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Jun.-Prof. Dr. Paul Lehmann

Supervisor - Dr.-Ing. Philip Tafarte

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Smock, Samuel

The following is an excerpt from a larger group project intended to showcase the authors own personal contribution. For the full work please contact the author at smock.samuel@gmail.com

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List of Abbreviations

AR – Afforestation and Reforestation

CBM – Carbon Budget Model

EU – European Union

FW – Fuelwood

GFTM – Global Forest Trade Model

GHG – Greenhouse Gas

HRO – High Roll Out

IPCC – Intergovernmental Panel of Climate Change

IRW – Industrial Roundwood

IRENA – International Renewable Energy Agency

IEA – International Energy Agency

JRC – Joint Research Council (European Commission)

LCA – Life Cycle Assessment

LRO – Low Roll Out

LULUCF – Land Use and Forestry Regulations

MCDA – Multicriteria Decision Analysis

NAI – Net Annual Increment

NREAP – National Renewable Energy Action Plans

REDI / RED II – Renewable Energy Directive I / II (2009)/ (2018)

SRF – Short Rotation Forests

SWE – Solid Wood Equivalent

SFM - Sustainable Forest Management

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ABSTRACT

According to many experts, bioenergy production is a key technology in the shift towards sustainable energy sources, especially in achieving emissions reduction targets in the short term. Nonetheless, this approach poses a range of sustainability challenges that must be carefully evaluated.

The objective of this study is to deepen the understanding of whether woody biomass for energy can be produced, processed, and used in a sustainable and efficient way to minimize greenhouse gas emissions in the mid to long run without causing collateral damage such as deforestation, habitat degradation, biodiversity loss or even increased greenhouse gas emissions in the short term.

This report focuses on the trade-offs involved in producing energy from woody biomass by considering three main criteria: (i) impacts on biodiversity, (ii) short-term carbon emissions and (iii) long-term atmospheric carbon mitigation over fossil fuel energy systems, collectively referred to as carbon accounting.

IMPACT ASSESSMENT

At the highest level, the impact analysis presented here is a synthesis of available information on the sources and uses of woody biomass energy in Europe (material flow balance), the types and relative contribution of various silvicultural practices to woody biomass flows (harvest scenarios), the carbon impact over time of each harvest scenario (carbon accounting), and the biodiversity and ecosystem impacts of each harvest scenario (biodiversity impacts). To the authors' knowledge, this is the first time that all four of these inputs have been synthesized to come up with an aggregated estimate of these impacts continent-wide. Within the literature, one generally finds for instance studies of carbon or biodiversity impacts within a specific biome or harvest practice, but not a link to the relative or absolute flows originating from that particular biome or harvest source. In their wide-ranging report on the Use of Woody Biomass within Europe, Camia et. al. (2021) provide an overview of these four variables but tend to treat each individually. They focus on uncertainties originating from a lack of data, particularly on harvest practices and net flows, and therefore avoid making too many assumptions to try to arrive at a full-scale impact assessment.

Despite these uncertainties, the authors feel it is important to make an attempt at a full-scale analysis using evidence-based best estimates along the way simply because when it comes to climate and ecosystems, impacts are deeply scale sensitive. A relatively benign practice can become problematic at too high of a scale just as the demand for woody biomass can become unsustainable when it passes a certain threshold determined by the availability of secondary sources and the stock of forest land under management among other factors.

Figure 4 shows a schematic representation of the methodology used in the impact analysis. The material flow analysis is focused on determining the net primary domestic solid wood equivalent (SWE) volumetric flow of woody biomass material in million cubic meters (M m^3). This step focuses on reconciling the gap between reported sources and uses and subtracting out imports and secondary flows. The net volumetric flow is one main input for determining the volumetric flows by harvest scenario. Atmospheric carbon impacts and biodiversity impacts are analyzed for each harvest scenario without regard to the relative contribution or prevalence of each harvest practice and are normalized to 1 for positive impacts (50 Year Carbon Mitigation) and -1 for negative impacts (10 Year

Carbon Emissions and Biodiversity Loss). The crucial step then comes when these impacts are volumetrically weighted relative to the absolute flows from each harvest scenario in Step 6. The output sent to the decision analysis now reflects very high-level information on industry and continent-wide material flows, mid-level information on the forestry practices constituting those flows, and low-level information on the impacts resulting from each forestry practice.

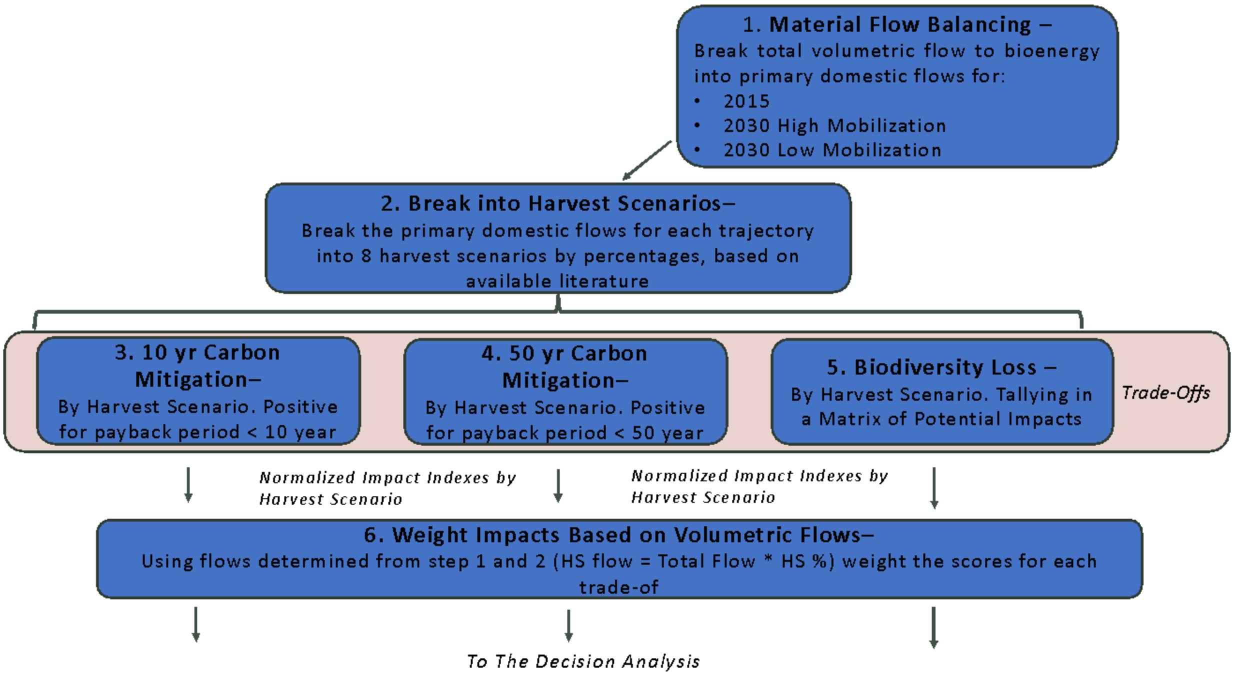

Figure 1. Schematic Overview of the Impact Analysis

1.1 Material Flow Analysis of Woody Biomass in Europe

Conducting a robust analysis of the impact of Europe's woody biomass energy goals on biodiversity and the climate requires an in-depth analysis of the stocks, flows, uses and sources of woody biomass within the bloc. The inherent fluidity of processed woody biomass energy makes this task untrivial and indeed a sufficiently granular outlook requires accounting all pathways such as imports, harvests, secondary sources, circularities, managed, and unmanaged sources into account. Further complicating this task is that many categories have overlap. For instance, a managed plantation can also be recently afforested, and can be producing wood products that may flow directly to bioenergy uses, and others that may eventually make it to a bioenergy use as a secondary product decades after harvesting.

To capture this complexity in a way that aggregates to a meaningful result, a variety of sources were used to fill any gaps in the balance of sources and uses of woody biomass, and more importantly to scale current flows to estimates of future flows required under two different 2030 biomass energy deployment scenarios. The ultimate goal of this analysis was to arrive at a "Domestic, Primary Flow," which can be interpreted as the yearly flow of harvested woody biomass from European forests going directly to energy uses.

The three scenarios that were modelled were a 2015 baseline, a 2030 "high mobilization" scenario, which closely corresponds to the renewable energy goals enshrined in the ReCast and REDII legislation paired with increased afforestation and sustainable harvesting practices and a 2030 "low mobilization" scenario corresponding to a lower rollout of woody biomass energy roughly in line with original RED goals from 2009 legislation paired with "business as usual" forestry practices where sources of woody biomass do not change substantially from 2015, but rather simply scale up.

Each scenario will be described in deeper detail below, but the general approach for each scenario was a three-step process. First, the net volume of woody biomass for energy use was determined. In 2015, this comes from analysis of the Joint Forest Sector Questionnaire (JFSQ) and the Joint Wood Energy Enquiry (JWEE) conducted by the EU's Joint Research Council (JRC), while in the two 2030 scenarios, total uses were scaled up proportionally to the energetic yearly totals for relevant solid biomass categories in analyses conducted by IRENA (2018) and the IEA (2021) of REDI and REDII targets. This reflects an assumption that the efficiency of biomass energy conversion and volumetric energy density will not appreciably change during this time period.

Imports and secondary flows were similarly scaled from real 2015 numbers. For secondary flows, the total volume was scaled proportionally to the maximum wood supply (MWS) in two different rollout scenarios as determined in analysis by Jonsson et. al. (2018). These MWS figures were compared to actual *total* (IRW + FW) harvests from 2015 for the scaling of secondary wood flows, under the assumption that the primary driver of secondary flows are domestic industrial processing of wood products and the flow of wood to the material industry, both of which should scale in rough proportion to the domestic harvest. Imports are difficult to predict, but for the purposes of this study, modest increases from 2015 flows are assumed using results from the Global Forest Trade

Model (GFTM) which is in keeping also with basic assumptions of this study, namely that exporting negative carbon or biodiversity externalities to other regions is not a sustainable option for Europe (Jonsson et al., 2018). The ratio of wood product imports going to bioenergy was further taken to be constant in the period under consideration, which was necessary because figures on import estimates were only available for all (IRW +FW) wood products. The third and final step taken in each scenario was to subtract imports and secondary flows from the total flow of woody biomass needed for bioenergy uses. The result of this arithmetic is an estimate of the primary flow from domestic harvests and is the principle number on which the rest of the impact analysis is based.

1.1.1 2015 Baseline

As was described above, the principal approach used here to forecast woody biomass flows into the future is based on scaling up past recorded numbers using estimates of future harvests and estimates of future demand for bioenergy. While the results of many of the surveys and energy reports such as the JFSQ, JWEE, and NREAP are available for more recent years, 2015 was chosen as a baseline because of the availability of a robust synthesis of data from multiple sources into one holistic picture largely following analysis by the Camia et. al. (2021). The analysis that follows from these numbers is therefore something of a snapshot, however based on the numbers from the 2020 JFSQ and the State of Europe's Forest Report, the growth of stated uses of primary woody biomass energy continue to outpace the stated sources indicating that the assumption of robust growth in the period of 2015-2030 is well founded as is the finding that a significant portion of uncategorized wood flows are attributable to primary flows (JRC, 2019).

Numerous studies (e.g., Pilli et al., (2015) and Jonsson et al., (2021)) have described the issue of underreporting of fellings as a potential explanation of the gap between sources and uses. For the purposes of the impact analysis, uncategorized sources were thus taken to be 100% primary. This assumption is in line with the fact that forestry industry production and trade data tend to be more reliable than data on fellings, resulting in a lower likelihood of a secondary source of woody biomass going unreported (Camia et al., 2021). The result of adding the 14% uncategorized share to the 37% known primary contribution results in a nearly even split between primary and secondary sources with primary sources making 51% of the total supply (Figure 5).

The most important number for our 2015 baseline is the total use of woody bioenergy quoted in Figure 5 as 451 Mm^3 SWE of which 223 Mm^3 is taken to be primary, including reported primary flows from the JWEE and JFSQ and uncategorized flows in line with the above assumption (Figure 5; Appendix C). The total domestic harvest of 562 Mm^3 is also of importance as this number is used as a baseline to scale secondary flows into the future as discussed above. The baseline primary energy figure of 4.0 EJ from woody biomass comes from analysis by IRENA (2018) and is used to scale net woody biomass energy uses into 2030.

