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Original Article

How much wood can we expect from European forests in the near future?

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Abstract

The demand for wood in Europe is expected to increase in the coming decades. However, any theoretical maximum supply will be affected by sustainability constraints, the motivations of forest owners and regional factors, such as incentives, species and assortments. However, the influence of these factors on supply is changeable. In this study, we quantify what might be realistically available as additional wood supply from currently existing European forests, based on a combination of results of the forest resource model EFISCEN-Space and a literature review of national supply projections. Wood mobilization scenarios for 10 representative Model Regions in Europe that assume forest owners and managers in the simulated regions will adapt their behaviour to alternative behaviour as recorded from other regions were projected with the EFISCEN-Space model. The realistic additional potential based on the literature review is 90 million m^3 yr^{-1}. This potential should be attainable within 10–20 years. However, the simulations in the Model Regions found potentials to be lower in 7 out of 10 cases as compared with the country they are located in. On average, the model regions reached less than half of the potential as compared with the literature review. This suggests that the realistic additional potential at the European scale may well be lower if all mobilization barriers are taken into account in more detail, but also highlights the uncertainty surrounding these estimates. We conclude from the analyses that although there are large differences in potential between regions and the analysis method employed, there are no 'hotspots' where a large pool of accessible wood can be quickly mobilized using existing infrastructure for nearby industries. An increase in harvest would therefore only be possible with a large effort that spans the whole chain, from forest owners' behaviour to capacity building, financial incentives and matching resources to harvesting capacity. The additionally available wood can most likely only be mobilized against higher marginal costs and will thus only become available in times of higher stumpage prices. The largest potential lies in privately owned forests which often have a fragmented ownership but will most likely be able to supply more wood, though mostly from deciduous species. In the long term (more than 20 years), additional wood, compared with the amounts we found for short term, can only be made available through investments in afforestation, forest restoration, improved forest management and more efficient use of raw material and recycled material.

Introduction

Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, requires greenhouse gas emissions to be reduced by at least 55 per cent by 2030 compared with 1990 (EC, 2021a). A possible route to this goal is via a global transition to a biobased economy. Biobased resources are renewable, can store carbon over a prolonged period and can substitute for materials that emit large amounts of fossil CO_2. Substitution of fossil-based materials and fuels by biobased

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alternatives at large scale will inevitably lead to an increased demand for biobased feedstocks. For example, under a biobased economy, the global demand for wood is projected to increase from 3.4 billion m^3 (2010) to 7.6 billion m^3 (2030) (World Wide Fund for Nature and International Institute for Applied Systems Analysis, 2012; UNECE/FAO, 2021).

An increase in wood demand is also expected for the EU-27 + UK (Bell et al., 2018), similar to or even higher than the global trend. This is due to the EU forests already being under regular management, having good accessibility and Europe having a well-developed processing industry and active policies for the development of a bioeconomy. However, if demand rises too fast or too high, the net result of the transition to a bioeconomy may be overharvesting and thus a net loss of carbon to the atmosphere (Gawel et al., 2019), and a risk of forest degradation. Recently, there were signals of a high additional harvest in Europe (Ceccherini et al., 2020), although the basis of these figures has been contested by Palahi et al. (2021). It gave rise to a heated debate in many European countries (e.g. Breidenbach et al., 2022; Wernick et al., 2021), showing the sensitivity of the topic of additional wood harvest.

The EU Bioeconomy Strategy aims to increase the use of wood for bioenergy and the construction sector (EC, 2018). However, other important EU policy strategies act in an opposite direction. The EU Biodiversity Strategy aims to protect 30 per cent of the land area in the EU (currently 26 per cent), with 10 per cent being strict reserves (currently 3 per cent; Nabuurs et al., 2019) by 2030 (EC, 2020). The EU Forest Strategy highlights the role of forests as natural sinks, stating that: ‘in the short to medium term, i.e. until 2050, the potential additional benefits from harvested wood products and material substitution are unlikely to compensate for the reduction of the net forest sink’ (EC, 2021b). It is clear that the different policy strategies for the EU forests have conflicting objectives. Finding a future feasible harvest level and balancing the different forest functions is crucial for a socially and ecologically acceptable development of the bioeconomy.

A key factor influencing the availability of wood is the area of forests available for wood supply (FAWS; Alberdi et al., 2020), which is determined by physical constraints, such as e.g. steep slopes, long transport distances or administrative restrictions including nature protection (Nabuurs et al., 2019). Currently some 77 per cent of the forest area in Europe is seen as FAWS (EU-27 + UK: 138 Mha, Europe: 170 Mha (Forest Europe, 2020)). This area is expected to decrease in the future under the EU Biodiversity Strategy. In addition, ownership structure in the FAWS areas is an important variable that influences wood harvest. A substantial amount of wood is located in forests that belong to an estimated 16 million private forest owners, covering over 50 per cent of the total European forest area (Forest Europe, 2015; Pulla et al., 2013). Therefore, wood harvest is strongly dependent on forest owners’ behaviour, as differences exist in the willingness of forest owners across the continent to mobilize wood (e.g. Blennow et al., 2014; Stjepan et al., 2015, Schelhaas et al., 2018b).

Other constraints which reduce the willingness of owners to harvest include low forest accessibility, lack of machinery and skilled labour, high harvesting costs, high regeneration costs, low, or perceived-low wood prices, taxes, priority given to other forest functions (e.g. soil protection) and a mismatch between available tree species assortments and regional demand (Orazio et al., 2017; Aurenhammer et al., 2017, 2018b). The influence of all these factors together determines the variety of regional current harvesting felling/increment ratios which vary between 40 per cent and close to 100 per cent of the increment (Levers et al., 2014). At the same time, there are varying signals concerning the increment of the forest, which seems to be declining due to ageing of the forest (Nabuurs et al., 2013) or is affected by mortality (Hlásny et al., 2021), thus also affecting the wood harvest, although these factors will take effect on quite long time scales.

