategies to strengthen sustainable forest management should be developed [48]. In 2006, a review of certification systems was published which aimed to provide a basis for developing evaluation criteria and certification systems for a more sustainable bioenergy trade [35]. However, more than one decade after that investigation, the development of effective regulations is still needed to protect forests from illegal logging and to decrease wood supply chain risks [13]. Despite existing certification systems (PEFC, FSC) providing evaluation criteria and control measures for sustainable forest management, there is still a need for an effective measurement system to avoid overharvesting [13], especially for wood used for energy production [29].

Domestic use versus the export of biomass is discussed at international levels since socioeconomically, exporting and importing countries are impacted differently. Developing countries benefit from the certified and sustainable production of biomass whilst exporting the excess of domestic demand [8]. However, in developed countries supply security is a pressing topic for some forest products and wood species [13,14]. Future challenges include a growing dependence on exporting countries, land use changes in those exporting countries, ecological and social sustainability criteria and measurement. Therefore, reliable and

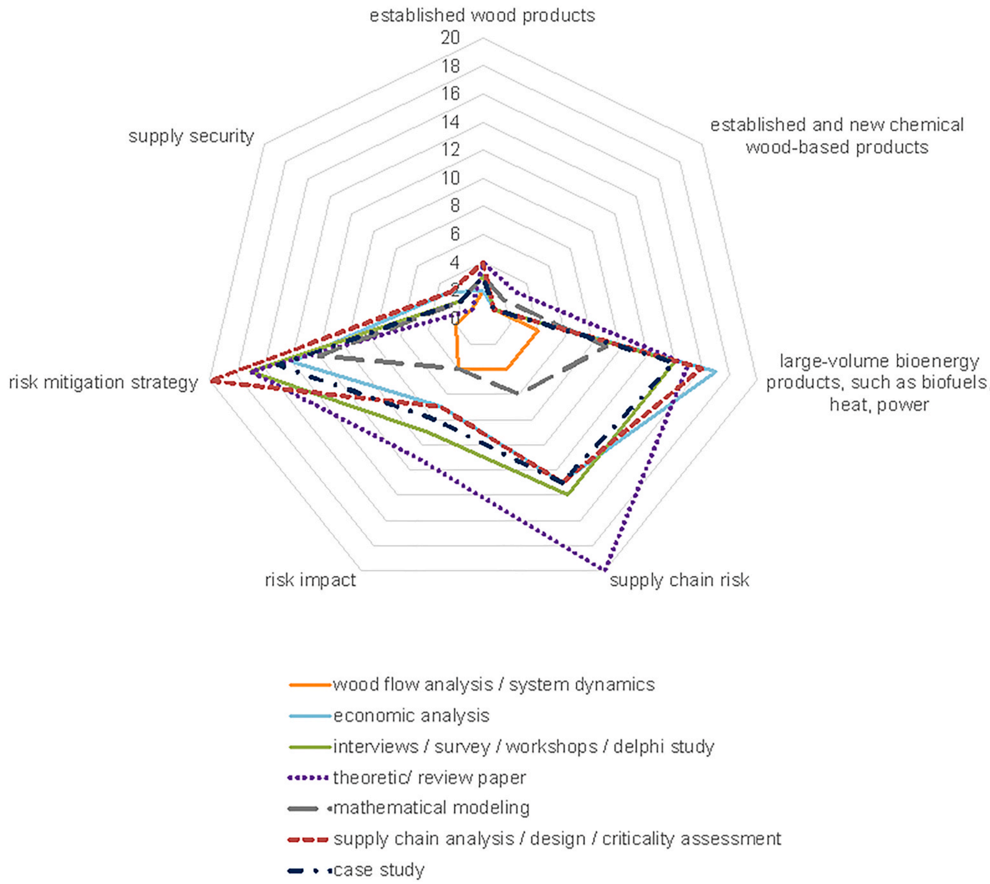

Fig. 6. Methods, research topic and type of wood-based product.

transparent sustainability assessment, for instance within established certification systems such as PEFC and FSC, for wood exporting and importing countries are a promising future research topic [16]. Additionally, more insight is required into global impact assessment based on transparent global forest and wood product trade flows when considering indirect imports, including direct and indirect land use changes and the impact of competing markets for biomass resources and the resulting biomass prices [8,44,51,53]. Identifying drivers and barriers in wood flows combined with a study of historical and actual wood flows will provide insights of how international trade effects local prosperity, industrial development and sustainable forest management in developed, emerging and developing countries.

Thereby, it is strongly recommended to further investigate the impacts of political regulations and agreements (e.g. Sustainable Development Goals of the United Nations such as SDG 15 Life on Land, SDG 12 Responsible Consumption and Production) on international wood supply chains.

Wood supply chain research regarding supply security issues is very limited, especially for the emerging established and new chemical wood-based products [54]. Thus, the integration of these new wood-based products in modelling technical, economic, and ecological impacts on biomass resources [44] especially on wood resources are needed. In order to mitigate supply chain risks, especially international trade risks, long-term international sourcing strategies should be based on wood utilisation studies. For instance, the growth of the Asian bioenergy will demand more biomass in the future, thus creating an increasing need for research on global wood supply chain strategies [17]. To analyse international wood flows, reliable and regular data needs to be extracted [52]. In order to develop overall supply chain strategies a dynamic approach is suitable for the evaluation of different scenarios of: forest management, wood utilisation, forest residues and bioenergy production [10].