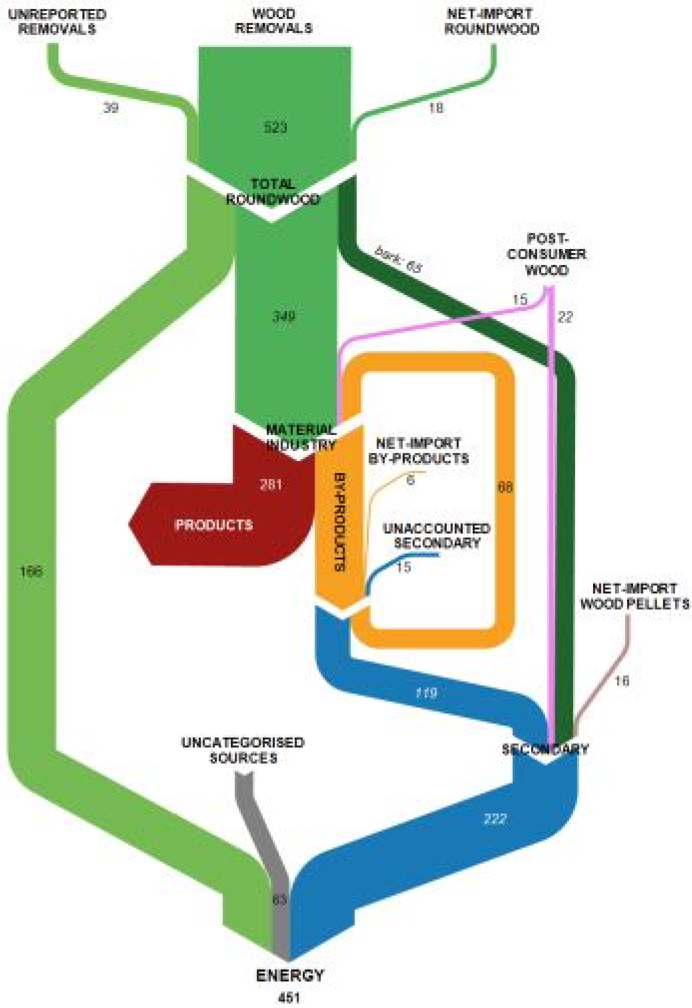

Figure 2. Sankey diagram of woody biomass flows in the EU (data 2015 in Mm 3 SWE) (Camia et al., 2021)

1.1.2 2030 Low Rollout

The low rollout 2030 scenario combines business-as-usual forestry practices and a modest rollout in the uses of woody bioenergy. The 2030 domestic harvest is set to 518 Mm^3 corresponding to heavy exploitation of existing stock in the period 2015-2030 and modest levels of afforestation, coppice reclamation, and conversion to short rotation plantations. This number is taken from analysis by Jonsson et al. (2018) employing the Carbon Budget Model (CBM) and the Global Forestry Trade Model (GFTM), which is a techno-economic model accounting for feedback effects on supply changes and demand in the global marketplace for wood products. This figure reflects a situation where forest management practices are successful in maintaining forest carbon stock on a yearly basis, but not successful in sustainably scaling up the supply from domestic forests and is therefore on the low end of harvest estimates for 2030 which range from 518Mm^3 to around 750Mm^3 (Forsell et al., 2016; Jonsson et al., 2021).

Estimates for the rollout of woody bioenergy use in this trajectory are based on a continuation of existing and planned energy policies within the EU-28 as of 2018 and correspond to a 24% renewable share in the primary energy supply in 2030, or just shy of the original RED goal of 27% enshrined in 2009 EU legislation (IRENA, 2018). This trajectory puts the EU-28 on track to achieve 6.2 EJ from solid biomass for industry, buildings, power, and district heating in 2030. This figure is used to scale woody biomass energy uses from 2015 based on the assumption that woody biomass energy uses will scale in proportion to primary solid biofuels (of which woody biomass is the principal component). This conclusion is a result of a synthesis of analyses by IRENA and the IEA (Figures 6 & 7) and is further supported by the dominance of woody biomass in the solid biofuel market. That said, for the purposes of this study, only the ratio of 2015 to 2030 solid biofuels energetic totals is of interest for projecting volumetric flows, so unless other streams of solid biomass such as municipal or agricultural waste significantly outpace woody biomass in the period of 2015-2030 the assumption of woody biomass energy uses scaling with aggregated primary solid biofuels remains sound.

Figure 3. Total primary energy supply of biomass in the EU-28 in 2010 and in 2030 under the different rollouts (IRENA, 2018)

1.1.3 2030 High Rollout

The high rollout scenario for 2030 combines an aggressive rollout of biofuels with a high mobilization of sustainable forestry practices such as afforestation, short rotation forests, and coppice reclamation and expansion. The total EU Harvest in this scenario for all uses is 756 Mm^3 which is simply the maximum wood supply (MWS) as determined by Jonsson et al. (2018) using the carbon budget model and reflects a scenario where the EU has grown and maximised its forest land available for wood supply. In this sense, it can be thought of as the upper limit to possible domestic supply without depletion. The volumetric flow of woody biomass energy uses are scaled in accordance with the REMap scenarios from IRENAs analysis of EU bioenergy policy and roughly coincide with REDII RECast goals of 32% renewables in the primary energy supply (IRENA, 2018; JRC, 2018). The total primary energy from solid biofuels is taken as 8.2 EJ in this scenario, and volumetric woody biomass uses are thus scaled to 924 Mm^3 in accordance with the methodology described above. Secondary uses are scaled in relation to total EU-wide harvest to 296 Mm^3 and imports are taken to be 56 Mm^3 of which 35 Mm^3 is used for energy following analysis by Jonsson et.al. (2018) using the GFTM and the assumption of a relatively constant share of imports going to the energy sector.

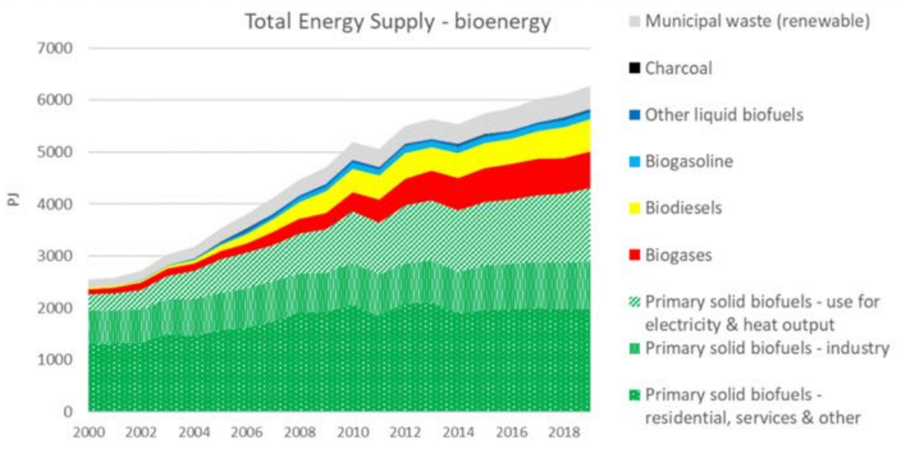

Figure 4. Development of total energy supply from bioenergy in the EU28 2000 – 2019 (IEA, 2021)

One notable feature of both 2030 trajectories examined here is that energy uses for woody biomass tend to crowd out material uses of the domestic harvest over the period of 2015-2030 with energy uses taking up over 78% percent of domestic harvests in 2030 under the high mobilisation trajectory (Table 1). This result is consistent with data from more recent years for which data is available and with the results from other attempts to model the trajectory of wood products in Europe using for instance GLOBIOM and G4M models (Frank et al., 2016; Jonsson et al., 2021).

WOODY BIOMASS FLOW BALANCES			
2015			
AGGREGATE Woody Miomass Flows (Mm^3)		Primary Energy Totals (EJ)	
Total EU-28 Harvest (incl. unreported)[1]	562	Bioenergy[6]	5.6
Total Forest Area (Harvested Area) (Mha)[9]	158 (108)		
Net Woody Bioenergy	451	Primary Solid Biofuels for industry, buildings, power and district heating[7]	4
Net Imports Imports (IRW +FW)[1]	34	Renewables	9.9
Import FW (Pellets + Byproducts)	22		
Secondary Flow (domestic)	206	Total	66
EU-28 Havest to Material Industry[1]	349		
Primary Flow (incl. uncategorized)	223		
2030 BAU Silvicultural Practices / RED I Target			
AGGREGATE Woody Miomass Flows (Mm^3)		Primary Energy Totals (EJ)	
EU-28 Maximum Wood Supply[2]	518	Bioenergy[7]	9.6
Total Forest Area (Harvested Area) (Mha)[9]	160 (115)		
Net Woody Bioenergy[3]	699.05	Primary Solid Biofuels for industry, buildings, power and district heating[7]	6.2
Net Imports (IRW + Pellets)[2]	40		
Import FW (Pellets + Byproducts)	26		
Secondary Flow (Domestic)[5]	204		
EU-28 Havest to Material Industry[1]	?		
Primary Flow	469.05		
2030 High Silvicultural Mobilization / RED II Targets			
AGGREGATE Woody Miomass Flows (Mm^3)		Primary Energy Totals (EJ)	
EU-28 Maximum Wood Supply[2]	754	Bioenergy	12.1
Total Forest Area (Harvested Area) (Mha)[9]	160 (113)		
Net Woody Bioenergy[3]	924.55	Primary Solid Biofuels for industry, buildings, power and district heating[7]	8.2
Net Imports (IRW + Pellets)[2]	56		
Import FW (Pellets + Byproducts)	36		
Secondary Flow (Domestic)[5]	296		
EU-28 Havest to Material Industry[1]	?		
Primary Flow	592.55		

Table 1. Material Flow Balance of Woody Biomass in the EU in 2015 and under 2 Different 2030 Trajectories

It is interesting to note that the contrapositive case where biomass energy is aggressively pursued in line with REDII targets without changes to silvicultural practices results in a situation where primary domestic woody bioenergy demand (net woody bioenergy uses minus secondary flows, minus imports) exceeds the total domestic harvest, implying a breakdown in the assumptions made here either on the limits of imports, the avoidance of widespread forest loss or both. This case is not explored in depth here due to the difficulty of extending the uncertainties on future sourcing decisions to a global level. However, one possible scenario would be a significant increase in imports, likely from North America, where forest resources are abundant, but woody

[1] (JRC, 2021 pg.49)
[2] From the Global Forest Trade
[3] Scaled Proportionally to Total Bioenergy Use 5.6 -> 9.6 EJ (IEA, 2021; IRENA, 2018)
[4] Scaled Proportionally to Total Bioenergy Use 5.6 -> 12.1 EJ (IEA, 2021; IRENA, 2018)
[5] Scaled Proportionally to Domestic Harvest
[6] (IEA, 2021)
[7] (IRENA, 2018)
[8] Scaling in proportion to the Use of Biofuels for Industry, Building, Power, and District Heating (IRENA, 2018)
[9] interpolated (JRC, 2021; Forsell et. al. 2016)

bioenergy uses are limited. The effects of such a trade relationship are however left to further research.

1.2 HARVEST SCENARIOS

With projections on energy uses of woody biomass now established for the 2015 baseline and two different 2030 trajectories, the next step in conducting an impact assessment of the demand for woody bioenergy on climate goals and biodiversity in the EU-28 is to establish estimates on sources. Numerous summaries of existing datasets have called attention to the problem of the underreporting of fellings, a lack of detail in the silvicultural practices in wood product sourcing, and a gap between reported uses and reported sources of woody biomass energy. Unfortunately for the purposes of a robust impact analysis, these sorts of specifics on the harvesting practices are the primary determinants of both carbon accounting and biodiversity loss. More specifically, for the purposes of computing carbon payback periods, details such as species type, rotation period, and the previous use of the land can yield payback periods that range from nearly 0 years to several hundred (Agostini et al., 2014). On the biodiversity side, the choice of whether to harvest residues such as trimmings, stumps, and root material has a tremendous impact on soil nutrient retention, organic carbon content, saproxylic community composition post-harvest, and habitat relevance just to name a few (Camia et al., 2021). It is therefore clear that in the absence of hard data, certain assumptions have to be made on the likely composition of primary domestic material flows determined above.

Domestic forest bioenergy flows were therefore broken into 8 different harvest scenarios on the basis of relevance for our trade-off criteria, their size relative to total primary woody energy uses, and the availability of data. They were further grouped into previous land uses as this factor has a deep impact on carbon payback period (Figure 8).

Harvest Scenario	
Existing managed Forest or Plantation	Broadleaf Stemwood (including coppice)
	Broadleaf Residue
	Conifer Stemwood
	Conifer Residue
Salvage	Conifer, Broadleaf
Afforestation and transition to plantation	Broadleaf, Conifer
Uncategorized/ assumed Forest Clearing with or without replanting	Conifer
	Broadleaf

Figure 5. Eight Harvest Scenarios Grouped by Previous Land Use and Silvicultural Practices

As discussed above, taxonomic division, harvest material (stem wood vs residue), and previous land use are all represented in this list of harvest scenarios due to these factors' strong correlation with carbon accounting and biodiversity impacts. Salvage harvesting and afforestation were added as separate categories in an effort to capture the unique effects of these silvicultural practices on carbon storage and biodiversity, though were collapsed to a single scenario regardless of tree or material type because the relative contribution was found to be less than around 5% in both trajectories considered (Table 2).