The theoretical harvest potential is often defined as 100 per cent of the net annual increment (NAI; Barreiro et al., 2017), and in the EU there is a considerable gap between this theoretical harvest potential and the actual harvest level (Mantau 2012). In the following we refer to this gap as the maximum additional potential, which is estimated to be 218 million m^3 yr^{-1} for the EU (Forest Europe, 2020). As discussed before, there are many and varied reasons why this wood is not harvested, and the efforts that are needed to reduce this gap will probably be very different for individual regions and types of forest owners. Earlier studies that tried to match wood demand and supply for Europe either assumed a constant supply (Mantau 2012), or produced national-level projections of supply assuming restrictions through e.g. nature conservation. None of these studies dealt with the high regional heterogeneity across Europe with respect to social and biophysical or resource characteristics.

The current study builds on the concept of sustainable wood mobilization through regional characterization in a high-resolution forest resource projection model: EFISCEN-Space (Schelhaas et al., 2022). Orazio et al. (2017) defines sustainable wood mobilization as initiatives and measures leading to harvesting and extraction of wood from forests, taking into account additional criteria that must ensure Sustainable Forest Management (SFM). In the current study, wood mobilization is defined as the actions that are needed to harvest additional volume compared with the business as usual.

We divide the maximum additional potential into the categories low, medium, high and impossible mobilization (see Figure 1). These categories are defined per region based on a current characterization and analyses of management style of various management groups and an expert and literature-based judgement on their willingness to change. For example, private owners in North Rhine Westphalia are currently already motivated towards volume production (Hagemann et al., 2015). Changing their behaviour to stimulate additional harvest is judged as relatively easy; thus, a low mobilization scenario has been deemed to be appropriate. However, changing the behaviour of e.g. Dutch forest owners, who consider nature conservation objectives to be high priority and interpret this to mean ‘minimum intervention’, will not be easy, and thus a medium mobilization category is probably most appropriate. These choices are explained further in the section ‘harvest regimes’.

We consider the sum of the shares of low and medium mobilization, as the realistic additional potential for wood harvest. Here, ‘realistic’ does not imply that we found the exact value, but rather that we have made a well-informed estimate, considering relevant constraints.

Our approach can thus be seen as a harmonized resource- and management-oriented approach that deals with the expected regional differences in environmental and societal factors. This is contrary to most forest sector models. In sector models such as EFI-GTM (Maarit et al., 2004), the maximization of welfare is the aim, whereby increased population and Gross Domestic Product lead to additional demand. With increasing demands, commodity prices shift and the supply curve (with a certain elasticity) shifts as well. A characteristic of the sector models is that the resource is of minor interest. The resource stock is assumed almost stable (for projections of usually only 10–15 years) and is assumed simply as an (partially) available stock although with certain supply

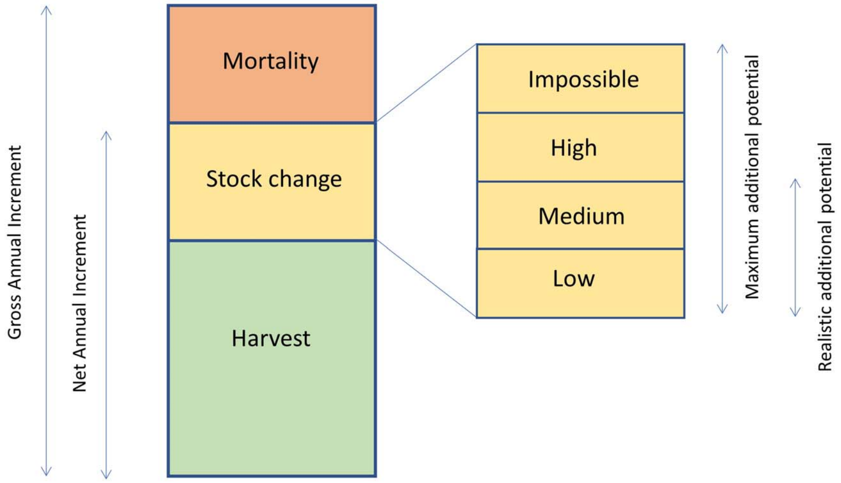

Figure 1. Schematic overview of maximum additional potential and realistic additional potential, assuming that the shares of 'stock change' and 'mortality' will not change due to the change in management.

elasticity, sometimes varying with large management groups. Our current approach is based on regional resource characteristics and owner behaviour per region. This is, from a resource perspective, a more advanced approach compared with the manner in which forest sector models simulate additional supply.

This study aims to estimate the realistic additional potential for wood harvest in the EU for the near future. As 'near future' we consider a time-frame of 10–20 years as the study is based on measures that can be quickly implemented. They do not require e.g. forest area expansion which would only have an impact on available wood in the longer term. Our study builds on two independent methods: (i) a literature review on national wood supply projections in all European countries and (ii) modelled mobilization potentials from a set of European Model Regions based on national forest inventories and a European forest resource projection model. We estimate the realistic additional potential for wood harvest in the EU based on results from the literature review and confront these national findings with the modelled mobilization potentials from our Model Regions.

Methods

Literature review

We performed a literature review regarding national projections of future harvest levels, see also Trinomics et al. (2021). We used data from the *State of Europe's Forests* (Forest Europe, 2020) to determine the maximum additional potential using current harvest and increment levels. For each country, we checked the National Forestry and Accounting Plans for the inclusion of such studies, and we performed an internet search on Google Scholar using the terms 'projection', 'harvest level' and the respective country.

Each scenario in the national projections we found was classified as baseline or possible mobilization scenario, including a (subjective) assessment of the mobilization effort (low, medium or high), based on the scenario description and the corresponding discussion. To estimate the realistic additional potential, we only used the scenarios classified as medium mobilization.

If the projections mentioned an increase in felling/increment ratio compared with the baseline, we increased the felling/increment ratio as found in *State of Europe's Forests* accordingly. If projections only mentioned absolute felling quantities, we increased the fellings as reported in *State of Europe's Forests* according to the difference between the medium mobilization scenario and the baseline scenario in the projections. If projections only mentioned a percentage increase in harvest as compared with the baseline, we applied this percentage to the fellings as reported in *State of Europe's Forests*. Over all countries that reported projections with increased harvest ($n = 14$), the weighted average increase in felling/increment ratio was 12 per cent. For countries that reported indications for a possible increase in harvest but without quantification, we applied this average increase. When no indications were found for a possible increase in harvest, we assumed no realistic additional potential to be present. If the increased fellings using any of the above methods would exceed the NAI as found in *State of Europe's Forests*, we capped it at the level of the NAI.