Secure wood supply for energy generation can be achieved by realising a multi-stage wood utilisation approach [11,119–121] that has considerable potential for reducing feedstock shortage and competition in forest-based industries. This should be further evaluated in future studies. Wood supply chain analyses considering all three types of wood-based products are missing in the context of wood supply security. Furthermore, studies viewing the entire wood supply chain with its multilevel interdependences and integrating cascading use of wood and wood-products are rare.

Regarding wood supply chain risks and risk mitigation strategies, more research is needed in long-term contracts, diversification strategies [87], supply chain integration [6], storage and pre-treatment [109], as well as wood supply risks induced by forest ownership characteristics [79]. Uncertainty in wood supply triggered by environmental (e.g. forest disturbances by wildfire or insect diseases) [16] or social factors should be investigated since especially the latter one is rarely addressed. Topics may, for example be forest owners' willingness to sell wood, civil acceptance of large scale plants, feed versus fuel discussion, and the social licence to operate [92]. Therefore, strategic wood procurement planning should consider current and future biomass availability in regions of potential supply. It is necessary to identify potential shortages or price fluctuations [17] along with the diversification of feedstock pre-treatments as well as storage strategies and contracting reducing supply chain risks for established and new chemical wood-based products [87].

7. Conclusion

Most papers dealing with wood supply chain risks focus on fuelwood supply risks affecting bioenergy generation [12,37,47,108]. Several studies were conducted to develop strategies to mitigate supply chain risks for large-scale, generally bioenergy, plants [e.g. 5,61]. The growing demand for forest residues driven by regulations, subsidies, or directives precipitated numerous studies on risk mitigation strategies within the bioenergy sector [44,51,65,77]. Europe especially has a focus in securing bioenergy production. Only a few studies consider the established and new chemical wood-based products and, therefore, rarely investigate wood supply chain risk issues for the sawmill, wood panel, pulp and paper industries, or biorefineries [23,33,60,78]. In this area, China published the most papers, whereas established and new chemical wood-based products have no clear regional focus.

The main risk mitigation strategies are resource and feedstock diversification, supply chain integration, as well as increasing process resilience, technology innovation and product shelf-life. Furthermore, long-term contracts and supplier integration is a common way to reduce supply chain risks.

Investigations of wood supply security are still rare, particularly for established and new chemical wood-based products. Therefore, this field offers a wide range of research opportunities. Developing and evaluating a robust mix of strategies, especially the analyses of supply potentials including cascading wood use and various resource restrictions (ecological, economical, technical, social) to calculate the wood supply available in the market, provides great potential for further research. Comprehensive analyses and investigations of the entire wood value chain with its multilevel interdependences and integrating cascading use of wood are missing.

Acknowledgement

Veronika Auer is grateful for the support received from the Conference of Women's and Gender Equality Representatives at the Bavarian Universities (Landeskonferenz der Frauen-und Gleichstellungsbeauftragten an Bayerischen Hochschulen (LaKoF)) within an educational program.