The effects of data availability on the conception and breakdown of harvest scenarios were profound. Splitting by taxonomic division was chosen due to findings by Jonsson et. al. (2018) indicating a relative blend of 76:24 of conifer to broadleaf harvests by SWE volume in 2015, with a slight shift toward coniferous harvests, attaining around 80:20 by 2030. It was further assumed that the blend of coniferous and broadleaf trees in the overall harvest would be representative of the blend within the woody bioenergy subcategory. Findings from Camia et. al. (2021) further showed relative contributions of around 20% from primary stem wood, split evenly between coppice harvests and non-coppice rotated harvesting, 17% from residues, 49% from secondary sources, and 14% uncategorized, assumed to be harvested of previously unmanaged forestland as outlined above. Due to the focus on primary domestic sources in this study, these percentages were then scaled to show their representation within just primary flows. Conveniently this involved just multiplying by a factor of two due to the nearly 50:50 split in assumed primary sources and secondary sources with the end result being: 20% Broadleaf Stemwood (Including Coppice), 20% Coniferous Stemwood, 32% Residue, and 28% Uncategorized, assumed encroachment on new forestland.

Determining annual volumetric flows from salvage logging operations was difficult again due to a lack of complete data. Though salvage operations figure prominently in the total wood removals within the bloc and amounted to around 45 Mm^3 in 2014 and 106 Mm^3 in 2018, only 17 EU MS representing 76% of forest area report salvage logging totals (Camia et al., 2021). Confounding the issue further is the fact that those flows go to several consumer products such as particle board and paper in addition to bioenergy.

From a time-series perspective, the fact that many of the events which cause natural disturbances in forest ecosystems such as windstorms, fire, drought, and pests are deeply linked to climate change indicates the possibility that there may be a significant increase in the flow of salvage wood in the midterm. Nevertheless, for the purposes of estimating this flow, the percentage of all wood removals going to bioenergy uses (40% in 2015 baseline; 90% in 2030 Low Rollout; 78% in 2030 High Rollout) was applied also to salvage wood. This could even be an underestimate for some trajectories because of the fact that wood degraded by fire, moisture or infection is less likely to be suitable for the materials sector. Despite the fact that only 17 countries report salvage logging totals, the reported estimates were not upscaled due in part to the fact that central and northern European countries like Czechia, Germany, Finland, Romania, and Bulgaria which have recently been afflicted with large scale natural disturbances such as beetle infestations resulting in large flows of salvage wood are among those reporting, while those absent tend to be southern European countries such as Spain Italy and Greece where salvage operations may be less significant (Camia et al., 2021; Kulakowski et al., 2017). Finally, and perhaps most significantly, total salvage removals were assumed to roughly level out post 2020 due to the fact that neither of the two trajectories included under consideration feature a rapid deforestation of the continent with total forested acres remaining stable after 2020, (FAO, 2020; Forsell et al., 2016). For this reason, reported totals of 2014 and 2018 were applied to the baseline and future projections respectively. After scaling for the percentage of salvage removals going to bioenergy as outlined above, this came to 18 Mm^3 for 2015, 95 Mm^3 for 2030 Low Rollout, and 83 Mm^3 2030 High Rollout. The large jump predicted here is in line with trends already witnessed in the years since 2015 and the higher value under the low rollout trajectory implies that low mobilization on improving silvicultural practices is more important than the lower deployment of renewables in this trajectory, therefore there is more "crowding out" of other uses by bioenergy uses within wood material flows.

The final input required to begin shaping the relative blend of harvest scenarios making up primary energy supply is the flow from recently afforested areas. While this scenario proved to be small relative to the others, it was included as a standalone scenario because it is a prime example of a sustainability win-win, with a carbon payback period of nearly 0 and numerous benefits to biodiversity such as providing wildlife habitat and improving soil health among many others (Agostini et al., 2014; Camia et al., 2021). While the inputs discussed above focused on reported flows of various subcategories of wood products, the approach here focused on changes to the forestry stock and derive from the modelling results of Forsell et. al. (2016) using the ReceBio model. The results of this model show a plateauing of the total forested area of the bloc at around 160 Mha paired with persistent afforestation activities totalling around 9 Mha between 2010 and 2030 balancing out forest loses due to deforestation and contributing to an increase in forest area under cultivation. To translate changes in stock to annual flows, a "recently afforested area" was defined as an area afforested within the last 8 years, corresponding to the maturation period of a short rotation forest or coppice, and afforestation was taken to be linear in the period of 2010 to 2030 at 0.5 Mha/yr (Zanchi et al., 2011). This reflects a logic that carbon sequestration and biodiversity benefits are felt from the moment of planting through to the moment of harvest and combustion, but airs on the shorter side how long a given piece of land can be called "recently afforested", before it becomes an existing forest under harvest or a plantation. Finally, a mean absolute stand volume of 5.2 m^3/ha was used to convert between the amount of new growth per hectare per year, which would equal the yearly yield of a coppice or otherwise sustainably harvested SRF, which was based on several Europe-wide averages from the literature (Camia et al., 2021; Eugen & Cojinovschi, 2014; Forsell et al., 2016). The result of the 8-year rule, the rate of afforestation and the conversion factor above is a yearly flow of 20.8 Mm^3 from recently afforested areas.

1.2.1 Synthesizing Inputs to Estimate Harvest Blend

Figure 9 provides an overview of the inputs used to estimate primary woody biomass flows by harvest scenario. It should be noted that there are potential areas of overlap. For instance, stemwood may be the result of salvage or afforestation and coniferous and broadleaf flows are comprised of all material types and past land uses aggregated to a net flow. Furthermore, some inputs are in percentages, while others are in absolute volumes such as those from salvage and afforestation. The methodology thus employed to synthesize these disparate inputs was as follows.

1. Subtract absolute flows (salvage and afforestation) from the total domestic primary uses.
2. Apply percentages of material type to the remainder (stemwood coppice, stemwood non-coppice, Residue, Uncategorized)
3. Within each category apply the blends of conifer to broadleaf to arrive at the final harvest scenario total as an absolute volume

The methodology described above assumes that the breakdown by material type applies to the remainder after salvage and afforestation flows are subtracted, and further that blends by taxonomic division (broadleaf and conifer) are valid within each category (e.g., that coniferous material makes up 76% of residue harvests for 2015 as well as total harvest for 2015). The process also helps make the scenarios proposed clearly defined. For instance, the full description of the scenario, “Conifer Stemwood” in Table 2, should by all rights be “Conifer Stemwood, not deriving from recently afforested or salvaged land.” These harvest scenario names are left in their brief form, but these further conditions should be kept in mind.

The decision was made to continue to include uncategorized sources in the low rollout 2030 scenario, but to assume that uncategorized sources have been eliminated by 2030 under the high rollout scenario, implying a shift to more responsible silvicultural practices in line with 2018 changes in the EU’s “recast” into the REDII around LULUCF. These changes require all industrial bioenergy generators to “demonstrate that the country of origin has laws in place a) avoiding the risk of unsustainable harvesting and b) accounting of emissions from forest harvesting.” (EC, 2018) This change would imply that sources of unknown origin would also rapidly be disallowed. While it is somewhat likely that these recent legislative accounting changes will result in closing the gap between reported uses and sources, it is also worth considering the possibility of this gap persisting into the 2030s in part because the last full-scale analysis for woody biomass flows published by the EU JRC from 2017 still include uncategorized sources (JRC, 2022). On this point, it is worth considering again a major aspect of the context and premise of this inquiry, namely that poor accountability and transparency on sourcing is the principal sustainability concern for forest biomass energy. Thus, the low rollout scenario can additionally be described as one in which legal efforts to constrain the sourcing of woody biomass to only those that hit high biodiversity and carbon sustainability metrics are poorly implemented. This interpretation gives further urgency to the question of what happens if an aggressive rollout of uses for woody biomass is paired with a weak rollout of sustainable forestry practices. This possibility is explored further in the discussion section.

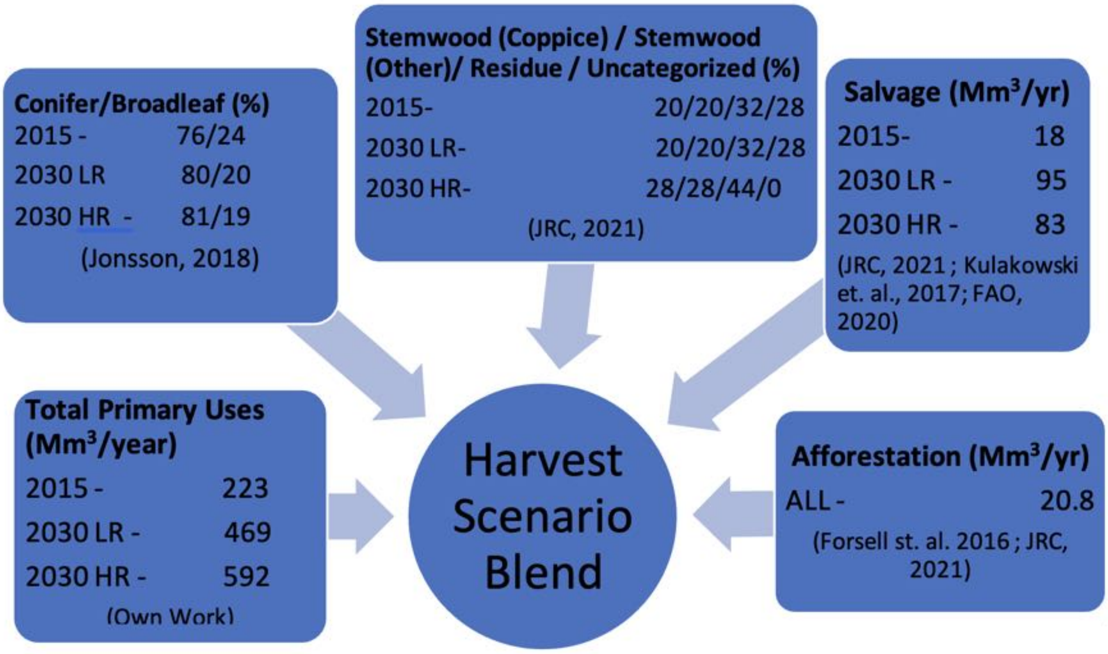

Figure 6. A summary of the Inputs to the Harvest Scenario Blend Synthesis

The synthesis of these inputs into full harvest scenario blends can be seen in Table 2. As was mentioned above the total woody biomass flows for each trajectory were carried over from the material flow balance analysis. A few important general trends can be observed. First, as the ambition for total contribution for bioenergy go up, the relative importance of afforestation, the only certain win-win scenario, go down. This is a result of limited available land for afforestation and projections of relatively steady rates of afforestation made by Forsell et.al. (2016) and mirrored by results from the EU Joint Research Council (2021). Second, the reliance on Salvage wood is seen to increase significantly by 2030, which is a result of an important assumption made that salvaged woody biomass flows will mirror relative percentages in the overall domestic market as salvage harvests increase. This projection is in line with a likely increase in natural disturbances such as pests, wildfires, and windstorms and is supported by results from Kulakowski et. al. (2017) and the UN FAO (2020). Finally, the roll of coppice forests is somewhat increased in the high mobilization scenario, again in line with recommendations from various agencies to reclaim historic coppice forests as part of an effort to expand sustainable forest practices. It should be repeated here that some numbers may appear distorted in the flows listed below relative to the initial inputs. For example, the explicitly broadleaf scenarios sum to 24.3% in the low mobilization 2030 trajectory instead of 20% as indicated in the inputs. This is because salvage and afforested flows are not broken down along taxonomic lines. In this case, it probably makes sense to assume that recently afforested and salvaged flows will be disproportionally coniferous, but more broadly speaking this is simply a result of the methodological hierarchy of scenario breakdown, in which broadleaf/coniferous ratios were applied to each material and prior land use as the final step as shown in the stepwise methodology above.

Harvest Scenario		2015		2030 BAU Silvicultural Practice / Low Rollout (RED I Targets)		2030 High Mobilization / High Rollout (RED II Targets)	
		Share of Primary Woody Sources (%)	Woody Biomass Flow for Energy (M m3)	Share of Primary Woody Sources (%)	Woody Biomass Flow for Energy (M m3)	Share of Primary Woody Sources (%)	Woody Biomass Flow for Energy (M m3)
Existing managed Forest or Plantation	Broadleaf Stemwood (including coppice) [2]	16.59	37	15.14	71	23.10	137
	Broadleaf Residue [3]	6.28	14	4.90	23	7.25	43
	Conifer Stemwood	16.59	37	14.93	70	23.10	137
	Conifer Residue	20.18	45	19.19	90	29.01	172
Salvage	Conifer, Broadleaf	8.07	18	20.26	95	14.00	83
Afforestation and transition to plantation [1,4]	Broadleaf, Conifer	9.42	21	4.48	21	3.54	21
Uncategorized/ assumed new forest harvest with or without replanting [5]	Conifer	17.49	39	16.84	79	-	-
	Broadleaf	5.38	12	4.26	20	-	-
TOTAL		100	223	100	469	100	593

Table 2. Harvest Scenario Breakdown as a Percentage and SWE Volumetric Flow for 2015 and Two 2030 Trajectories

In the following sections, biodiversity and carbon impacts will be analysed for each harvest scenario outlined above. These results will then be combined with the above material flow analysis in the impact synthesis section to obtain an overall picture of the trade-offs associated with higher rollout targets for forest bioenergy. The outcome of this impact analysis will be then used to answer the overall question of whether forest bioenergy can be sustainably scaled inline with REDII targets. The final section will then explore how policy instruments might be tailored to help achieve sustainable levels of woody biomass uses and responsible sourcing.