Simulations

We performed simulations of wood mobilization potential for ten European Model Regions (Figure 2). The selected regions cover a range of biophysical, technical and socio-economic circumstances and barriers as found in the EU27 + UK. These regions cover in total 8 386 800 ha of forest, for which measurements on 26 430 NFI plots are available (Table 1). This is 5.2 per cent of the 162 million ha of forest area in the EU27 + UK.

The EFISCEN-Space model

We used the EFISCEN-Space model to simulate the forest resource development in the Model Regions. EFISCEN-Space simulates the development of structure and composition of forest resources, from local to European scale, for individual trees within inventory plots at whatever spatial distance between plots is applied in the NFI of a region or country (Schelhaas et al., 2022). The model enables the assessment of the impact of forest management strategies, such as mobilization strategies. EFISCEN-Space simulates the forest as a collection of 1-ha model stands, where each model stand is representative of a larger area. The model stands are initialized using national forest inventory (NFI) data, either plot-based or stand-based. Just as in the NFI, each simulated plot is representative of a certain area of forest, and the whole collection of stands representative of the whole area under study. Forest development for each model stand is modelled as the change in the number of trees per diameter class per tree species. There are

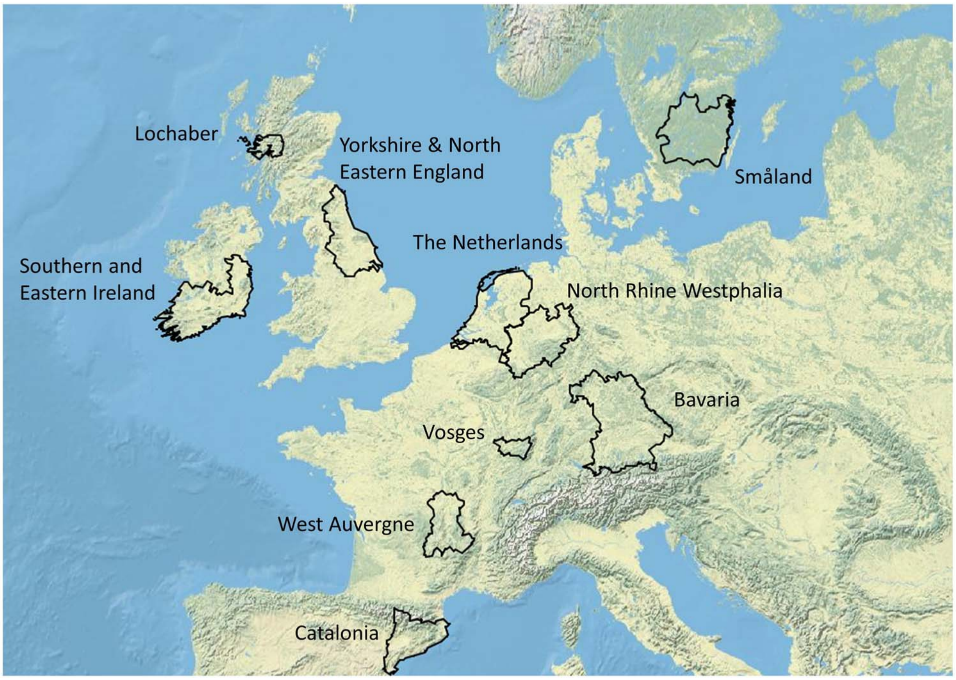

Figure 2. Map with Model Regions for the simulations (basemap source: US National Park Service).

Table 1. Overview of NFI data used for the modelling study and the forest area that each plot represents

Region	Forest area (ha)	NFI plots in simulation	Area represented per NFI plot (ha)
Lochaber	126 900	286	440.6
Yorkshire & North Eastern England	203 900	929	218.3
Netherlands	370 000	3062	120.8
Vosges	298 000	1050	283.8
West Auvergne	198 000	2703	73.3
Bavaria	2 500 000	7123	340.4
Småland	2 100 000	2103	1030.4
Catalonia	1 300 000	6482	200.6
North Rhine Westphalia	915 000	1973	434.0
Southern and Eastern Ireland	375 000	719	521.6
Totals	**8 386 800**	**26 430**	

40 diameter classes of 2.5-cm width, starting with diameter class 1 at 0–2.5 cm. A maximum of 20 predetermined species groups can be used, corresponding to the most common tree species in Europe (Schelhaas et al., 2018a).

Transitions to a higher diameter class are derived from species-specific growth functions that are calibrated using a large set of observed diameter increment data from all over Europe (Schelhaas et al., 2018a). The growth functions are sensitive to diameter, basal area in the stand and a number of abiotic variables. These include soil (Panagos et al., 2012), nutrient deposition (EMEP data, www.emep.int), climate and weather (Agri4Cast website, https://agri4cast.jrc.ec.europa.eu/). The locations of the model stands are used to extract information from the respective databases.

Mortality and harvest are modelled as the removal of stems of a particular diameter class. These are implemented as fixed fractions, derived from observed local repeated NFI observations (Schelhaas et al., 2018b). Recruitment is not included in the model, which is not considered a problem for supply projections up to 20 years. Diameters are converted into over bark wood volume using local volume functions, usually derived from NFI data. In this study, the simulation was performed for each Model Region on its own, so harmonization of NFI data was not needed. The model runs on an annual timescale. The model produces annual outputs on the forest state, mortality and harvest, expressed in terms of tree numbers, basal area and volume; per model stand, per species and per diameter class. These outputs can be aggregated to yearly overviews per model stand and on the total modelled area scale.

Harvest regimes and scenarios

Management groups were defined in every model region, based on differences in forest management. The process of defining management groups has been done in consultation with representatives from the Model Regions and observed differences in harvesting intensity based on NFI data. This approach is similar to the one used by Arets & Schelhaas (2019). Harvest and mortality regimes are derived from repeated inventory data, expressed as the annual probability that a tree is harvested, in relation to its species, its diameter and the management group it belongs to (Schelhaas et al., 2018b). An example of management regimes for *Pinus sylvestris* for two different management groups is shown in Figure 3, as derived from repeated Dutch NFI data. As the owners of the plots are known, the management regimes (in terms of harvest probability by species and diameter) can be derived.