References

[1] B. Hillring, World trade in forest products and wood fuel, Biomass Bioenergy 30 (10) (2006) 815–825, https://doi.org/10.1016/j.biombioe.2006.04.002.
[2] C. Söderberg, K. Eckerberg, Rising policy conflicts in Europe over bioenergy and forestry, For Policy Econ 33 (2013) 112–119, https://doi.org/10.1016/j.forpol.2012.09.015.
[3] A. Sosa, M. Acuna, K. McDonnell, G. Devlin, Controlling moisture content and truck configurations to model and optimise biomass supply chain logistics in Ireland, Appl. Energy 137 (2015) 338–351, https://doi.org/10.1016/j.apenergy.2014.10.018.
[4] S. Pätäri, Industry- and company-level factors influencing the development of the forest energy business — insights from a Delphi Study, Technol. Forecast. Soc. Change 77 (1) (2010) 94–109, https://doi.org/10.1016/j.techfore.2009.06.004.
[5] M. Junginger, A. Faaij, R. van den Broek, A. Koopmans, W. Hulscher, Fuel supply strategies for large-scale bio-energy projects in developing countries. Electricity generation from agricultural and forest residues in Northeastern Thailand, Biomass Bioenergy 21 (4) (2001) 259–275, https://doi.org/10.1016/S0961-9534(01)00034-4.
[6] C. Lloyd, P. Dey, Supply chain integration in the UK bioenergy industry: findings from a pilot study, J. Clean. Prod. 79 (2014) 41–52, https://doi.org/10.1016/j.jclepro.2014.05.080.
[7] D. Gonzales, E.M. Searcy, S.D. Ekşioğlu, Cost analysis for high-volume and long-haul transportation of densified biomass feedstock, Transp Res A Policy Pract 49 (2013) 48–61, https://doi.org/10.1016/j.tra.2013.01.005.
[8] A. Faaij, J. Domac, Emerging international bio-energy markets and opportunities for socio-economic development, Energy Sustain Dev X (1) (2006).
[9] I. Lewandowski, Securing a sustainable biomass supply in a growing bioeconomy, Glob Food Sec 6 (2015) 34–42, https://doi.org/10.1016/j.gfs.2015.10.001.
[10] M.L. Chitawo, A.F. Chimphango, S. Peterson, Modelling sustainability of primary forest residues-based bioenergy system, Biomass Bioenergy 108 (2018) 90–100, https://doi.org/10.1016/j.biombioe.2017.10.022.
[11] A.L. Bais-Moleman, R. Sikkema, M. Vis, P. Reumerman, M.C. Theurl, K.-H. Erb, Assessing wood use efficiency and greenhouse gas emissions of wood product cascading in the European Union, J. Clean. Prod. (2017), https://doi.org/10.1016/j.jclepro.2017.04.153.
[12] A. Karhunen, M. Laihanen, T. Ranta, Supply and demand of a forest biomass in application to the region of South-East Finland, SGRE 3 (1) (2012) 34–42, https://doi.org/10.4236/sgre.2012.31005.
[13] D. Ioannidou, R. Pommier, G. Habert, G. Sonnemann, Evaluating the risks in the construction wood product system through a criticality assessment framework, Resour. Conserv. Recycl. (2019) 68–76, https://doi.org/10.1016/j.resconrec.2019.03.021.
[14] F. Schier, C. Morland, N. Janzen, H. Weimar, Impacts of changing coniferous and non-coniferous wood supply on forest product markets: a German scenario case study, Eur. J. For. Res. 137 (3) (2018) 279–300, https://doi.org/10.1007/s10342-018-1111-6.
[15] C. Hennig, A. Brosowski, S. Majer, Sustainable feedstock potential – a limitation for the bio-based economy? J. Clean. Prod. 123 (2016) 200–202, https://doi.org/10.1016/j.jclepro.2015.06.130.
[16] A. Santos, A. Carvalho, A.P. Barbosa-Póvoa, A. Marques, P. Amorim, Assessment and optimization of sustainable forest wood supply chains – a systematic literature review, For Policy Econ 105 (2019) 112–135, https://doi.org/10.1016/j.forpol.2019.05.026.
[17] S. Ko, P. Lautala, R.M. Handler, Securing the feedstock procurement for bioenergy products: a literature review on the biomass transportation and logistics, J. Clean. Prod. 200 (2018) 205–218, https://doi.org/10.1016/j.jclepro.2018.07.241.
[18] C. Abbati de Assis, R. Gonzalez, S. Kelley, H. Jameel, T. Bilek, J. Daystar, et al., Risk management consideration in the bioeconomy, Biofuel Bioprod Biorefin 11 (3) (2017) 549–566, https://doi.org/10.1002/bbb.1765.
[19] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altmann, The PRISMA Group, Preferred reporting Items for systematic reviews and meta-analyses: the PRISMA Statement, PLoS Med. 6 (7) (2009), https://doi.org/10.1371/journal.pmed.1000097.g001.