[1] Considered the amount of harvest deriving from area afforested in the last 5 years prior to harvest and a linear increase of 0.5 Mha/yr and 5.2 Mm3/Mha "used" forest (JRC, 2021; Forsell et al. 2016)
[2] All coppice is considered broadleaf (JRC, 2021; Jonsson 2018)
[3] Residual wood is broken up proportionally to the total blend of broadleaf and coniferous harvests.
[4] Afforested land 2015-2025 split between Broadleaf coppice and Coniferous Stemwood plantations at a ratio of 20:80
[5] "Uncategorized" sources have been eliminated, with increased coppice harvests limited to a portion of afforested lands. The remaineder is left to coniferous harvests of stemwoods and residues.

1.3 CARBON ACCOUNTING

There is general agreement within the literature that Comprehensive Lifecycle Assessment (CLCA) is the best approach to account for the carbon impacts of forest-based bioenergy on different timescales. This method involves gathering detailed descriptions of the harvest such as previous land-use, harvest material, rotation period, species, climate, and growth rates, as well as a counterfactual scenario which contains information on the fossil fuel system to be replaced, final energy commodity (heat or electricity) and the details of forest use in the absence of any harvesting. With so many degrees of freedom, lifecycle analyses of forest bioenergy can yield wide ranges of results, even within relatively constrained scenarios (Laganière et al., 2017).

Nevertheless, there are broad trends that can be pulled from a review of carbon accounting studies. One such broad trend across nearly all harvest scenarios is that the immediate result of replacing any fossil fuel system with primary forest bioenergy is an increase in GHG emissions relative to the reference case (Matthews et al., 2018). This is due to the lower energy density of wood relative to fossil fuels and leads to a crucial result from lifecycle assessments in forestry biomass- that the carbon impact is strongly *time dependent*. While fossil fuel use can be thought of as a single pulse of carbon introduced to the biosphere, woody bioenergy is better thought of as an additional step or “shortcut” in a naturally occurring carbon cycle. It is for this reason that regulations treating biomass energy as “carbon neutral,” and intimidating headlines stating that woody biomass energy is “worse” than coal can both be correct (FDA, 2022; IPCC, 2014). The truth is simply a bit more complicated.

To capture this complexity in a way that can ultimately be applied to the European Union’s specific energy mix, two different time horizons were explored. A short term (10 year) and long term (50 year) analysis was conducted synthesizing results from dozens of lifecycle carbon accounting studies. The key value that was pulled from these studies was the payback period, also sometimes referred to as the carbon parity period. This was chosen over other metrics such as carbon intensity (in $kg_{co2}/kWh_{primary}$), or the global warming potential of bioenergy (GWP_{bio}), because it allows the time-dependent and context-sensitive nature of fossil fuel substitution to be most clearly presented and interpreted in the context of the different time horizons, yet it provides a deeper level of granularity than simply ascribing a positive or negative impact on any time horizon. It should be noted however that payback period, GWP_{bio}, carbon intensity, carbon neutrality factor (CNP), and indeed many other quantities often encountered in the literature, are mathematically equivalent efforts to quantify the same thing. Interchanging for instance between payback period and GWP_{bio} for a specified horizon is a somewhat trivial task, the mathematics for which are laid out in studies by Agostini et. al. (2014), Lagiére et.al. (2017) and elsewhere.

In the remainder of this section, the concept of carbon payback period and its relation to carbon debt and forest biogenic carbon will be explored in greater detail. Once these concepts have been established, payback periods from the literature will be matched with the harvest scenarios above. Specific focus will be placed on instances where judgement calls were made on the part of the authors around matching and weighting literature values to best represent actual and anticipated use cases of woody biomass in the energy system for EU-28 member states. The results of this comparative literature review will drive the decision analysis later and hopefully elucidate the value judgments implicit in current policy.

1.3.1 Carbon Debt and Payback Period

In the following analysis, the idea of carbon debt and payback period will be deployed following the detailed analysis of Holtsmark (2012) and Agostini et al. (2014). These approaches consider the net emissions originating from a single plot of land defined by the combustion of its harvest plus the difference in forest carbon stock (FCS) between the harvested and unharvested land. Figure 10 shows how the difference of FCS is calculated for a continually harvested parcel and highlights the importance of the counterfactual. A similar diagram can be imagined for formerly unmanaged forests (a grey line straight across) or non-replanted land (blue and green bars stay at or near zero). The decomposition of harvest residues over time is a significant factor in payback times in many harvest scenarios.

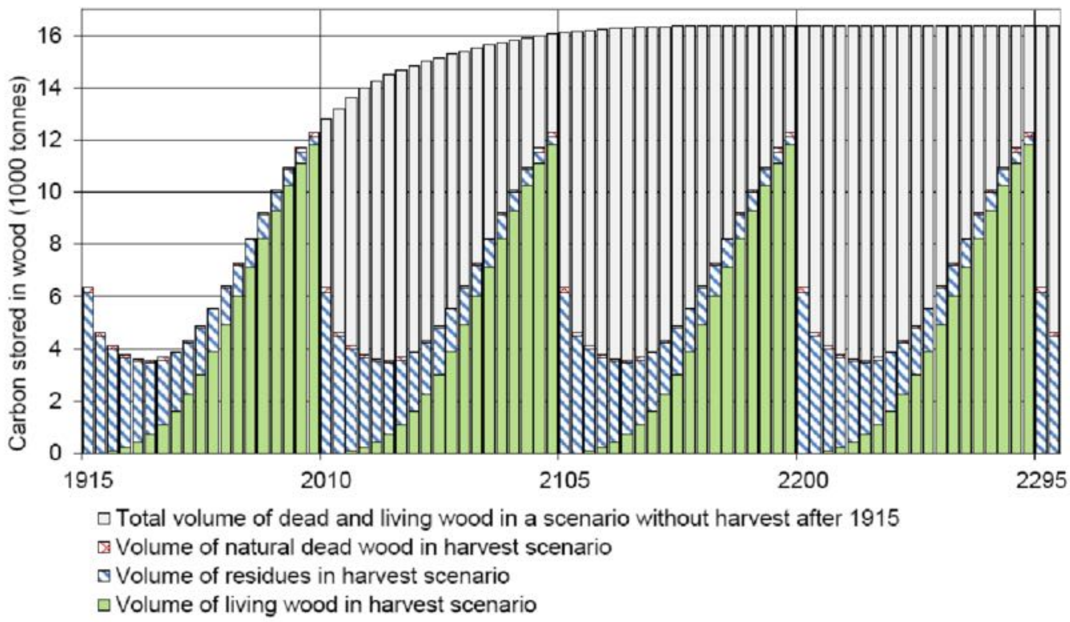

Figure 7. Forest Carbon Stock in a parcel with and without harvest. The case with clear-cutting for years 2010, 2105, 2200 and 2295, and without harvest after 1915 (Holtsmark, 2012).

The analysis from the parcel level can be aggregated up over time and space to a continuously producing rotating harvest cycle as in plantations or managed forests, or in such a way to reflect other scenarios in which harvested land had very little carbon stock before (afforestation) or wood that would otherwise have been left entirely as dead, decaying matter is harvested for energy (salvage).

The process of summing up carbon impacts to the forest level is not exactly trivial and reveals the importance of rotation times within forestry. The details are presented in Holtsmark et. al. (2012), but the overall result is that the combustion of woody biomass results in an initial "carbon debt" which pays back in a time-dependent way based on the fossil fuel replaced, rotation times, growth rates, and residue harvest practices among other factors. Figure 11 illustrates this aggregate effect in a simple way showing how carbon emissions outpaces fossil fuels until a certain point in time called the "payback period." At this point, a biomass system becomes preferable to the fossil fuel system in terms of total emitted carbon, but is not yet, "carbon neutral." Carbon neutrality is not reached till a later time, called the atmospheric carbon parity point. For the purposes of this analysis, the payback period is the chief concern, because the trade-offs explored in this paper explicitly look at the ability to mitigate carbon over fossil fuel systems as part of the energy transition. A subtle, but important distinction emerges if the point of comparison is with more nearly carbon-neutral alternatives such as wind and solar. In this case, the atmospheric carbon parity point would be the operative quantity.

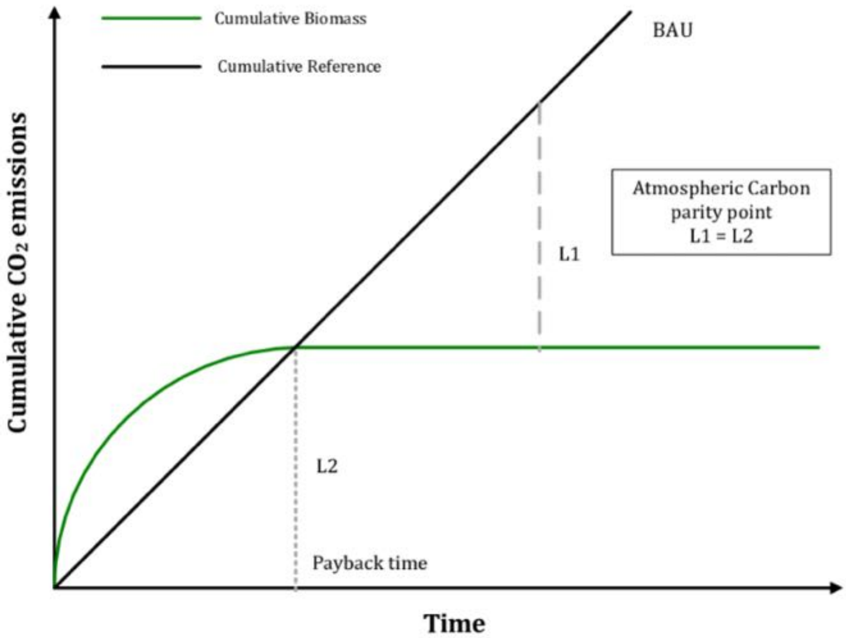

Figure 8. Visual description of payback time and atmospheric carbon parity point. Green Line: drop in the forest carbon stock due to bioenergy production; Black line: accumulated reduction in carbon emissions from substitution of fossil fuels (note its linearity) (Agostini, 2014)

A few final things to note about this framework for carbon accounting is that in addition to using fossil fuels as the direct point of comparison rather than another energy source, it is further assumed that the fossil fuel system remains static as represented by the straight line for the business-as-usual case. Additionally, at the payback time when net emissions are the same, the cumulative radiative forcing is greater because there has been a higher GHG concentration up to that point. This point is discussed in the decision analysis section, where it is argued that additional emissions on the 10-year time horizon should be factored into the 50-year carbon budget with additional weighting.

1.3.2 Matching Pay Back Periods to Harvest Scenarios

To flesh out the overall picture of payback periods of aggregate woody biomass flows through Europe, studies were matched to harvest scenarios as can be seen in Appendix B. In many cases, multiple studies were used to arrive at a representative payback period for one harvest scenario by taking an arithmetic mean, which implies similar confidence levels in each study. In cases where different studies represented different potential pathways within a harvest scenario, every effort was made to weigh the sub pathways appropriately before listing rather than simply giving them equal weight. For instance, the considerable difference of payback period for residues whose counterfactual is roadside burning versus natural decomposition was managed by taking the lower bound of likely payback periods rather than listing as a separate source, which would have errantly implied that half of residue is burned on the roadside (Laganière et al., 2017). In some cases, multiple studies representing slightly different pathways were included when resulting payback periods were more comparable and an assumption of roughly equal flows was more justifiable.

As with the material flow analysis and harvest scenario breakdown, the high number of variables going into each study contributed to uncertainty as did a dearth of research in certain niche areas. For instance, the majority of studies found on forest bioenergy carbon accounting investigated replacing coal power plants, though the majority of woody biomass in Europe goes to producing heat, which in turn mostly substitutes natural gas (BioEnergy Europe, 2023; IEA, 2021). Another issue is that the existing literature tends to skew in favor of study areas in Canada and the United States (see for example Jonker et al., 2014; Laganière et al., 2017). In regard to geography, studies from Europe or North America were considered as viable inputs due to the relative climatic and species overlap between the two regions (e.g., Willow and Loblolly Pine).