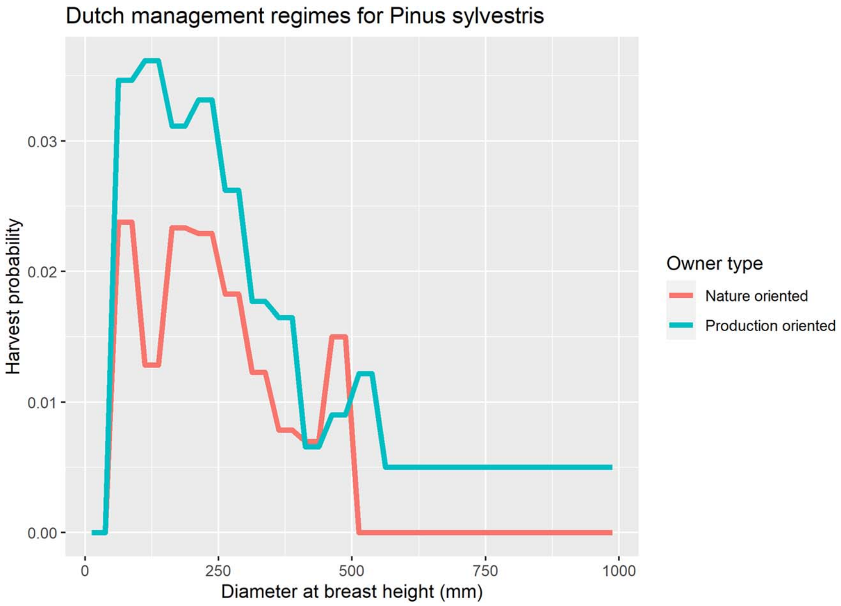

Figure 3. Dutch management regimes for *P. sylvestris*, expressed as the harvest probability per DBH class.

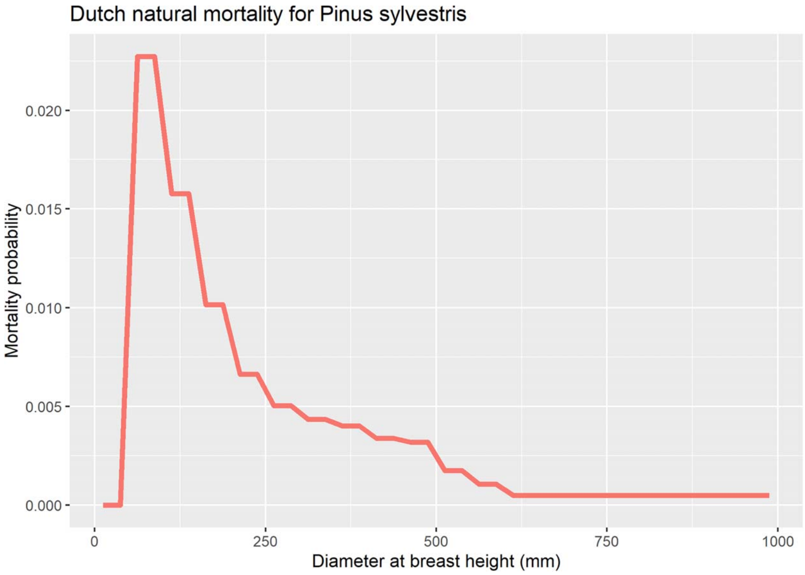

Figure 4. Dutch natural mortality for *P. sylvestris*, expressed as the mortality probability per DBH class.

Using the management regimes, EFISCEN-Space models the over bark felled wood volume without harvesting residues. Natural mortality is deduced from the NFI data in a similar manner as the management. An example of a mortality pattern, as used by EFISCEN-Space, is shown in Figure 4.

For each Model Region we implemented a baseline scenario and one or more mobilization scenarios. The baseline scenario was defined as a continuation of current management. More intensive management regimes from management groups within the same region or from another region were used to implement the mobilization scenarios. The difference in harvest potential between the maximum additional potential and the high mobilization scenario was classified as 'impossible to mobilise'. If harvest in the baseline or mobilization scenario exceeded the increment, the harvest was capped at the level of the increment. In Appendix 1, the scenarios per Model Region are explained.

Results

The projected additional harvest potentials per Model Region have been classified in terms of ease of mobilization (see Table 2; for the classification, see Appendix 1). The relative (%) increase or decrease in harvest per mobilization scenario per Model Region was calculated, compared with the baseline (see Figure 5). Specific results per Model Region can be found in Appendices 2 and 3. Based on the simulated 8.4 million ha, in total, 2.1 million m^3 could be harvested additionally via the low and medium mobilization scenarios (see Table 2 and Figure 5). A feature that EFISCEN-space simulations capture very well is how strongly the results vary from region to region, depending on current forest resources, ownership structure, accessibility, etc.

Literature review of national projection studies

The results of the literature review per country are listed in Table 3. Compiling all the countries' results resulted in a realistic

Table 2. Overview of the modelled additional harvest potential per model region, ranked by mobilization effort

Country	Region	NAI	Current fellings over bark	Maximum additional potential	Mobilization effort			
					Low	Medium	High	Impossible
France	West Auvergne	1587	890	697	0	381	307	9
	Vosges	2267	1551	716	0	0	493	223
Germany	Bavaria	24 984	24 735	249	0	249	0	0
	North Rhine Westphalia	8990	8681	309	0	0	309	0
Spain	Catalonia	2465	1270	1195	0	0	1136	59
Ireland	Southern and Eastern Ireland	5630	2334	3296	155	416	128	2597
Great Britain	Lochaber	1774	645	1129	35	170	597	327
	Yorkshire & NEE	2700	720	1980	84	402	469	1025
Netherlands	Netherlands	2172	1512	660	0	190	194	276
Sweden	Småland	10 701	12880*	0	0	0	0	0
TOTAL		**63 270**	**55 218**	**10 231**	**274**	**1808**	**3633**	**4516**

All units are 1000 m^3 per year *Note that this was influenced by salvage fellings following storm (Gudrun 2005)