[20] P.J. Lucas, J. Baird, L. Arai, C. Law, H.M. Roberts, Worked examples of alternative methods for the synthesis of qualitative and quantitative research in systematic reviews, BMC Med. Res. Methodol. 7 (2007) 4, https://doi.org/10.1186/1471-2288-7-4.
[21] Y. Xiao, M. Watson, Guidance on conducting a systematic literature review, J. Plann. Educ. Res. 39 (1) (2019) 93–112, https://doi.org/10.1177/0739456X17723971.
[22] I. Manuj, J.J. Mentzer, Global supply chain risk management, J. Bus. Logist. 29 (1) (2008) 133–155.
[23] O. Schwab, G. Bull, T. Maness, A mill-specific roundwood demand equation for southern and central Finland, J. For. Econ. 11 (2) (2005) 95–106, https://doi.org/10.1016/j.jfe.2005.05.001.
[24] A. Roos, Business - bioproducts in the bioeconomy, in: A. Kutnar, S.S. Muthu (Eds.), Environmental Impacts of Traditional and Innovative Forest-based Bioproducts, Springer Singapore, Singapore, 2016, pp. 205–226.
[25] R.N. Cooper, Natural resources and national security, Resour. Pol. 1 (4) (1975) 192–203, https://doi.org/10.1016/0301-4207(75)90099-9.
[26] B.W. Risch, The raw material supply of the European Community: the importance of secondary raw materials, Resour. Pol. 4 (3) (1978) 181–188, https://doi.org/10.1016/0301-4207(78)90045-4.
[27] R.G. Florence, Forestry in transition in Australia: from the primacy of wood production to ecologically sustainable development, Commonw. For. Rev. 72 (4) (1993) 321–337.
[28] A.K. Mahapatra, C.P. Mitchell, Biofuel consumption, deforestation, and farm level tree growing in rural India, Biomass Bioenergy 17 (4) (1999) 291–303, https://doi.org/10.1016/S0961-9534(99)00056-2.
[29] J.-E. Mattsson, C.P. Mitchell, IEA bioenergy agreement task IX harvesting and supply of woody biomass for energy 1992 – 1994, Biomass Bioenergy 9 (1) (1995) 117–125, https://doi.org/10.1016/0961-9534(95)00084-4.
[30] C.L. Shaw, New light — and heat — on forests as energy reserves, Energy Pol. 23 (7) (1995) 607–617, https://doi.org/10.1016/0301-4215(95)98216-F.
[31] P. Rauch, U.J. Wolfsmayr, S.A. Borz, M. Triplat, N. Krajnc, M. Kolck, et al., SWOT analysis and strategy development for forest fuel supply chains in South East Europe, For Policy Econ 61 (2015) 87–94, https://doi.org/10.1016/j.forpol.2015.09.003.
[32] P. Gegg, L. Budd, S. Ison, The market development of aviation biofuel: drivers and constraints, J. Air Transport. Manag. 39 (2014) 34–40, https://doi.org/10.1016/j.jairtraman.2014.03.003.
[33] E.A. Gunn, Integrated mill/resource capacity planning in the Canadian forest industry, J For 1 (2) (2011) 38–44.
[34] L. Karlberg, H. Hoff, F. Flores-López, A. Goetz, I. Matuschke, Tackling biomass scarcity—from vicious to virtuous cycles in sub-Saharan Africa, Curr Opin Environ Sustain 15 (2015) 1–8, https://doi.org/10.1016/j.cosust.2015.07.011.
[35] I. Lewandowski, A.P.C. Faaij, Steps towards the development of a certification system for sustainable bio-energy trade, Biomass Bioenergy 30 (2) (2006) 83–104, https://doi.org/10.1016/j.biombioe.2005.11.003.
[36] R. Sikkema, A.P.C. Faaij, T. Ranta, J. Heinimö, Y.Y. Gerasimov, T. Karjalainen, et al., Mobilization of biomass for energy from boreal forests in Finland & Russia under present sustainable forest management certification and new sustainability requirements for solid biofuels, Biomass Bioenergy 71 (2014) 23–36, https://doi.org/10.1016/j.biombioe.2013.11.010.
[37] P. Rauch, Developing and evaluating strategies to overcome biomass supply risks, Renew. Energy 103 (2017) 561–569, https://doi.org/10.1016/j.renene.2016.11.060.
[38] C. Gibson, A. Warren, Resource-sensitive global production networks: reconfigured geographies of timber and acoustic guitar manufacturing, J. Econ. Geogr. 92 (4) (2016) 430–454, https://doi.org/10.1080/00130095.2016.1178569.
[39] T. Plieninger, A. Thiel, O. Bens, R.F. Hüttl, Pathways and pitfalls of implementing the use of woodfuels in Germany's bioenergy sector, Biomass Bioenergy 33 (3) (2009) 384–392, https://doi.org/10.1016/j.biombioe.2008.08.013.