Another decision had to be made surrounding how to treat different fuel sources (natural gas/coal) and final energy product (heat vs gas). As can be seen in Table 3, the weighting of natural gas and coal was made explicit in the formulation of payback periods, and is weighted at a rate of 70:30, natural gas to coal in line with the assumption that only coal and gas are being replaced by woody biomass and in line with their current usage as a percentage of their primary energy inputs (IEA, 2021). The breakdown of heat vs power production on the other hand had to be treated on a case-by-case basis depending on the context and boundary conditions of the study. In studies replacing coal power production, payback periods were taken directly, reflecting the fact that coal for dedicated heat production is a relatively uncommon practice in Europe and unlikely to be replaced with biomass at scale. In cases where both heat and power payback periods were quoted for natural gas, such as in Lagniére et al. (2017), heat and power were weighed at 85% to 15%. In some exceptional cases, where payback periods for only one final commodity type could be found, a payback period of 2-2.5 times longer for power than for heat was applied following results from Lagniére et. al (2017) and Walker et. al. (2012), as long as the fuel type remained the same. An example of this was the study by Mickinney et. al.

(2011), which quotes a payback period for willow coppice forests at around 20 years for heat production with natural gas. Here, payback for natural gas electricity production was taken to be 50 years following the reasoning laid out above, which was then weighted at 85:15 heat to power generation to obtain a payback period of around 24 years.

In general, if a study presented a range of values or a high, medium, and low intensity of silvicultural practices such as fertilization in a plantation or rotation times, middle values were favored. Additionally, some studies were excluded for not matching with current harvest trends. In particular, extremely high payback times for boreal forest were excluded from coniferous scenarios because of evidence that regulations, particularly around protected areas have largely excluded these sources from the overall woody bioenergy mix (Camia et al., 2021).

		Payback Period		
Harvest Scenario		Natural Gas	Coal	Weighted (70/30 : Gas/Coal) [1]
Existing Forest or Plantation	Broadleaf Stemwood	33.5	32	33.1
	Broadleaf Residue	29	12	20.3
	Conifer Stemwood	42	22	29.4
	Conifer Residue	39	14	27.3
Salvage	Broadleaf, Conifer	100	63	70.0
Afforestation	Broadleaf, Conifer	0	0	0.0
Forest Clearing, Transition to Plantation	Conifer	85.75	68.5	60.0
	Broadleaf	114	89.5	79.8

Table 3. Representative Carbon Pay Back Periods (Years) for Each Harvest Scenario. Full Synthesis of Sources can be found in Appendix B

The results of matching payback periods to harvest scenarios can be seen in Table 3. One broad trend that immediately emerges is that payback periods tend to be significantly less for coal than for natural gas. This is to be expected as coal is a more carbon-intensive source and thus replacing it incurs a smaller initial carbon debt (Agostini et al., 2014). Another perhaps surprising result is the rather long payback periods of salvage wood, this results from the fact that the carbon in dead stem wood would otherwise be locked into the soil and the biosphere through decomposition and may result

[1] (IEA, 2021) based on just the resource input weights.

from logging on land that would otherwise be off-limits to logging including protected areas (Kulakowski et al., 2017; Thorn et al., 2018). This is the same reason that residue harvesting may have a higher pay back time than may be expected. Not surprisingly, forest clearing or transition to plantation has the highest payback period. Even if trees are replanted, the clearing of trees and roots systems that is required to make way for fresh seedlings results in a large initial "carbon shock" at the time of conversion, lower carbon at maturity, and quite possibly lower long term soil carbon content (Camia et al., 2021). It should be noted that this category has perhaps the widest range of scenarios ranging from payback periods as low as 15 years for conversion to a short rotation, high productivity plantation and ranging all the way up to over 100 years when no intentional forest management follows the initial use of otherwise virgin forest, as might be the case in "clear-cutting" (Laganière et al., 2017; Zanchi et al., 2011). This is ultimately a result of the fact that this scenario represents unknown sources and is by definition, the most uncertain. An interesting sensitivity analysis can be done by substituting a payback period of some 15 years or 120 years to the following decision analysis corresponding to a success or failure of eliminating unknown sources, and enforcing iLUC provisions in carbon counting laws, but here a middle figure is used implying a likely blend of forestry practices in wood flows of unknown origin.

1.4 Indexing, Normalizing, and Weighting

With estimates of payback periods and a tally of biodiversity impacts in hand for each harvest scenario, a normalized index is now needed for each criterion to provide points of comparison. Carbon impacts were assigned an index for each time horizon (10 year / 50 year) based on the mitigation or additional emissions relative to fossil fuels. Table 7 shows the rationale for this process. For each time horizon, a 0 was assigned at the center (indicating an ambivalence between fossil and woody bioenergy) and the index was simply counted up and down in increments of 10 years with longer payback times indicating negative outcomes and vica versa. For biodiversity, the number of impacts was simply tallied for each harvest scenario.

Carbon Impact Factor Indexing		
Weighted Payback	10yr	50yr
0-5 years	1	5
5-15 Years	0	4
15-25 years	-1	3
25-35 Years	-2	2
35-45 years	-3	1
55-65 years	-4	0
65-75 Years	-5	-1
75-85 years	-6	-2
85-95 Years	-7	-3
95+ Years	-8	-4

Table 4. Mapping Payback Times to carbon impact indices

The values of the indices were then normalized, which had to be done independently for each criterion and time horizon to provide an equal point of comparison between carbon accounting and biodiversity impacts.

On the carbon accounting side, the most negative effect was used on the 10-year time horizon and most positive was used for the 50-year time horizon. The logic of this choice follows from the net positive carbon effects on the 50-year time horizon and net negative on the 10 years across all harvest scenarios.

Finally, the normalized scores for each criterion were multiplied by the volumetric SWE flows for each harvest scenario determined in the material flow balance and harvest scenario sections. These normalized, weighted impact indices were then summed across all harvest scenarios in the final step of the impact synthesis. The results of this multi-step process can be seen in Appendix C. The summed weighted impacts are essentially a unitless impact measure that captures the on-the-ground impacts of harvesting wood in a particular way as well as the effects of an evolving market for wood products over time and demand projections.

The key result of this analysis is unsurprisingly that significant negative trade-offs in the form of increased short-term carbon emissions, and biodiversity loss emerge at higher levels as woody biomass use increases. These trade-offs existed in 2015 as well as in both 2030 trajectories, though in different relative proportions. In the next section on decision analysis, these trade-offs between short-term carbon emissions and biodiversity loss on the one hand and long-term emissions reductions on the other will be explored in depth. In particular, weights will be applied to each criterion in an effort to recreate the logic of current policy in the area of woody bioenergy and make the value judgments in these trade-offs explicit. Relative social, economic, and environmental vulnerability to these impacts as well as any potential feedback among them will then be considered towards the goal of providing critical policy recommendations around 2030 targets and developing a governance structure that reflects the trade-offs inherent in harvesting forest resources for bioenergy.DISCUSSION

The preceding analysis sought to fill gaps in knowledge around material flow, sourcing, carbon cycles, and biodiversity impacts with evidence-based estimates in order to paint a holistic picture of the sustainability of European forest bioenergy now and in the future. In particular, estimates were made on what types of flows might be necessary to achieve high-level climate-related goals and sought to downscale these economy-wide targets to effects on specific pathways that wood products take from the forest to the incinerator. In imagining possible future trajectories, the authors chose to pair policy instruments affecting the uses of forest bioenergy such as subsidies and ETS rules with policy instruments affecting sources such as LULUCF, FRLs, and sourcing standards and certifications. In so doing, a major assumption was made that if revised goals for the use of woody biomass such as those contained in the ReCast Renewable Energy Directive are to be met, the rules governing sourcing will also be fulfilled in good faith. This situation is embodied in the 2030 high rollout trajectory.

It is worth pointing out that reconciling uses and sources is perhaps the key sustainability struggle within forest bioenergy, and that there exists a third option for future trajectories in which policy governing uses are effective in growing demand, yet policies governing sources are weakly enforced or perhaps avoided by their intended targets within the industry. This possibility has not been explored in a rigorous quantitative way here but would likely result in significant imports of wood products as well as an export of negative environmental externalities from the European continent.

With respect to biodiversity loss, there are countless adverse effects on the Earth's ecosystems, ranging from reduced carbon storage, pollination, and genetic resources to the endangerment of native species and decreased food security (Aravanopoulos, 2018; FAO, 2020; Krishnan et al., 2020; Ranius et al., 2018; Thorn et al., 2018). One of the most significant effects of biodiversity loss is the reduction of carbon storage in ecosystems, with trees, vegetation, and soil acting as carbon sinks (Goodale et al., 2002). However, biomass logging and related anthropogenic activities also cause large-scale biodiversity loss across forest ecosystems, reducing the ability of forests and dependent ecosystems to sequester carbon thereby exacerbating climate change (Ellis et al., 2019). This feedback effect was discussed as a potential reason to increase the decision weight of biodiversity impacts in the Decision section above.

Biodiversity loss further leads to a reduction of important ecosystem services such as pollination, with reduction in pollinator populations leading to effects such as reduced productivity of agricultural systems, loss of plant-pollinator interactions, simplification and homogenization of ecosystems, and overall reduced resilience and adaptability (Heil & Burkle, 2019; Krishnan et al., 2020; Osborne et al., 1991; Priess et al., 2007; Ranius et al., 2018). Largely, biodiversity loss, which endangers native species and disrupts the balance of ecosystems, can have far-reaching effects on ecosystem functioning.

In terms of the abovementioned harvest scenarios, *afforestation and transitioning to plantation* scenario is an effective strategy for enhancing biodiversity or mitigating loss. Through the deliberate establishment and management, forests can be tailored to specific conservation goals, providing habitat for native species, promoting carbon sequestration, and mitigating climate change (Bodo et al., 2021; Cerasoli et al., 2021; Jiang et al., 2016; Krishnan et al., 2020; Oldfield et al., 2014; Pierre et al., 2016; Ravenek et al., 2014; Vedavathy, 2003). Conversely, the *salvage* scenario, which involves the removal of trees in areas that have already been impacted by disturbance, can potentially be beneficial for biodiversity levels (Camia et al., 2021; Heil & Burkle, 2019; Leverkus et al., 2015; Lucas-Borja et al., 2020; Ravenek et al., 2014; Thorn et al., 2018), but it is generally less effective than the *afforestation or transition to plantation* scenario from a carbon perspective. The most damaging scenarios were found to be *existing managed forests or plantations* and uncategorized *or assumed forest clearing*, as they involved the loss of intact natural forests, which are critical habitats that provide countless ecosystem services and are the key to mitigating climate change (Abdallah & Lasserre, 2007; Aravanopoulos, 2018; Camia et al., 2021; Chaudhary et al., 2016; de Jong et al., 2022; European Forest Institue, 2021; Giuntoli et al., 2016; Giuntoli & Searle, 2019; Klapwijk et al., 2016; Krishnan et al., 2020; Kuuluvainen et al., 2021; Letourneau & Dyer, 1998; Pace et al., 1999; Peter & Harrington, 2018; Ranius et al., 2018; Ravenek et al., 2014; Savolainen & Kärkkäinen, 1992; Vellend et al., 2007). The two aforementioned scenarios result in the fragmentation of habitat and the loss of biodiversity, particularly for species that are specialized to forest ecosystems (Bodo et al., 2021; Camia et al., 2021; European

Forest Institue, 2021; Ranius et al., 2018). The effects were found to be the worst in broadleaf forests since they tend to be more biodiverse than their counterparts, i.e., conifer forests, and many species in these broadleaf forests are specialized to the specific microhabitats created by the complex structure of broadleaf trees (European Forest Institue, 2021; Spracklen et al., 2013). The loss of broadleaf forests can therefore have more severe impacts on biodiversity.

When considering land-use impacts linked to bioenergy production in Europe, it should be underlined that impacts can also take place outside Europe since the quantity of wood required to satisfy the EU Renewable Energy target for 2020 is already too large to be met by domestic resources alone and will likely lead to increasing imports in the futurre (Pelkonen, 2014).

In terms of the methodology that has been employed here for carbon accounting, the choice of payback period as a primary metric reflects that the point of comparison in this approach is always fossil fuels and not other renewables. This is important to make explicit for two reasons. First, as the overall carbon intensity of the European economy decreases, the marginal benefit of substituting current energy sources for forest bioenergy will decrease, and payback periods will increase. Second, a favorable trade-off based on payback period does not imply that forest bioenergy is carbon neutral. For this, the atmospheric carbon parity point would need to be examined, which is generally around twice the payback period as explained in section 2.3.1, and a minimum some 20 years for nearly all harvest scenarios (Table 3).

For this reason, in situations where forest bioenergy is competing with renewables such as solar or wind energy due to limited financial resources or simply for legislative or social priority, more nearly carbon-neutral renewables would almost always be favorable from an atmospheric carbon perspective. This point is a strong argument for limiting the uses of woody bioenergy in Europe and globally to a level that can be supplied by secondary sources. While this report does not entirely discourage policies that spur continued growth in uses for woody biomass energy, the potential risks involved in all but the most careful sourcing scenarios should hopefully by now be clear.

The advantages of harvested wood products and material substitutions are unlikely to offset the decrease in the net forest sink caused by amplified harvesting over the short and medium term, through the year 2050. Hence, when deciding on the implementation of bioenergy as a transitional tool, it is the Member States' responsibility together with other stakeholders to prioritize in their judgment the risks associated with different time horizons in order to make better decisions (New EU Forest Strategy for 2030, 2021).