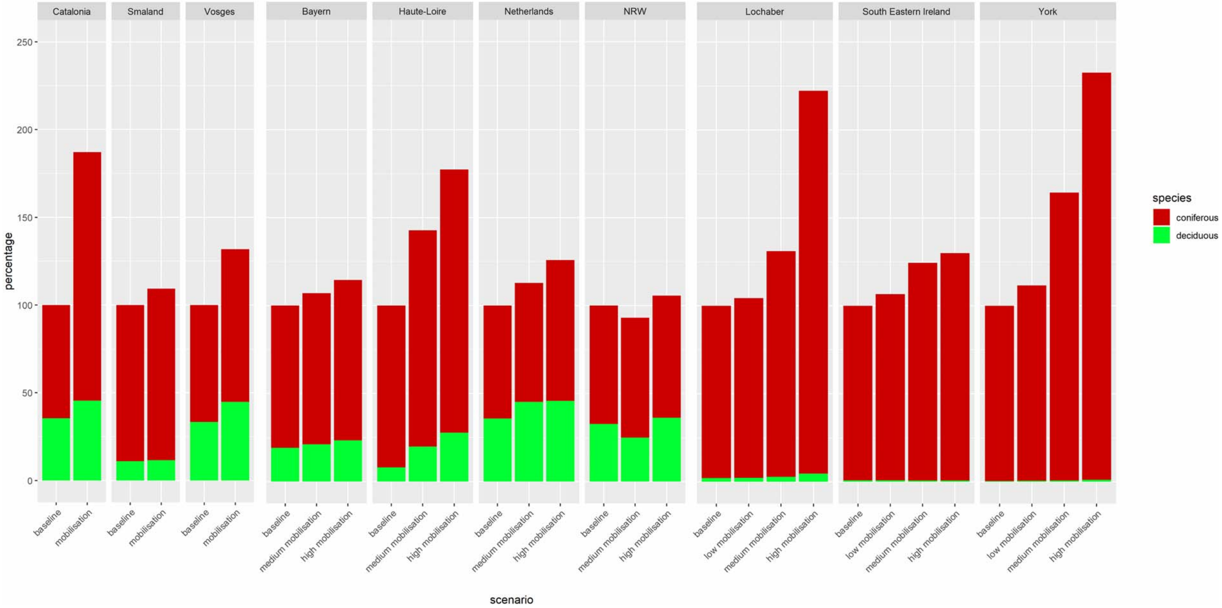

Figure 5. Relative (%) increase or decrease in harvest in deciduous and coniferous species, per mobilization scenario per model region, compared with the baseline, which is set to 100 per cent.

additional potential for the EU27 + UK of 90 million m^3. This implies a rise in the felling/increment ratio from 71 per cent to 83 per cent. The literature results show that almost all countries assume or simulate that harvesting intensity can go up to 70 per cent or more. Only the urbanized countries or countries with a lesser developed forest sector stay below this 70 per cent under the projected realistic potential. These countries are Denmark, Netherlands, Bulgaria, Romania, Spain, Italy, Cyprus and Greece. In Appendix 4, the results per country are described.

We compared the results from the Model Regions to those of the corresponding countries of the literature review in Table 4. It is clear that the realistic potentials from the Model Regions are considerably lower than those of the literature review. For 7 out of 10 Model Regions, the ratio of realistic potential to theoretical potential was lower than the ratio as found in the literature review for the corresponding country. On average, for these countries, the ratio of realistic potential to theoretical potential was 58 per cent in the literature review, whereas it was 24 per cent in the Model Regions. Furthermore, it is striking that there are large differences between Model Regions in the same country, e.g. Bavaria where the realistic potential was 100 per cent of the theoretical potential, whereas it was 0 per cent in North Rhine Westphalia.

Discussion

In this study, we used a literature review to estimate the realistic additional potential for roundwood harvest for the EU-27 + UK. From the literature review, the realistic additional potential was assessed to be 90 million m^3 yr^{-1}. Hence, the realistic additional potential for wood harvest as found in this study is in the range of 90 million m^3, which is an increase of 21 per cent compared with the harvest level of 432.2 million m^3 in 2015. The additional potential as found in this study is expected to be attainable within a time period of 10 to 20 years. However, the simulations in the Model Regions found potentials to be lower in 8 out of 10 cases, as compared with the country they are located in. On average, the model regions reached less than half of the potential as compared with the literature review. This suggests that the realistic additional potential at the European scale may well be lower if all mobilization barriers are taken into account in more detail, but also highlights the uncertainty surrounding these estimates.

The gap between the modelled realistic additional potential in Model Regions and the realistic additional potential as assessed in the literature review can for a large part be explained by two factors. Some national-level projections assume an increase

Table 3. Overview of the results from the literature review on national projection studies