[40] L. Torjai, J. Nagy, A. Bai, Decision hierarchy, competitive priorities and indicators in large-scale ‘herbaceous biomass to energy’ supply chains, Biomass Bioenergy 80 (2015) 321–329, https://doi.org/10.1016/j.biombioe.2015.06.013.
[41] E.A. Kaditi, Bio-energy policies in a global context, J. Clean. Prod. 17 (Supplement 1) (2009) S4–S8, https://doi.org/10.1016/j.jclepro.2008.08.023.
[42] T. Ranta, P. Lahtinen, J. Elo, J. Laitila, The effect of CO2 emission trade on the wood fuel market in Finland, Biomass Bioenergy 31 (8) (2007) 535–542, https://doi.org/10.1016/j.biombioe.2007.01.006.
[43] S. Ghafghazi, K. Lochhead, A.-H. Mathey, N. Forsell, S. Leduc, W. Mabee, et al., Estimating mill residue surplus in Canada: a spatial forest fiber cascade modeling approach, For. Prod. J. 67 (3–4) (2017) 205–218, https://doi.org/10.13073/FPJ-D-16-00031.
[44] R. Hoefnagels, M. Banse, V. Dornburg, A. Faaij, Macro-economic impact of large-scale deployment of biomass resources for energy and materials on a national level—a combined approach for The Netherlands, Energy Pol. 59 (2013) 727–744, https://doi.org/10.1016/j.enpol.2013.04.026.
[45] O. Olsson, A. Eriksson, J. Sjöström, E. Anerud, Keep that fire burning: fuel supply risk management strategies of Swedish district heating plants and implications for energy security, Biomass Bioenergy 90 (2016) 70–77, https://doi.org/10.1016/j.biombioe.2016.03.015.
[46] B. Emer, S. Grigolato, D. Lubello, R. Cavalli, Comparison of biomass feedstock supply and demand in Northeast Italy, Biomass Bioenergy 35 (8) (2011) 3309–3317, https://doi.org/10.1016/j.biombioe.2010.09.005.
[47] A. Karhunen, M. Laihanen, T. Ranta, Supply security for domestic fuels at Finnish combined heat and power plants, Biomass Bioenergy 77 (2015) 45–52, https://doi.org/10.1016/j.biombioe.2015.03.019.
[48] Y.S. Mohammed, N. Bashir, M.W. Mustafa, Overuse of wood-based bioenergy in selected sub-Saharan Africa countries: review of unconstructive challenges and suggestions, J. Clean. Prod. 96 (2015) 501–519, https://doi.org/10.1016/j.jclepro.2014.04.014.
[49] J. Wohlfahrt, F. Ferchaud, B. Gabrielle, C. Godard, B. Kurek, C. Loyce, et al., Characteristics of bioeconomy systems and sustainability issues at the territorial scale. A review, J. Clean. Prod. 232 (2019) 898–909, https://doi.org/10.1016/j.jclepro.2019.05.385.
[50] T. Ranta, O.-J. Korpinen, How to analyse and maximise the forest fuel supply availability to power plants in Eastern Finland, Biomass Bioenergy 35 (5) (2011) 1841–1850, https://doi.org/10.1016/j.biombioe.2011.01.029.
[51] R. Hoefnagels, G. Resch, M. Junginger, A. Faaij, International and domestic uses of solid biofuels under different renewable energy support scenarios in the European Union, Appl. Energy 131 (2014) 139–157, https://doi.org/10.1016/j.apenergy.2014.05.065.
[52] V. Burg, G. Bowman, M. Erni, R. Lemm, O. Thees, Analyzing the potential of domestic biomass resources for the energy transition in Switzerland, Biomass Bioenergy 111 (2018) 60–69, https://doi.org/10.1016/j.biombioe.2018.02.007.
[53] K. Ericsson, L.J. Nilsson, International biofuel trade—a study of the Swedish import, Biomass Bioenergy 26 (3) (2004) 205–220, https://doi.org/10.1016/S0961-9534(03)00122-3.
[54] L. Knight, A. Pfeiffer, J. Scott, Supply market uncertainty: Exploring consequences and responses within sustainability transitions, J. Purch. Supply Manag. 21 (3) (2015) 167–177, https://doi.org/10.1016/j.pursup.2015.04.002.
[55] G. Behzadi, M.J. O’Sullivan, T.L. Olsen, A. Zhang, Agribusiness supply chain risk management: a review of quantitative decision models, Omega 79 (2018) 21–42, https://doi.org/10.1016/j.omega.2017.07.005.
[56] S. Friedemann, M. Schumann, Potentials and limitations of RFID to reduce uncertainty in production planning with renewable resources, in: LISS 2011 - Proceedings of the 1st International Conference on Logistics, Informatics and Service Science vol. 3, 2011.