Rather than attempting to capture all impacts of each pathway with complete accuracy and precision, our assessment aimed to provide a foundation for further inquiry and research, as well as an assessment of how policy implementation is progressing. While aware of biodiversity and socioeconomic impacts, this study has revealed a lack of literature on their trade-offs. Thus, future bioenergy sustainability research should incorporate integrated assessments that consider the effects of bioenergy on socioeconomics, the environment (emphasizing biodiversity), and climate change. This presents an opportunity to improve transparency in the decision-making process by requiring greater disclosure of potential environmental and social impacts and associated mitigation measures to demonstrate compliance with relevant laws and regulations.

The need for a coordinated effort between policymakers, researchers and stakeholders to ensure that concerns and proposals are translated into practical policies and financial incentives at the local, national, and international levels should also by now be quite clear. The transition to sustainable bioenergy cannot be effective without aligning these policies and incentives with the National Energy and Climate Plans. As part of ensuring transparency and accountability in the bioenergy supply chain, a reliable system for monitoring wood use for energy production is essential. In the end, the implementation of these recommendations will play a significant role in promoting sustainable bioenergy and achieving long-term climate objectives.

APPENDIX

Appendix A1 - Vulnerability factors exacerbated by biodiversity loss in each harvest scenario

Appendix A2 - Scoring based on above identified effects, and normalization for each harvest scenarios

Appendix A3 - References for table A1

Appendix B - Matching Payback Periods to Harvest Scenarios

KEY MAPPING HARVEST SCENARIO TO FIGURES FROM LITERATURE

Harvest Scenario as defined in this paper		Description of Scenario from Literature	Source	Gas Payback Period	Coal Payback Period	#NAME?	AVG COAL
Existing Forest or Plantation	Broadleaf Stemwood	Payback period for coppice willows replacing natural gas for heating : 18-22 years [4]	Mckinney, et. al 2011	24	-		
		Study of UK use in CHP, payback period slightly over 40 years for the whole powersystem [6]	(Agostini, 2014)	43	32	33.50	32.00
	Broadleaf Residue	Harvest Residues weighted for broadleaf/conifer. Conterfactual: left on forest floor (20 yr power/coal ; 50yr heat /NG ; >100yr power/NG)[5]	(Laganière et al., 2017)	38	12		
		11.5% residue decay rate replacing natural gas heat and power	(Giuntoli et. al. 2015)	20	-	29.00	12.00
	Conifer Stemwood	Softwood high productive plantation with medium management intensity (including fertilization) biomass combustion efficiency 41%. Counterfactual: nor harvest of plantation [2]	(Jonker, 2013)	-	27		
		Additional harvest of managed forests (20-30% MAI -> 60%) (22yr heat/coal ; 27 heat/NG ; 75 power/ng)	(Walker, 2010 ; Agostini, 2014)	42	22		
		Average of shortleaf loblolly pine and longleaf slash pine inj managed plantaions in the south central and southeastern US	(Rolls & Forster, 2020)	-	18	42.00	22.33
	Conifer Residue	Harvest Residues weighted for broadleaf/conifer. Conterfactual: left on forest floor (12 yr power/coal ; 27yr heat /NG ; >100yr power/NG)	Lagniere et. al 2017	38	12		
		Additional wood harvest. Counterfactual: BAU for wood products	(McKechnie, 2011)	-	16		
		3-6%/ year decay rate replacing natural gas heat and power [3]	(JRC, 2021)	40	-	39.00	14.00
Afforestation	ALL	Short rotation plantation on Marginal Agricultural land with low carbon stock	(Zanchi, 2011)	0	0		
		Afforesting post-agricultural land	(Mitchell, 2012)	0	0	0.00	0.00
Salvage	ALL	Salvaged coniferous standing trees killed by natural disturbance counter factual left to decompose (85:15 - Heat:Power) [2]	(Laganière et al., 2017)	100	63	100.00	63.00
Forest Clearing	Conifer	Forest Clearing – Substitution with short high productivity plantation. Wood for bioenergy	(Zanchi, 2011)	15	17		
		Forest Clearing – Substitution with short low productivity plantation (10 year rotation. Wood for bioenergy	(Zanchi, 2011)	108	114		
		Green Trees (living biomass Stemwood only) 45yr Mean Annual Increment (MAI) (85:15 Heat:Power)	(Laganière et al., 2017)	100	78		
		Oak-Hickory Clear cut and Converted to short leaf loblolly pine plantation	(Sterman et. al. 2018; JRC, 2021)	120	65	85.75	68.50
	Broadleaf	Forest Clearing – Substitution with short low productivity plantation (20 yr rotation). Wood for bioenergy	(Zanchi, 2011)	108	114		
		Oak-Hickory Clear cut and Converted to short leaf loblolly pine plantation	(Sterman et. al. 2018; JRC, 2021)	120	65	114.00	89.50

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[1] (JRC, 2019)

[2] Softwood is considered analogous to Coniferous.

[3] Broadleaf residues generally have a higher decomposition rate than coniferous (Zhang, 2020)

[4] Payback period of natural gas for electricity assumed at 50 years following ratio of 1:2.5 (see Lagniere, 2017)

[5] Lower bounds on the likely range were taken to account for the much lower payback period of residues whose counterfactual is roadside burning. Little data is available on the extent of this practice in Europe.

[6] Overall payback period of slightly over 43 years has been disaggregated here for illustration of gas and coal contribution.

Appendix C - Full Synthesis of Carbon and Biodiversity Impacts with Normalized Impact Indices and Examples of Decision Weights

IMPACT SYNTHESIS											
IMPACTS						2015					
Harvest Scenario		CARBON1MPACT INDEXED 10YRTH	CARBON IMPACT INDEXED 50YRTH	BIODIVERSITY IMPACT COUNT		Share of Primary Woody Sources (%)	Woody Biomass Flow for Energy (M m3)	Carbon Impact 10YR *FLOW WEIGHTED* [10]	Carbon Impact 50yr *FLOW WEIGHTED* [10]	BIODIVERSITY IMPACT *FLOW WEIGHTED*	
Existing managed Forest or Plantation	Broadleaf Stemwood (including coppice) [2]	-0.33	0.4	-0.63		16.6	37	-12.33	14.8	-23.37	
	Broadleaf Residue [3]	-0.17	0.6	-0.47		6.3	14	-2.33	8.4	-6.63	
	Conifer Stemwood	-0.33	0.4	-0.58		16.6	37	-12.33	14.8	-21.42	
	Conifer Residue	-0.33	0.4	-0.42		20.2	45	-15.00	18	-18.95	
Salvage	Conifer, Broadleaf	-1.00	-0.4	-0.37		8.1	18	-18.00	-7.2	-6.63	
Afforestation and transition to plantation [1,4]	Broadleaf, Conifer	0.17	1	0.37		9.4	21	3.50	21	7.74	
Uncategorized/ assumed Forest Clearing with or without replanting	Conifer	-0.83	-0.2	-1.00		17.5	39	-32.50	-7.8	-39.00	
	Broadleaf	-1.00	-0.4	-1.00		5.4	12	-12.00	-4.8	-12.00	
					TOTAL	100.0	223	-	-	-	
					NORMALIZED AND Volume Weighted IMPACT			-101	57.2	-120.2631579	
					Decision Weights			2	10	2.5	
					THE "IMPORTANCE" OF EACH IMPACT (AS FOR DECISION MAKERS			-202	572	-300.6578947	69.3421053

1 Considered the amount of harvest deriving from area afforested in the last 5 years prior to harvest and a linear increase of 0.5 Mha/yr and 5.2 Mm3/Mha "used" forest (JRC, 2021 ; Forsell et al. 2016)

2 All coppice is considered broadleaf (JRC, 2021 ; Jonsson 2018)

3 Residual wood is broken up proportionally to the total blend of broadleaf and coniferous harvests

4 Afforested land 2015-2025 split between Broadleaf coppice and Coniferous Stemwood plantations at a ratio of 20:80

5 "Uncategorized" sources have been eliminated, with increased coppice harvests limited to a portion of afforested lands. The

IMPACT SYNTHESIS																	
IMPACTS						2030 BAU Silvicultural Practice / Low Rollout (RED I Targets) [5]						2030 High Mobilization / High Rollout (RED II Targets)					
Harvest Scenario		CARBON IMPACT INDEXED 10YR TH	CARBON IMPACT INDEXED 50YR TH	BIODIVERSITY IMPACT COUNT		Share of Primary Woody Sources (%)	Woody Biomass Flow for Energy (M m3)	Carbon Impact 10YR *FLOW WEIGHTED* [10]	Carbon Impact 50yr *FLOW WEIGHTED* [10]	BIODIVERSITY IMPACT *FLOW WEIGHTED*		Share of Primary Woody Sources (%)	Woody Biomass Flow for Energy (M m3)	Carbon Impact 10YR *FLOW WEIGHTED* [10]	Carbon Impact 50yr *FLOW WEIGHTED* [10]	BIODIVERSITY IMPACT *FLOW WEIGHTED*	
Existing managed Forest or Plantation	Broadleaf Stemwood (including coppice) [2]	-0.33	0.4	-0.63		15.14	71.00	-23.67	28.40	-44.84		23.10	137.00	-45.67	54.80	-86.53	
	Broadleaf Residue [3]	-0.17	0.6	-0.47		4.90	23.00	-3.83	13.80	-10.89		7.25	43.00	-7.17	25.80	-20.37	
	Conifer Stemwood	-0.33	0.4	-0.58		14.93	70.00	-23.33	28.00	-40.53		23.10	137.00	-45.67	54.80	-79.32	
	Conifer Residue	-0.33	0.4	-0.42		19.19	90.00	-30.00	36.00	-37.89		29.01	172.00	-57.33	68.80	-72.42	
Salvage	Conifer, Broadleaf	-1.00	-0.4	-0.37		20.26	95.00	-95.00	-38.00	-35.00		14.00	83.00	-83.00	-33.20	-30.58	
Afforestation and transition to plantation [1,4]	Broadleaf, Conifer	0.17	1	0.37		4.48	21.00	3.50	21.00	7.74		3.54	21.00	3.50	21.00	7.74	
Uncategorized/ assumed Forest Clearing with or without replanting	Conifer	-0.83	-0.2	-1.00		16.84	79.00	-65.83	-15.80	-79.00		-	-	-	-	-	
	Broadleaf	-1.00	-0.4	-1.00		4.3	20	-20	-8	-20		-	-	-	-	-	
					TOTAL	100	469					100.0	593				
					NORMALIZED AND Volume Weighted IMPACT			-258.1666667	65.4	-260.4210526				-235.33	192	-281.4736842	
					Decision Weights			2	10	2.5				2	10	2.5	
					THE "IMPORTANCE" OF EACH IMPACT (AS FOR DECISION MAKERS			-516.3333333	654	-651.0526316	-513.3859649			-470.6666667	1920	-703.6842105	745.6491228

1 Considered the amount of harvest deriving from area afforested in the last 5 years prior to harvest and a linear increase of 0.5 Mha/yr and 5.2 Mm3/Mha "used" forest (JRC, 2021 ; Forsell et al. 2016)

2 All coppice is considered broadleaf (JRC, 2021 ; Jonsson 2018)

3 Residual wood is broken up proportionally to the total blend of broadleaf and coniferous harvests

4 Afforested land 2015-2025 split between Broadleaf coppice and Coniferous Stemwood plantations at a ratio of 20:80

5 "Uncategorized" sources have been eliminated, with increased coppice harvests limited to a portion of afforested lands. The

REFERENCES

Abba, K., Umar, H., & Mohammed Abba, H. (2020). *Impact of Medicinal Plants and Deforestation on Communities in Wawa -Zange Forest Reserve, Gombe State, Nigeria*.