Region	Country	Year	NAI (1000 m^3 per year) (Forest Europe, 2020)	Fellings over bark (1000 m^3 per year) (Forest Europe, 2020)	Current felling/ NAI ratio	Maximum additional potential (NAI minus current fellings)	Estimated realistic additional potential (this study)	Increased felling/NAI ratio under the estimated realistic potential	Reference
North Europe	Sweden	2015	94 843	89 025	94%	5818	5818	100%	Swedish Ministry for the Environment(2019)
	Finland	2015	96 200	77 348	80%	18 852	15 000	96%	The Finnish Forest Decision Support System Tool MELA: http://mela2.metla.fi/mela/julkaisut/oppaat-en.htm (accessed on 29 April, 2022).
	Denmark	2015	6608	4426	67%	2182	0	67%	No indication for mobilization potential found
	Estonia	2015	12 326	10 221	83%	2105	1579	96%	Lesta (2019)
	Latvia	2010*	19680*	12831*	65%	6849	2343	77%	Default increase in felling/increment ratio. Indication for mobilization potential based on Lazdins et al. (2019).
	Lithuania	2015	13 580	9550	70%	4030	1314	80%	Brukas et al. (2011)
Central-West Europe	Ireland	2015	7291	4702	64%	2589	2589	100%	Phillips et al. (2016)
	UK	2015	21 488	13 517	63%	7971	3283	78%	Forestry Commission (2014a,b)
	Germany	2015	104 160	79 663	76%	24 497	24 497	100%	Oehmichen et al. (2017)
	Netherlands	2015	2156	1026	48%	1130	190	56%	EFISCEN-Space model results
	Belgium	2015	5291	5221	99%	70	0	99%	Perin et al. (2018)
	Luxembourg	2010	760	NA	NA	NA	NA	NA	No indication for mobilization potential found
	France	2015	81 375	48 805	60%	32 570	8158	70%	Roux et al. (2017)
	Austria	2015	27 024	23 534	87%	3490	3217	99%	Default increase in felling/increment ratio. Indication for mobilization potential based on Braun et al. (2016).
Central-East Europe	Poland	2010*	62300*	46600*	75%	15 700	7417	87%	Default increase in felling/increment ratio. Indication for mobilization potential based on Kobuszynska (2017).
	Czech Republic	2015	21 696	18 247	84%	3449	−2747	71%	Synek et al. (2014)
	Slovakia	2015	12 681	10 000	79%	2681	0	79%	Moravcík (2020)
	Hungary	2015	10 869	7201	66%	3668	1294	78%	Default increase in felling/increment ratio. Indication for mobilization potential based on Földművelésügyi Minisztérium Erdészeti és Vadgazdálkodási Főosztályán (2016).
	Bulgaria	2010	14 361	6972	49%	7389	1710	60%	Default increase in felling/increment ratio. Indication for mobilization potential based on Boshnakova (2017)
	Romania	2015	41 383	18 164	44%	23 219	3724	53%	Ciceu et al. (2019)
South-West Europe	Spain	2010	35 479	19 707	56%	15 772	3871	66%	Ministerio Para La Transición Ecológica (2019)
	Portugal	2005*	18870*	13347*	71%	5523	0	71%	No indication for mobilization potential found
	Italy	2010	32 543	12 755	39%	19 788	3051	49%	Vitullo & Federici (2018)
South-East Europe	Croatia	2015	8863	6340	72%	2523	1690	91%	Ministry of Environment and Energy & Ministry of Agriculture, 2018
	Cyprus	2010	47	9	20%	38	0	19%	Menelaou & Christodoulou, 2019
	Greece	NAI 1990 fellings 2010	3813	1486	39%	2327	454	51%	Default increase in felling/increment ratio. Indication for mobilization potential based on Ministry of Environment & Energy (2019)
	Malta		NA	NA	NA	NA	NA	NA	No indication for mobilization potential found
	Slovenia	2015	8565	5251	61%	3314	1173	75%	Poljanec et al. (2019)
	EU27 + UK		**764 252**	**545 948**	**71%**	**218 304**	**89 625**	**83%**	

*Data from Forest Europe (2015)

Table 4. Comparison of the results per country from the literature review to the results from the simulations of the Model Regions

Country	Literature theoretical potential	Literature realistic potential	Percentage	Model region	Modelled theoretical potential	Modelled realistic potential	Percentage	Relative
France	32 570	8158	25%	West Auvergne	697	381	55%	218%
				Vosges	716	0	0%	0%
Germany	24 497	24 497	100%	Bavaria	249	249	100%	100%
				North Rhine Westphalia	309	0	0%	0%
Spain	15 772	3871	25%	Catalonia	1195	0	0%	0%
Ireland	2589	2589	100%	Southern and Eastern Ireland	3296	571	17%	17%
Great Britain	7971	3283	41%	Lochaber	1129	205	18%	44%
				Yorkshire & NEE	1980	486	25%	60%
Netherlands	1130	190	17%	Netherlands	660	190	29%	171%
Sweden	5818	5818	100%	Småland	0	0	0%	0%

in increment (e.g. Swedish Ministry for the Environment, 2019). Furthermore, there are also national-level projections that accept a decrease in growing stock (e.g. Oehmichen et al., 2017), whereas we (where necessary) capped the felling/increment ratio at 100 per cent in our approach.

The Model Regions that were used for this study cover as much as possible the regional heterogeneity across Europe with respect to social and biophysical and resource characteristics. Nevertheless, the Southern and Eastern European countries were less well represented than Western and Northern European countries. This was mostly due to inaccessibility of NFI data in Southern and Eastern European countries. The accuracy of the simulation study would benefit considerably from input data from NFIs of more Southern and Eastern European countries.

The maximum additional potential, i.e. the difference between NAI and annual fellings, is considerably larger than the realistic potential found in this study (218 million m^3 versus 90 million m^3). The reasons for this difference are many and varied. To meet the maximum additional potential, almost all forest owners must intensify wood mobilization in their forest management regime. All restrictions (e.g. for biodiversity conservation, erosion risks, recreation) could be lifted but this is often not desirable. Furthermore, the wood industry sector would need to upscale in a very short time frame. In addition to these impediments, there are multiple other barriers in the forest itself: e.g. rough terrain conditions, lack of infrastructure and the motivations of forest owners. The combination of all these factors explains why the maximum additional potential will never be realized in the medium long term and is not desirable either. Such an increase may only likely be realized after a large investment in additional forest resources has been made.

Vauhkonen et al. (2019) made a projection of the felling in a set of European countries between 2015 and 2040, based on different Production Possibility Frontiers. In a scenario with all forest land being regarded as FAWS, fellings would increase ca. 8 per cent between 2015 and 2040. Forsell et al. (2016) modelled a scenario with increased use of biomass for energy and material, which would lead to a forest harvest level that is 12 per cent higher in 2050 than in 2010. Jonsson et al. (2021) modelled a scenario with increased use of wood for construction, biochemicals and biofuels, leading to an increase of 15 per cent in the harvest level by 2030. In the European Forest Sector Outlook Studies II (UNECE/FAO, 2010), an increase in stemwood removals of 15 per cent is expected in 2030 compared with 2010, from 595 million m^3 to 685 million m^3. EFSOS III also projects an increase in industrial roundwood supply by 25 per cent or 96 million m^3 from 2020–2040 (UNECE/FAO, 2021). Nabuurs et al. (2018) showed that under the continuation of current forest management regimes, the wood removals could increase by 140 million m^3 (33 per cent) from the period 2000–2009 to 2050, due to forests maturing and being able to sustain higher harvest levels. Altogether, these studies estimated increases within a range of 8–33 per cent and our projection of an increase of 21 per cent is within this range.