[57] B. Batidzirai, A. Faaij, E. Smeets, Biomass and bioenergy supply from Mozambique, Energy Sustain Dev 10 (1) (2006) 54–81, https://doi.org/10.1016/S0973-0826(08)60507-4.
[58] B. Batidzirai, M. Valk, B. Wicke, M. Junginger, V. Daioglou, W. Euler, et al., Current and future technical, economic and environmental feasibility of maize and wheat residues supply for biomass energy application: illustrated for South Africa, Biomass Bioenergy 92 (2016) 106–129, https://doi.org/10.1016/j.biombioe.2016.06.010.
[59] J. Vilko, A. Rumpu, Information exchange methods and disruptions in wood supply chains, in: LISS 2011 - Proceedings of the 1st International Conference on Logistics, Informatics and Service Science, vol. 2, 2011.
[60] W. Yanbin, C. Baodong, Y. Chang, L. Tingting, The risk assessment of China’s timber import based on SWI index, Adv. J. Food Sci. Technol. 6 (11) (2014) 1184–1189, https://doi.org/10.19026/ajfst.6.182.
[61] R. Madlener, M. Bachhiesl, Socio-economic drivers of large urban biomass cogeneration: sustainable energy supply for Austria’s capital Vienna, Energy Pol. 35 (2) (2007) 1075–1087, https://doi.org/10.1016/j.enpol.2006.01.022.
[62] N.R. Baral, R. Davis, T.H. Bradley, Supply and value chain analysis of mixed biomass feedstock supply system for lignocellulosic sugar production, Biofuel Bioprod Biorefin (2019), https://doi.org/10.1002/bbb.1975.
[63] J.D. Stephen, S. Sokhansanj, X. Bi, T. Sowlati, T. Kloeck, L. Townley-Smith, et al., The impact of agricultural residue yield range on the delivered cost to a biorefinery in the Peace River region of Alberta, Canada, Biosyst. Eng. 105 (3) (2010) 298–305, https://doi.org/10.1016/j.biosystemseng.2009.11.008.
[64] M. Junginger, J. van Dam, S. Zarrilli, F.A. Mohamed, D. Marchal, A. Faaij, Opportunities and barriers for international bioenergy trade, Energy Pol. 39 (4) (2011) 2028–2042, https://doi.org/10.1016/j.enpol.2011.01.040.
[65] P. Lamers, R. Hoefnagels, M. Junginger, C. Hamelinck, A. Faaij, Global solid biomass trade for energy by 2020: an assessment of potential import streams and supply costs to North-West Europe under different sustainability constraints, GCB Bioenergy 7 (4) (2015) 618–634, https://doi.org/10.1111/gcbb.12162.
[66] R. Madlener, S. Vögtli, Diffusion of bioenergy in urban areas: a socio-economic analysis of the Swiss wood-fired cogeneration plant in Basel, Biomass Bioenergy 32 (9) (2008) 815–828, https://doi.org/10.1016/j.biombioe.2008.01.006.
[67] U.J. Wolfsmayr, P. Rauch, M. Gronalt, R. Merenda, F. Longo, Evaluating primary forest fuel rail terminals with discrete event simulation: a case study from Austria, Ann. For. Res. 59 (1) (2016) 145–164, https://doi.org/10.15287/afr.2015.428.
[68] K. Fan, X. Li, L. Wang, M. Wang, Two-stage supply chain contract coordination of solid biomass fuel involving multiple suppliers, Comput. Ind. Eng. (2019), https://doi.org/10.1016/j.cie.2019.01.016.
[69] M. Lee, S. Cho, J. Kim, A comprehensive model for design and analysis of bioethanol production and supply strategies from lignocellulosic biomass, Renew. Energy 112 (2017) 247–259, https://doi.org/10.1016/j.renene.2017.05.040.
[70] M. Langholtz, E. Webb, B.L. Preston, A. Turhollow, N. Breuer, L. Eaton, et al., Climate risk management for the U.S. cellulosic biofuels supply chain, Clim Risk Manag 3 (2014) 96–115, https://doi.org/10.1016/j.crm.2014.05.001.
[71] P. Rauch, M. Gronalt, The effects of rising energy costs and transportation mode mix on forest fuel procurement costs, Biomass Bioenergy 35 (1) (2011) 690–699, https://doi.org/10.1016/j.biombioe.2010.10.015.
[72] G. Kalt, L. Kranzl, An assessment of international trade related to bioenergy use in Austria—methodological aspects, recent developments and the relevance of indirect trade, Energy Pol. 46 (2012) 537–549, https://doi.org/10.1016/j.enpol.2012.04.026.
[73] R.J. Arnold, Y.J. Xie, S.J. Midgley, J.Z. Luo, X.F. Chen, Emergence and rise of eucalypt veneer production in China, Int. For. Rev. 15 (1) (2013) 33–47, https://doi.org/10.1505/146554813805927200.