Abdallah, S. B., & Lasserre, P. (2007). Endangered species, real options, and forest management. *PAMM*, *7*(1), 1080803–1080804. https://doi.org/10.1002/pamm.200701097

Abdollahnejad, A., & Panagiotidis, D. (2020). Tree Species Classification and Health Status Assessment for a Mixed Broadleaf-Conifer Forest with UAS Multispectral Imaging. *Remote Sensing*, *12*(22), Article 22. https://doi.org/10.3390/rs12223722

Agostini, A., Giuntoli, J., Marelli, L., & Amaducci, S. (2020). Flaws in the interpretation phase of bioenergy LCA fuel the debate and mislead policymakers. *The International Journal of Life Cycle Assessment*, *25*(1), 17–35. https://doi.org/10.1007/s11367-019-01654-2

Agostini, A., Marelli, L., Giuntoli, J., & Boulamanti, A. (2014). *Carbon accounting of forest bioenergy: Conclusions and recommendations from a critical literature review*. Publications Office of the European Union. https://data.europa.eu/doi/10.2788/29442

Alba-Sánchez, F., López-Sáez, J. A., Abel-Schaad, D., Sabariego Ruiz, S., Pérez-Díaz, S., González-Hernández, A., & Linares, J. C. (2019). The impact of climate and land-use changes on the most southerly fir forests (Abies pinsapo) in Europe. *The Holocene*, *29*(7), 1176–1188. https://doi.org/10.1177/0959683619838043

Aljbory, Z., & Chen, M.-S. (2018). Indirect plant defense against insect herbivores: A review. *Insect Science*, *25*(1), 2–23. https://doi.org/10.1111/1744-7917.12436

Ameray, A., Bergeron, Y., Valeria, O., Montoro Girona, M., & Cavard, X. (2021). Forest Carbon Management: A Review of Silvicultural Practices and Management Strategies Across Boreal, Temperate and Tropical Forests. *Current Forestry Reports*, *7*(4), 245–266. https://doi.org/10.1007/s40725-021-00151-w

Applequist, W. L., Brinckmann, J. A., Cunningham, A. B., Hart, R. E., Heinrich, M., Katerere, D. R., & Andel, T. van. (2020). Scientists' Warning on Climate Change and Medicinal Plants. *Planta Medica*, *86*(1), 10–18. https://doi.org/10.1055/a-1041-3406

Aravanopoulos, F. A. (Phil). (2018). Do Silviculture and Forest Management Affect the Genetic Diversity and Structure of Long-Impacted Forest Tree Populations? *Forests*, *9*(6), Article 6. https://doi.org/10.3390/f9060355

Ballogh, A. (2021, December 13). *The rise and fall of monoculture farming | Research and Innovation*. https://ec.europa.eu/research-and-innovation/en/horizon-magazine/rise-and-fall-monoculture-farming

Barlow, J., Ewers, R. M., Anderson, L., Aragao, L. E. O. C., Baker, T. R., Boyd, E., Feldpausch, T. R., Gloor, E., Hall, A., Malhi, Y., Milliken, W., Mulligan, M., Parry, L., Pennington, T., Peres, C. A., Phillips, O. L., Roman-Cuesta, R. M., Tobias, J. A., & Gardner, T. A. (2011). Using learning networks to understand complex systems: A case study of biological, geophysical and social research in the Amazon. *Biological Reviews*, *86*(2), 457–474. https://doi.org/10.1111/j.1469-185X.2010.00155.x

Bernards, D. M. (2022, December 7). *Adaptation or extinction: What climate change and land use mean for biodiversity*. Aktuelles aus der Goethe-Universität Frankfurt.

https://aktuelles.uni-frankfurt.de/news-in-brief/adaptation-or-extinction-what-climate-change-and-land-use-mean-for-biodiversity/

Bhardwaj, K., Silva, A. S., Atanassova, M., Sharma, R., Nepovimova, E., Musilek, K., Sharma, R., Alghuthaymi, M. A., Dhanjal, D. S., Nicoletti, M., Sharma, B., Upadhyay, N. K., Cruz-Martins, N., Bhardwaj, P., & Kuča, K. (2021). Conifers Phytochemicals: A Valuable Forest with Therapeutic Potential. *Molecules*, *26*(10), 3005. https://doi.org/10.3390/molecules26103005

BioEnergy Europe. (2023). *About bioenergy*. https://bioenergyeurope.org/about-bioenergy.html

Bodo, T., Gimah, B. G., & Seomoni, K. J. (2021). Deforestation and Habitat Loss: Human Causes, Consequences and Possible Solutions. *Journal of Geographical Research*, *4*(2), Article 2. https://doi.org/10.30564/jgr.v4i2.3059

Boekhout van Solinge, T. (2013). Equatorial deforestation as a harmful practice and a criminological issue. In *Global Environmental Harm* (pp. 20–36). Willan. https://doi.org/10.4324/9781843927983-3

Bringhurst, K., & Jordan, P. (2015). The impact on nutrient cycles from tropical forest to pasture conversion in Costa Rica. *Sustainable Water Resources Management*, *1*(1), 3–13. https://doi.org/10.1007/s40899-015-0003-x

Brown, A. R., Hosken, D. J., Balloux, F., Bickley, L. K., LePage, G., Owen, S. F., Hetheridge, M. J., & Tyler, C. R. (2009). Genetic variation, inbreeding and chemical exposure—Combined effects in wildlife and critical considerations for ecotoxicology. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1534), 3377–3390. https://doi.org/10.1098/rstb.2009.0126

Camia, A., Giuntoli, J., Jonsson, K., Robert, N., Cazzaniga, N., Jasinevičius, G., Avitabile, V., Grassi, G., Barredo, C. J. I., & Mubareka, S. (2021, January 25). *The use of woody biomass for energy production in the EU*. JRC Publications Repository. https://doi.org/10.2760/831621

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., Narwani, A., Mace, G. M., Tilman, D., Wardle, D. A., Kinzig, A. P., Daily, G. C., Loreau, M., Grace, J. B., Larigauderie, A., Srivastava, D. S., & Naeem, S. (2012). Biodiversity loss and its impact on humanity. *Nature*, *486*(7401), Article 7401. https://doi.org/10.1038/nature11148

Cerasoli, S., Yin, J., & Porporato, A. (2021). Cloud cooling effects of afforestation and reforestation at midlatitudes. *Proceedings of the National Academy of Sciences*, *118*(33), e2026241118. https://doi.org/10.1073/pnas.2026241118

Chaudhary, A., Burivalova, Z., Koh, L. P., & Hellweg, S. (2016). Impact of Forest Management on Species Richness: Global Meta-Analysis and Economic Trade-Offs. *Scientific Reports*, *6*(1), Article 1. https://doi.org/10.1038/srep23954

Climate Action (2023a, February 23). European Climate Law. Retrieved from https://climate.ec.europa.eu/eu-action/european-green-deal/european-climate-law_en

Climate Action (2023b, February 24). 2020 climate & energy package. Retrieved from https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2020-climate-energy-package_en

Climate Action (2023c, February 24). 2030 climate & energy framework. Retrieved from https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2030-climate-energy-framework_en

Collins, K. (2021, July 28). Why Is The Amazon Rainforest So Important? *Medium*. https://karinacollins.medium.com/why-is-the-amazon-rainforest-so-important-895e8c0d55b7

Commisision Staff Working Document Impact Assessment. (2016). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52016SC0249&from=EN

Cox, P. A., Banack, S. A., Murch, S. J., Rasmussen, U., Tien, G., Bidigare, R. R., Metcalf, J. S., Morrison, L. F., Codd, G. A., & Bergman, B. (2005). Diverse taxa of cyanobacteria produce beta-N-methylamino-L-alanine, a neurotoxic amino acid. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(14), 5074–5078. https://doi.org/10.1073/pnas.0501526102

Crenna, E., Marques, A., La Notte, A., & Sala, S. (2020). Biodiversity Assessment of Value Chains: State of the Art and Emerging Challenges. *Environmental Science & Technology*, *54*(16), 9715–9728. https://doi.org/10.1021/acs.est.9b05153

Daily, G., Alexander, S., Ehrlich, P., Goulder, L., Lubchenco, J., Matson, P., Mooney, H., Postel, S., Schneider, S., Tilman, D., & Woodwell, G. (2007). *ECOSYSTEM SERVICES: Benefits Supplied to Human Societies by Natural Ecosystems*. https://www.semanticscholar.org/paper/ECOSYSTEM-SERVICES%3A-Benefits-Supplied-to-Human-by-Daily-Alexander/48273bf32f860b4350ed16164e602ba4c94a2de4

de Jong, A., de Vries, W., Kros, H., & Spijker, J. (2022). Impacts of harvesting methods on nutrient removal in Dutch forests exposed to high-nitrogen deposition. *Annals of Forest Science*, *79*(1), 33. https://doi.org/10.1186/s13595-022-01149-5

Demessie, A., Singh, B. R., & Lal, R. (2015). Land Degradation and Soil Carbon Pool in Different Land Uses and Their Implication for Food Security in Southern Ethiopia. In R. Lal, B. R. Singh, D. L. Mwaseba, D. Kraybill, D. O. Hansen, & L. O. Eik (Eds.), *Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa* (pp. 45–62). Springer International Publishing. https://doi.org/10.1007/978-3-319-09360-4_3

Díaz, S., Fargione, J., Iii, F. S. C., & Tilman, D. (2006). Biodiversity Loss Threatens Human Well-Being. *PLOS Biology*, *4*(8), e277. https://doi.org/10.1371/journal.pbio.0040277

Dornelas, M., Gotelli, N. J., McGill, B., Shimadzu, H., Moyes, F., Sievers, C., & Magurran, A. E. (2014). Assemblage Time Series Reveal Biodiversity Change but Not Systematic Loss. *Science*, *344*(6181), 296–299. https://doi.org/10.1126/science.1248484

Duncker, P., Raulund-Rasmussen, K., Gundersen, P., Katzensteiner, K., Jong, J., Ravn, H., Smith, M., Eckmüllner, O., Spiecker, H., Duncker, P., Raulund-Rasmussen, K., Gundersen, P., Katzensteiner, K., Jong, J., Ravn, H., Smith, M., Eckmüllner, O., & Spiecker, H. (2012). How Forest Management affects Ecosystem Services, including Timber Production and Economic Return: Synergies and Trade-Offs. *Ecology and Society*, *17*. https://doi.org/10.5751/ES-05066-170450

EC. (2018). *Biomass*. https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/biomass_en

Egenolf, V., Vita, G., Distelkamp, M., Schier, F., Hüfner, R., & Bringezu, S. (2021). The Timber Footprint of the German Bioeconomy—State of the Art and Past Development. *Sustainability*, *13*(7), Article 7. https://doi.org/10.3390/su13073878

Ellis, P. W., Gopalakrishna, T., Goodman, R. C., Putz, F. E., Roopsind, A., Umunay, P. M., Zalman, J., Ellis, E. A., Mo, K., Gregoire, T. G., & Griscom, B. W. (2019). Reduced-impact logging for climate change mitigation (RIL-C) can halve selective logging emissions from tropical forests. *Forest Ecology and Management*, *438*, 255–266. https://doi.org/10.1016/j.foreco.2019.02.004

Emmerson, M., Morales, M. B., Oñate, J. J., Batáry, P., Berendse, F., Liira, J., Aavik, T., Guerrero, I., Bommarco, R., Eggers, S., Pärt, T., Tscharntke, T., Weisser, W., Clement, L., & Bengtsson, J. (2016). How Agricultural Intensification Affects Biodiversity and Ecosystem Services. In *Advances in Ecological Research* (Vol. 55, pp. 43–97). Elsevier. https://doi.org/10.1016/bs.aecr.2016.08.005

Environment (2023, February 25). Biodiversity strategy for 2030. Retrieved from https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en

Estes, J. A., Terborgh, J., Brashares, J. S., Power, M. E., Berger, J., Bond, W. J., Carpenter, S. R., Essington, T. E., Holt, R. D., Jackson, J. B. C., Marquis, R. J., Oksanen, L., Oksanen, T., Paine, R. T., Pikitch, E. K., Ripple, W. J., Sandin, S. A., Scheffer, M., Schoener, T. W., … Wardle, D. A. (2011). Trophic downgrading of planet Earth. *Science (New York, N.Y.)*, *333*(6040), 301–306. https://doi.org/10.1126/science.1205106

Eugen, R., & Cojinovschi, A.-D. (2014). Structural Dynamics of Romanian Forests after 1990. *Present Environment and Sustainable Development*, *8*. https://doi.org/10.2478/pesd-2014-0002

European Comission. (n.d.). *Biodiversity strategy for 2030*. Environment. https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en

European Commission (2023, February 25). A European Green Deal. Retrieved from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

European Commission. (2021). *Energy systems evaluation. (Volume 1), Sustainability assessment*. Springer.

European Commission. (n.d.a). *2030 Climate Target Plan*. https://climate.ec.europa.eu/eu-action/european-green-deal/2030-climate-target-plan_en

European Commission. (n.d.b). *National action plans and annual progress reports (NREAPs)*. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/national-action-plans-and-annual-progress-reports_en

European Commission. Directorate General for Environment., Arcadis., IEEP., Birdlife., Stella., Niras., & Ecosystems Ltd. (2020). *Potential impacts of bioenergy developments on habitats and species protected under the birds and habitats directives: final report.* Publications Office. https://data.europa.eu/doi/10.2779/614742

European Commission. Joint Research Centre. (2019). *Brief on biomass for energy in the European Union.* Publications Office. https://data.europa.eu/doi/10.2760/546943

European Commission. Joint Research Centre. (2021a). *Environmental sustainability of energy generation from forest biomass*. https://joint-research-centre.ec.europa.eu/jrc-news/environmental-sustainability-energy-generation-forest-biomass-2021-01-26_en

European Commission. Joint Research Centre. (2021b). *The use of woody biomass for energy production in the EU.* Publications Office. https://data.europa.eu/doi/10.2760/831621

European Forest Institue. (2021). *What are the key factors affecting forest biodiversity? | European Forest Institute*. https://efi.int/forestbiodiversity/factors

European Union. (n.d.). *National energy and climate plans (NECPs)*. https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en

Eurostat. (n.d.). *Database*. https://ec.europa.eu/eurostat/web/main/data/database

Eurostat. (n.d.). *Shares (Renewables)*. Eurostat. https://ec.europa.eu/eurostat/web/energy/data/shares

Faith, D. P. (2021). Biodiversity. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy* (Spring 2021). Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/spr2021/entries/biodiversity/

FAO. (2013, May 15). *Forests and trees outside forests are essential for global food security and nutrition*. International Conference on Forests for Food Security and Nutrition, Rome, Italy. https://www.fao.org/3/aq110e/aq110e.pdf

FAO. (2015). *Climate change and food security: Risks and responses*.