To realize higher harvest levels than modelled in the previously mentioned studies, the scope for wood mobilization could be widened to e.g. include other sources of wood such as stumps and residues. Verkerk et al. (2011) estimated the realistic biomass potential at 744 million m^3 in 2010 and the realisable potential in 2030 at between 623 and 895 million m^3. Furthermore, no afforestation or conversion of species has been assumed in our study. Nabuurs et al. (2014) found that shortening of broadleaved forest rotation length and planting 50 per cent of the felled area with fast-growing coniferous species could increase coniferous wood supply from 473 to 561 million m^3 yr^{-1} in 2065, although total wood demand could reach 1200 million m^3 yr^{-1} by that time. Thus, although all studies above project that supply can increase somewhat, most of them put clear limits on supply. For example, Mantau (2012) simply assumed a constant supply, or national-level projections of supply, assuming restrictions through e.g. nature conservation. This approach led to a projected shortage of 185 million m^3 yr^{-1} in 2050 compared with the overall demand.

The share of the realistic additional potential with a low mobilization effort found in this study is mostly located in regions with economically attractive species, good infrastructure and gentle terrain conditions. Large forest owners ensure that harvesting can be done in a cost-effective way, which enabled larger wood processing industries to establish themselves. This is the case in Northern Europe and Central-West Europe. However, for the regions Småland and Bavaria, we found felling/increment ratios that are already close to 100 per cent. The potential in the Southern and Eastern regions of Europe are more often considered to require a medium-high or high mobilization effort to be realized, due to the barriers addressed in the following paragraphs. There were no regions or countries that could be considered 'hotspots', i.e. where the harvest ratio could increase by more than 50 per cent.

In many regions, broadleaved species will account for a larger share in the additional harvest than in current harvest volumes. The simulation results from the Model Regions in Western Europe showcase this issue. For example, mobilization scenarios in North-Rhine Westphalia, West Auvergne and Vosges show considerably higher volumes of beech (*Fagus sylvatica*) in the additional harvest compared with the baseline. Currently, broadleaved species are generally underused, as they are less attractive to the industry. Finding high-end applications for wood of broadleaved species is key to kickstart the wood mobilization in almost all European regions. Numerous studies address this topic in general (Kleinschmit, 2017; Hemery et al., 2010), as well as for specific species, e.g. for Betula spp. (Dubois et al., 2020), Tilia spp. (De Jaegere et al., 2016) and Alnus spp. (Salca, 2019).

Matching regional demand with regional forest resources is another mobilization issue. The industry demands logs of certain dimensions, depending on the species, intended application, processing capacity, etc. The optimal diameter ranges are subject to local variations. E.g. the optimal diameter range for pulpwood in Ireland is about 7–13 cm, whereas 14–19 cm is preferred for pallet and > 20 cm for sawlog (Phillips et al., 2016). Smaller logs are more expensive to harvest and yield only little volume, whereas large logs may get too large to be harvested mechanically and/or to be processed in certain sawmills. This is reflected by the harvesting patterns in relation to the diameter as found in Schelhaas et al. (2018b). These industry preferences limit the harvest possibilities in young stands and over-mature stands. The diameter distributions in European forests differ considerably across the countries. For example in Ireland, 37 per cent of the growing stock volume is in trees less than 20 cm DBH; 45 per cent of the Irish stocked forest is less than 20 years old (Forest Service, 2017), due to its extensive recent afforestation with mainly Sitka spruce (*Picea sitchensis*). Due to their fast growth rate, the increment is very high, but many of these forests will be only ready for a first thinning in the coming decade. In contrast, in many Eastern European countries, the large stem diameters of broadleaved species in older forests are a barrier for the wood processing industry (Orazio et al., 2017).

In many European regions, the forest area and ownership is fragmented. There are more than 16 million private forest owners in Europe, of which two-thirds own a forest property smaller than 3 ha (Schmithüsen et al., 2010). The objectives of the private owners and their associations regarding their forests vary widely, as does their background in forestry. The inheritance laws in some countries further increase fragmentation. The potential in privately owned forests can only be unlocked in a cost-effective way by forest owners acting together and forming co-operatives, such as Södra in Sweden, which has 53 000 owners. The barrier of fragmented ownership could be addressed by setting up forest owners' associations (FOAs; Aurenhammer et al., 2018a). In particular Eastern European countries have drawn much attention to the establishment or faciliation of FOAs in recent decades. However, in countries with former communist regimes, private forest owners are reluctant to again join a state-organized initiative (Hrib et al., 2018). Another issue is a lack of sufficient funding from government bodies for the administration and management tasks of the FOA (Hrib et al., 2018). Many owners are also not interested in joining an FOA, as their objective with their forest area is solely focused on recreation or biodiversity (Pezdevsek et al., 2017) and does not include timber production.

Lawrence (2018) notes that it is case dependent which forest owners must be targeted by an association, e.g. the unengaged or the ones less likely to harvest. Also, the activities of the association have to be tailored to the specific situation. The activities can differ from organizing platforms for timber buyers and small-scale owners to connecting forest management consultants to multiple owners.

An important physical barrier to wood mobilization is the lack of infrastructure in combination often with steep slopes, which result in prohibitive harvesting costs. For forest areas that do have a higher density of roads, the road network might not comply with best practice requirements. Planning tools for forest managers can help to assess if building a road network is feasible and where roads have to be built (e.g. Bont et al., 2018). Similar planning tools can play an important role in forestry in mountainous regions. Due to steep slopes, costly equipment is needed to harvest wood in an efficient manner. Decision support systems (e.g. Accastello et al., 2017) can assist forest managers in developing cost-effective harvesting strategies. In Switzerland for example, Bont et al., (2021) deduced the economically most feasible harvesting method for all NFI plots and found a quarter of the forest area was not suitable for harvesting wood.

One of the most important indicators for SFM is to harvest less than the increment. This has led to an increase in the growing stock in almost all countries over the past decades. This will inevitably lead to an increased risk for natural disturbances in high-stocked forests. Switzerland already identified this issue and set a goal to harvest 100 per cent of the increment to stop the increase in the growing stock (FOEN, 2013). Stadelmann et al. (2016) mention that further increasing the growing stock in Switzerland would increase the risk of natural disturbance such as wind damage, snow-breakage or bark beetle infestations.