[74] S. Veenman, D. Liefferink, B. Arts, A short history of Dutch forest policy: the ‘de-institutionalisation’ of a policy arrangement, For Policy Econ 11 (3) (2009) 202–208, https://doi.org/10.1016/j.forpol.2009.03.001.
[75] H. Thomson, C. Liddell, The suitability of wood pellet heating for domestic households: a review of literature, Renew. Sustain. Energy Rev. 42 (2015) 1362–1369, https://doi.org/10.1016/j.rser.2014.11.009.
[76] C. Sun, Recent growth in China’s roundwood import and its global implications, For Policy Econ 39 (2014) 43–53, https://doi.org/10.1016/j.forpol.2013.11.006.
[77] A. Mansikkasalo, Changes in European forest raw material trade: consequences of implementing the RES2020 Directive, Biomass Bioenergy 37 (2012) 150–160, https://doi.org/10.1016/j.biombioe.2011.12.018.
[78] C. Baodong, D. Gang, L. Tingting, Y. Chang, Risk assessment and analysis of diversification of China’s round wood import, Adv. J. Food Sci. Technol. 8 (12) (2015) 853–860, https://doi.org/10.19026/ajfst.8.2719.
[79] G. Hauer, S. Cumming, F. Schmiegelow, W. Adamowicz, M. Weber, R. Jagodzinski, Tradeoffs between forestry resource and conservation values under alternate policy regimes: a spatial analysis of the western Canadian boreal plains, Ecol. Model. 221 (21) (2010) 2590–2603, https://doi.org/10.1016/j.ecolmodel.2010.07.013.
[80] A. Ahl, J. Eklund, P. Lundqvist, M. Yarime, Balancing formal and informal success factors perceived by supply chain stakeholders: a study of woody biomass energy systems in Japan, J. Clean. Prod. 175 (2018) 50–59, https://doi.org/10.1016/j.jclepro.2017.11.108.
[81] S. Ferreira, E. Monteiro, P. Brito, C. Vilarinho, Biomass resources in Portugal: current status and prospects, Renew. Sustain. Energy Rev. 78 (2017) 1221–1235, https://doi.org/10.1016/j.rser.2017.03.140.
[82] L.J. Nilsson, M. Pisarek, J. Buriak, A. Oniszk-Popławska, P. Bućko, K. Ericsson, et al., Energy policy and the role of bioenergy in Poland, Energy Pol. 34 (15) (2006) 2263–2278, https://doi.org/10.1016/j.enpol.2005.03.011.
[83] U.J. Wolfsmayr, P. Rauch, Primary forest fuel supply chain: assessing barriers and drivers for the modal shift from truck to train, Silva Fenn. 48 (5) (2014) 1–17, https://doi.org/10.14214/sf.1217.
[84] K. Sahoo, E. Bilek, S. Mani, Techno-economic and environmental assessments of storing woodchips and pellets for bioenergy applications, Renew. Sustain. Energy Rev. 98 (2018) 27–39, https://doi.org/10.1016/j.rser.2018.08.055.
[85] C. Hsion Lim, B.S. How, Ng WP. Qin, H.L. Lam, Debottlenecking of biomass element deficiency in a multiperiod supply chain system via element targeting approach, J. Clean. Prod. 230 (2019) 751–766, https://doi.org/10.1016/j.jclepro.2019.05.127.
[86] N. Martinkus, G. Latta, K. Brandt, M. Wolcott, A multi-criteria decision analysis approach to facility siting in a wood-based depot-and-biorefinery supply chain model, Front Energy Res 6 (NOV) (2018), https://doi.org/10.3389/fenrg.2018.00124.
[87] R. Golecha, J. Gan, Optimal contracting structure between cellulosic biorefineries and farmers to reduce the impact of biomass supply variation: game theoretic analysis, Biofuel Bioprod Biorefin 10 (2) (2016) 129–138, https://doi.org/10.1002/bbb.1626.
[88] S. Wiedenmann, J. Geldermann, Supply planning for processors of agricultural raw materials, Eur. J. Oper. Res. 242 (2) (2015) 606–619, https://doi.org/10.1016/j.ejor.2014.10.021.
[89] M. Virkkunen, J. Raitila, O.-J. Korpinen, Cost analysis of a satellite terminal for forest fuel supply in Finland, Scand. J. For. Res. 31 (2) (2016) 175–182, https://doi.org/10.1080/02827581.2015.1082617.
[90] X. Zhang, K. Luo, Q. Tan, A game theory analysis of China’s agri-biomass-based power generation supply chain: a Co-opetition strategy, Energy Procedia 105 (2017) 168–173, https://doi.org/10.1016/j.egypro.2017.03.297.
[91] M. Maesano, B. Lasserre, M. Marchetti, Increasing wood mobilization through sustainable forest management in protected areas of Italy, Annals of Silvicultural Research 38 (1) (2014) 13–21, https://doi.org/10.12899/ASR-754.