The effect of natural disturbances on the wood harvest potential in Europe is complex. A major natural disturbance event can significantly increase wood harvest in the year and location of the event, e.g. storm Kyrill in 2007 (Jochem et al., 2015) and can unlock potential that would otherwise not be used. In case of extreme events, markets can also saturate [e.g. storm Vaia in Italy (Udali et al., 2021), storm Gudrun in Sweden (Björheden, 2007)] and industry in regions around the event may have to compete against cheap raw material flooding onto the market. However, after smaller events, market saturation does not usually happen, as the demand for wood is expected to remain considerably higher than the supply in the coming decade (Gardiner et al., 2013). The negative effects on wood harvest potential after natural disturbance events follow in subsequent years, due to the lower stocking in the forest and the unbalanced age class distribution. In our study, we based both the modelling approach and the literature review on historical data. Major natural disturbances that will happen in the future and that will influence the realistic additional potential have not been taken into account.

Natural disturbances are of increasing concern in European forest management, and are expected to be mainly related to storms (Seidl et al., 2014), drought (Senf et al., 2020) and consequently outbreaks of pests and diseases (Senf et al., 2018). The European bark beetle (*Ips typographus*) caused 8 per cent of all tree mortality due to natural disturbances in Europe between 1850 and 2000 (Schelhaas et al., 2003). Its major host, Norway spruce (*Picea abies* L.), accounts for ca. 7 billion m^3 of growing stock (Hlásny et al., 2021). Hence, more than one quarter of the growing stock of European forests is at risk due to the bark beetle alone. The largest threat, however, is posed by storm damage, which is expected to damage three times more growing stock than fires and insect outbreaks (Seidl et al., 2014).

An increased wood harvest is generally perceived to lead to trade-offs with other functions, most notably biodiversity protection (Verkerk et al., 2014; Eyvindson et al., 2018, Di Fulvio et al., 2019). Conflicting aims between different functions of the forest can be an important additional barrier for increased wood mobilization for the bioeconomy development. For example, in the Netherlands where one-third of the forest is designated to nature conservation, about 57 per cent of the maximum additional potential cannot be mobilized because of restrictions due to nature protection.

Recently published policy strategies, such as the European Forest Strategy and the Biodiversity Strategy, do not favour an increase in wood harvest and even state some conflicting goals. The European Forest Strategy favours a bioeconomy, but also states that wood should be used more efficiently and supply of wood products should be done in synergy with improving the conservation status. It furthermore states: 'in the short to medium term, i.e. until 2050, the potential additional benefits from harvested wood products and material substitution are unlikely to compensate for the reduction of the net forest sink' (EC, 2021b). The Biodiversity Strategy (which aims for 30 per cent of the forest area under protection, one third of which should be strictly protected) proposed different measures that will have a negative effect for the realistic additional potential. Dieter et al. (2020) estimated for example decreases in roundwood production for Germany in the period 2018–2052 as a result of the following measures: 10 per cent forest set-aside (6.4 million m^3 yr^{-1}), non-utilization of old-growth forests scenario for Germany (18.1 million m^3) and 30 per cent natural habitats (1 million m^3 yr^{-1}).

The EFISCEN-Space model and the results from our simulations certainly show the advantages of being able to deal with the regional circumstances. The evidence from a comparison of the two approaches used in this study, is that taking into account regional characteristics is very important to estimate future harvesting potential and seems to (further) limit the potential. However, in our approach we still lack understanding of the choices of the forest owners. Why do they choose a certain type of management, or decide to not harvest at all? And how can they be convinced to change their behaviour? We tackled this in our study by assuming owners would be willing to switch to management types (harvest patterns) already practiced in the region or in neighboring regions, combined with a subjective interpretation of the effort needed to convince them. One element in the decision to harvest or not is the expected costs versus the expected revenues. EFISCEN-Space currently does not model the costs of harvesting activities. When a cost module is implemented in the model, the modelled realistic additional potential in mobilization scenarios can be further classified in cost efficiency classes. This would contribute to a better estimation of a realistic additional potential. In addition, the EFISCEN-Space model could be linked to a forest trade model, to match supply and demand. The level of detail of the EFISCEN-Space output (i.e. wood per species and diameter class) could also help to improve forest trade models. For example, the Global Forest Products Model that is used in the UNECE/FAO outlook studies (UNECE/FAO, 2021) only uses forest growing stock as input, without imposing any constraints on any country's harvest. The modelled harvests are only based on economic variables and do not take account factors such as regulations or sustainability principles.

As a final limitation of our approach, we acknowledge that recruitment is not taken into account in the current version of EFISCEN-Space. Due to the relatively short simulation time, this shortcoming was deemed to have a negligible effect on the outcomes in this study but may still be a topic of future research.

Conclusion

Many of the Model Regions in the simulations and countries from the literature review have the potential for increased wood mobilization. An increase in the harvest level to 100 per cent of the increment, the maximum additional potential, is unrealistic because forests have to fulfill many different functions and harvesting may also be restricted by cost in some areas. Based on the results of the literature review from this study, an increase in annual fellings of 90 million m^3 in the coming 20 years is attainable. This would mean an increase of 21 per cent compared with the felling level in 2015. However, the simulations in the Model Regions found potentials to be lower in 7 out of 10 cases as compared with the country they are located in. On average, the model regions reached less than half of the potential as compared with the literature review. This suggests that the realistic additional potential at the European scale may well be lower if all mobilization barriers are taken into account in more detail, but also highlights the uncertainty surrounding these estimates.

The EFISCEN-Space model and the results from our simulations certainly show the advantages of being able to deal with the regional circumstances in terms of resource characteristics, owner characteristics and the practicalities of forest management. It is clear from the comparison of the two approaches in this study that taking into account regional characteristics is very important to estimate future harvesting potential and also seems to (further) limit the potential for wood mobilization, which is an important outcome.

Two further important findings of this study were that the largest wood mobilization potential lies in forests of private owners and that we could not identify any 'secret hotspots' where great potential is hidden, in terms of wood volume, wood quality, infrastructure and nearby industries.

Thus, an increase in harvest would come with an increase in the costs of the additional harvest activities, to cover investments in infrastructure or setting up of owner associations, or to cope with more difficult terrain conditions. This will be challenging, as the most important driver for steering where the wood is harvested is the economic driver. Another challenge will be the larger share of broadleaves in the additional harvest, which are generally preferred less by the wood processing industry. In the long term (more than 20 years), additional wood, compared with the amounts we found for the short term, can only be made available through investments in afforestation, in forest restoration, in improved forest management and in more efficient use of raw material and recycled material.

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Supplementary data

Supplementary data are available at *Forestry* online.

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Conflict of interest statement

None declared.

Data availability

Data are owned by a third party.

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