[92] S. Wang, Managing forests for the greater good: the role of the social license to operate, For Policy Econ (2019) 101920, https://doi.org/10.1016/j.forpol.2019.05.006.
[93] R. van den Broek, S. Teeuwisse, K. Healion, T. Kent, A. van Wijk, A. Faaij, et al., Potentials for electricity production from wood in Ireland, Energy 26 (11) (2001) 991–1013, https://doi.org/10.1016/S0360-5442(01)00050-0.
[94] J-F Van Belle, M. Temmerman, Y. Schenkel, Three level procurement of forest residues for power plant, Biomass Bioenergy 24 (4) (2003) 401–409, https://doi.org/10.1016/S0961-9534(02)00161-7.
[95] D.N. Thompson, T. Campbell, B. Bals, T. Runge, F. Teymouri, L.P. Ovard, Chemical preconversion: application of low-severity pretreatment chemistries for commoditization of lignocellulosic feedstock, Biofuels 4 (3) (2013) 323–340, https://doi.org/10.4155/bfs.13.15.
[96] N.S. Bentsen, M.W. Jack, C. Felby, B.J. Thorsen, Allocation of biomass resources for minimising energy system greenhouse gas emissions, Energy 69 (2014) 506–515, https://doi.org/10.1016/j.energy.2014.03.045.
[97] A. Kalinichenko, V. Havrysh, Feasibility study of biogas project development: technology maturity, feedstock, and utilization pathway, Arch. Environ. Protect. 45 (1) (2019) 68–83, https://doi.org/10.24425/aep.2019.126423.
[98] T.A. Maung, C.R. Gustafson, D.M. Saxowsky, J. Nowatzki, T. Miljkovic, D. Ripplinger, The logistics of supplying single vs. multi-crop cellulosic feedstocks to a biorefinery in southeast North Dakota, Appl. Energy 109 (2013) 229–238, https://doi.org/10.1016/j.apenergy.2013.04.003.
[99] A. Shooshtarian, J.A. Anderson, G.W. Armstrong, M.K. Luckert, Growing hybrid poplar in western Canada for use as a biofuel feedstock: a financial analysis of coppice and single-stem management, Biomass Bioenergy 113 (2018) 45–54, https://doi.org/10.1016/j.biombioe.2018.02.020.
[100] J.D. Stephen, S. Sokhansanj, X. Bi, T. Sowlati, T. Kloeck, L. Townley-Smith, et al., Analysis of biomass feedstock availability and variability for the Peace River region of Alberta, Canada, Biosyst. Eng. 105 (1) (2010) 103–111, https://doi.org/10.1016/j.biosystemseng.2009.09.019.
[101] C. Dou, R. Bura, S. Ewanick, R. Morales-Vera, Blending short rotation coppice poplar with wheat straw as a biorefinery feedstock in the State of Washington, Ind. Crop. Prod. 132 (2019) 407–412, https://doi.org/10.1016/j.indcrop.2019.02.033.
[102] P. Rauch, M. Gronalt, P. Hirsch, Co-operative forest fuel procurement strategy and its saving effects on overall transportation costs, Scand. J. For. Res. 25 (3) (2010) 251–261, https://doi.org/10.1080/02827581003766967.
[103] Y.-C. Wang, J.-C. Lin, Analysis of timber supplier selection and domestic timber requirements of the forest products industry in Taiwan, Tai Wan Lin Ye Ke Xue 26 (2) (2011) 135–149.
[104] M. Eriksson, L. LeBel, O. Lindroos, The effect of customer-contractor alignment in forest harvesting services on contractor profitability and the risk for relationship breakdown, Forests 8 (10) (2017), https://doi.org/10.3390/f8100360.
[105] A. Barkaoui, A.Z. Dragicevic, Nash bargaining and renegotiation with social preferences: case of the roundwood log supply contracts in the French timber market, For Policy Econ 69 (2016) 90–100, https://doi.org/10.1016/j.forpol.2016.04.007.
[106] E. Erlandsson, The impact of industrial context on procurement, management and development of harvesting services: a comparison of two Swedish forest owners associations, Forests 4 (4) (2013) 1171–1198, https://doi.org/10.3390/f4041171.
[107] R.E. Sims, P. Venturi, All-year-round harvesting of short rotation coppice eucalyptus compared with the delivered costs of biomass from more conventional short season, harvesting systems, Biomass Bioenergy 26 (1) (2004) 27–37, https://doi.org/10.1016/S0961-9534(03)00081-3.
[108] M. Gronalt, P. Rauch, Designing a regional forest fuel supply network, Biomass Bioenergy 31 (6) (2007) 393–402, https://doi.org/10.1016/j.biombioe.2007.01.007.
[109] M. Pérez-Fortes, J.M. Laínez-Aguirre, P. Arranz-Piera, E. Velo, L. Puigjaner, Design of regional and sustainable bio-based networks for electricity generation using a multi-objective MILP approach, Energy 44 (1) (2012) 79–95, https://doi.org/10.1016/j.energy.2012.01.033.
[110] J van Dam, A.P.C. Faaij, I. Lewandowski, B. van Zeebroeck, Options of biofuel trade from central and Eastern to western European countries, Biomass Bioenergy 33 (4) (2009) 728–744, https://doi.org/10.1016/j.biombioe.2008.11.006.
[111] A. Eriksson, L. Eliasson, L. Sikanen, P.-A. Hansson, R. Jirjis, Evaluation of delivery strategies for forest fuels applying a model for Weather-driven Analysis of Forest Fuel Systems (WAFFS), Appl. Energy 188 (2017) 420–430, https://doi.org/10.1016/j.apenergy.2016.12.018.
[112] E. Anerud, R. Jirjis, G. Larsson, L. Eliasson, Fuel quality of stored wood chips – influence of semi-permeable covering material, Appl. Energy 231 (2018) 628–634, https://doi.org/10.1016/j.apenergy.2018.09.157.
[113] J. Shi, K.W. George, N. Sun, W. He, C. Li, V. Stavila, et al., Impact of pretreatment technologies on Saccharification and isopentenol fermentation of mixed lignocellulosic feedstocks, Bioenerg Res 8 (3) (2015) 1004–1013, https://doi.org/10.1007/s12155-015-9588-z.
[114] M. Alsaleh, A.S. Abdul-Rahim, H.O. Mohd-Shahwahid, An empirical and forecasting analysis of the bioenergy market in the EU28 region: Evidence from a panel data simultaneous equation model, Renew. Sustain. Energy Rev. 80 (2017) 1123–1137, https://doi.org/10.1016/j.rser.2017.05.167.
[115] L.C. Zulu, The forbidden fuel: charcoal, urban woodfuel demand and supply dynamics, community forest management and woodfuel policy in Malawi, Energy Pol. 38 (7) (2010) 3717–3730, https://doi.org/10.1016/j.enpol.2010.02.050.
[116] J.P.P. Vilko, J.M. Hallikas, Risk assessment in multimodal supply chains, Int. J. Prod. Econ. 140 (2) (2012) 586–595, https://doi.org/10.1016/j.ijpe.2011.09.010.
[117] P. Trkman, K. McCormack, Supply chain risk in turbulent environments—a conceptual model for managing supply chain network risk, Int. J. Prod. Econ. 119 (2) (2009) 247–258, https://doi.org/10.1016/j.ijpe.2009.03.002.
[118] G.A. Zsidisin, A grounded definition of supply risk, Journal of Purchasing and Supply Management 9 (5-6) (2003) 217–224. https://doi.org/10.1016/j.pursup.2003.07.002.
[119] M.S. Taskhiri, M. Garbs, J. Geldermann, Sustainable logistics network for wood flow considering cascade utilisation, Journal of Cleaner Production 110 (2016) 25–39. https://doi.org/10.1016/j.jclepro.2015.09.098.
[120] A. Brosowski, D. Thrän, U. Mantau, B. Mahro, G. Erdmann, P. Adler, et al., A review of biomass potential and current utilisation – Status quo for 93 biogenic wastes and residues in Germany, Biomass and Bioenergy 95 (2016) 257–272. https://doi.org/10.1016/j.biombioe.2016.10.017.
[121] U. Mantau, Wood flow analysis: Quantification of resource potentials, cascades and carbon effects, Biomass and Bioenergy 79 (2015) 28–38. https://doi.org/10.1016/j.biombioe.2014.08.013.