FAO. (2020). *Global Forest Resources Assessment 2020: Main report*. FAO. https://doi.org/10.4060/ca9825en

FAO. (2020). *Indicators of the genetic diversity of trees – State, pressure, benefit and response. The State of the World's Forest Genetic Resources – Thematic study |Policy Support and Governance| Food and Agriculture Organization of the United Nations*. http://www.fao.org/3/cb2492en/CB2492EN.pdf

Favero, A., Daigneault, A., & Sohngen, B. (2020). Forests: Carbon sequestration, biomass energy, or both? *Science Advances*, *6*(13), eaay6792. https://doi.org/10.1126/sciadv.aay6792

FDA. (2022). New Report Shows Biomass Industry Is Lighting Facts on Fire With Sustainability Claims. *Forest Defenders Alliance*. https://forestdefenders.eu/new-report-shows-biomass-industry-is-lighting-facts-on-fire-with-sustainability-claims/

Fischer, M. (2019, April 18). Mixed forests are more productive. *Naturwald Akademie*. https://naturwald-akademie.org/studies/mixed-forests-are-more-productive/

Fit for 55 (2023a, February 25). Retrieved from https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

Fit for 55: how the EU plans to boost renewable energy (2023b, February 25). Retrieved from https://www.consilium.europa.eu/en/infographics/fit-for-55-how-the-eu-plans-to-boost-renewable-energy/

Fit for 55: reaching climate goals in the land use and forestry sectors (2023c, February 25). Retrieved from https://www.consilium.europa.eu/en/infographics/fit-for-55-lulucf-land-use-land-use-change-and-forestry/

Fit for 55: reform of the EU emissions trading system (2023d, February 25). Retrieved from https://www.consilium.europa.eu/en/infographics/fit-for-55-eu-emissions-trading-system/

Fletcher, S., & Islam, M. Z. (2018). Comparing sets of patterns with the Jaccard index. *Australasian Journal of Information Systems*, *22*. https://doi.org/10.3127/ajis.v22i0.1538

Forest Europe. (n.d.). *Sustainable Forest Management*. Forest Europe Growing Life. https://foresteurope.org/workstreams/sustainable-forest-management/

Forsell, N., Korosuo, A., Havlik, P., & Valin, H. (2016). *Study on impacts on resource efficiency of future EU demand for bioenergy*. https://pure.iiasa.ac.at/id/eprint/14009/1/Task%203.pdf

Frank, S., Böttcher, H., Gusti, M., Havlík, P., Klaassen, G., Kindermann, G., & Obersteiner, M. (2016). Dynamics of the land use, land use change, and forestry sink in the European Union: The impacts of energy and climate targets for 2030. *Climatic Change*, *138*(1), 253–266. https://doi.org/10.1007/s10584-016-1729-7

Fuller, R. J. (1992). Effects of coppice management on woodland breeding birds. In G. P. Buckley (Ed.), *Ecology and Management of Coppice Woodlands* (pp. 169–192). Springer Netherlands. https://doi.org/10.1007/978-94-011-2362-4_9

Gardner, T. A., Ferreira, J., Barlow, J., Lees, A. C., Parry, L., Vieira, I. C. G., Berenguer, E., Abramovay, R., Aleixo, A., Andretti, C., Aragão, L. E. O. C., Araújo, I., de Ávila, W. S., Bardgett, R. D., Batistella, M., Begotti, R. A., Beldini, T., de Blas, D. E., Braga, R. F., … Zuanon, J. (2013). A social and ecological assessment of tropical land uses at multiple scales: The Sustainable Amazon Network. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *368*(1619), 20120166. https://doi.org/10.1098/rstb.2012.0166

Giuntoli, J., & Searle, S. (2019). *Does Bioenergy Demand Improve Forest Management?* https://theicct.org/sites/default/files/publications/ICCT_bioenergy_demand_20190719.pdf

Giuntoli, J., Agostini, A., Caserini, S., Lugato, E., Baxter, D., & Marelli, L. (2016). Climate change impacts of power generation from residual biomass. *Biomass and Bioenergy*, *89*, 146–158. https://doi.org/10.1016/j.biombioe.2016.02.024

Giuntoli, J., Barredo, J. I., Avitabile, V., Camia, A., Cazzaniga, N. E., Grassi, G., Jasinevičius, G., Jonsson, R., Marelli, L., Robert, N., Agostini, A., & Mubareka, S. (2022). The quest for sustainable forest bioenergy: win-win solutions for climate and biodiversity. *Renewable and Sustainable Energy Reviews*, *159*, 112180. https://doi.org/10.1016/j.rser.2022.112180

Giuntoli, J., Caserini, S., Marelli, L., Baxter, D., & Agostini, A. (2015). Domestic heating from forest logging residues: Environmental risks and benefits. *Journal of Cleaner Production*, *99*, 206–216. https://doi.org/10.1016/j.jclepro.2015.03.025

Goodale, C. L., Apps, M. J., Birdsey, R. A., Field, C. B., Heath, L. S., Houghton, R. A., Jenkins, J. C., Kohlmaier, G. H., Kurz, W., Liu, S., Nabuurs, G.-J., Nilsson, S., & Shvidenko, A. Z. (2002). Forest Carbon Sinks in the Northern Hemisphere. *Ecological Applications*, *12*(3), 891–899. https://doi.org/10.1890/1051-0761(2002)012[0891:FCSITN]2.0.CO;2

Haase, M., Baumann, M., Wulf, C., Rösch, C., & Zapp, P. (2021). 4.3 Multikriterielle Analysen zur Entscheidungsunterstützung in der Technikfolgenabschätzung. In S. Böschen, A. Grunwald, B.-J. Krings, & C. Rösch (Eds.), *Technikfolgenabschätzung* (pp. 306–320). Nomos Verlagsgesellschaft mbH & Co. KG. https://doi.org/10.5771/9783748901990-306

Halewood, M., Chiurugwi, T., Sackville Hamilton, R., Kurtz, B., Marden, E., Welch, E., Michiels, F., Mozafari, J., Sabran, M., Patron, N., Kersey, P., Bastow, R., Dorius, S., Dias, S., McCouch, S., & Powell, W. (2018). Plant genetic resources for food and agriculture: Opportunities and challenges emerging from the science and information technology revolution. *New Phytologist*, *217*(4), 1407–1419. https://doi.org/10.1111/nph.14993

Hao, M., Corral-Rivas, J. J., González-Elizondo, M. S., Ganeshaiah, K. N., Nava-Miranda, M. G., Zhang, C., Zhao, X., & von Gadow, K. (2019). Assessing biological dissimilarities between five forest communities. *Forest Ecosystems*, *6*(1), 30. https://doi.org/10.1186/s40663-019-0188-9

Harfoot, M., Glaser, S. A. M., Tittensor, D. P., Britten, G. L., McLardy, C., Malsch, K., & Burgess, N. D. (2018). Unveiling the patterns and trends in 40 years of global trade in CITES-listed wildlife. *Biological Conservation*, *223*, 47–57. https://doi.org/10.1016/j.biocon.2018.04.017

Hassani, N. J. M. (2018, June 3). Coppice System—Everything You Need to Know about Silvicultural System. *Forestrypedia*. https://forestrypedia.com/coppice-system-detailed-note/

Hebblewhite, M., White, C. A., Nietvelt, C. G., McKenzie, J. A., Hurd, T. E., Fryxell, J. M., Bayley, S. E., & Paquet, P. C. (2005). Human Activity Mediates a Trophic Cascade Caused by Wolves. *Ecology*, *86*(8), 2135–2144. https://doi.org/10.1890/04-1269

Hedrick, P. W. (2005). A standardized genetic differentiation measure. *Evolution; International Journal of Organic Evolution*, *59*(8), 1633–1638.

Heil, L. J., & Burkle, L. A. (2019). The effects of post-wildfire salvage logging on plant reproductive success and pollination in Symphoricarpos albus, a fire-tolerant shrub. *Forest Ecology and Management*, *432*, 157–163. https://doi.org/10.1016/j.foreco.2018.09.013

Helmholtz Working Group MCDA for Sustainability Assessment. (2022). *MCDA for sustainability assessment – insights to Helmholtz Association activities*. https://elib.dlr.de/192296/1/HGF%20-%20MCDA%20for%20sustainability%20assessment%20-%20insights%20to%20Helmholtz%20Association%20activities%20-%202022-11-02.pdf

Hoffmann, J. P. (2004). Social and Environmental Influences on Endangered Species: A Cross-National Study. *Sociological Perspectives*, *47*(1), 79–107. https://doi.org/10.1525/sop.2004.47.1.79

Holtsmark, B. (2012). Harvesting in boreal forests and the biofuel carbon debt. *Climatic Change*, *112*(2), 415–428. https://doi.org/10.1007/s10584-011-0222-6

Hooper, D. U., Chapin III, F. S., Ewel, J. J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J. H., Lodge, D. M., Loreau, M., Naeem, S., Schmid, B., Setälä, H., Symstad, A. J., Vandermeer, J., & Wardle, D. A. (2005). Effects of Biodiversity on Ecosystem Functioning: A Consensus of Current Knowledge. *Ecological Monographs*, *75*(1), 3–35. https://doi.org/10.1890/04-0922

Hossain, M. N., Rokanuzzaman, M., Rahman, M. A., Bodiuzzaman, M., & Miah, M. A. (2013). Causes of Deforestation and Conservation of Madhupur Sal Forest in Tangail Region. *Journal of Environmental Science and Natural Resources*, *6*(2), Article 2. https://doi.org/10.3329/jesnr.v6i2.22105

IEA Bioenergy. (2018). *Is energy from woody biomass positive for the climate?* https://www.ieabioenergy.com/wp-content/uploads/2018/01/FAQ_WoodyBiomass-Climate_final-1.pdf

IEA Bioenergy. (2022). *Annual Report 2021*. https://www.ieabioenergy.com/wp-content/uploads/2022/04/IEA-Bioenergy-Annual-Report-2021.pdf

IEA. (2021). *Implementation of bioenergy in the European Union – 2021 update*. https://www.ieabioenergy.com/wp-content/uploads/2021/11/CountryReport2021_EU28_final.pdf

IPCC. (2014). *Annex III Technology-specific Cost and Performance Parameters*. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf

IPCC. (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

IRENA. (2018). *Renewable Energy Prospects for the European Union*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Feb/IRENA_REmap_EU_2018.pdf

Jetz, W., Wilcove, D. S., & Dobson, A. P. (2007). Projected Impacts of Climate and Land-Use Change on the Global Diversity of Birds. *PLOS Biology*, *5*(6), e157. https://doi.org/10.1371/journal.pbio.0050157

Jiang, W., Yang, S., Yang, X., & Gu, N. (2016). Negative impacts of afforestation and economic forestry on the Chinese Loess Plateau and proposed solutions. *Quaternary International*, *399*, 165–173. https://doi.org/10.1016/j.quaint.2015.04.011

Jochem, D., Weimar, H., Bösch, M., Mantau, U., & Dieter, M. (2015). Estimation of wood removals and fellings in Germany: A calculation approach based on the amount of used roundwood. *European Journal of Forest Research*, *134*(5), 869–888. https://doi.org/10.1007/s10342-015-0896-9

Johnson, W. E., Onorato, D. P., Roelke, M. E., Land, E. D., Cunningham, M., Belden, R. C., McBride, R., Jansen, D., Lotz, M., Shindle, D., Howard, J., Wildt, D. E., Penfold, L. M., Hostetler, J. A., Oli, M. K., & O'Brien, S. J. (2010). Genetic restoration of the Florida panther. *Science (New York, N.Y.)*, *329*(5999), 1641–1645. https://doi.org/10.1126/science.1192891

Jonker, J. G. G., Junginger, M., & Faaij, A. (2014). Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States. *GCB Bioenergy*, *6*(4), 371–389. https://doi.org/10.1111/gcbb.12056

Jonsell, M. (2007). Effects on biodiversity of forest fuel extraction, governed by processes working on a large scale. *Biomass and Bioenergy*, *31*, 726–732. https://doi.org/10.1016/j.biombioe.2007.06.018

Jonsson, R., Blujdea, V. N. B., Fiorese, G., Pilli, R., Rinaldi, F., Baranzelli, C., & Camia, A. (2018). Outlook of the European forest-based sector: Forest growth, harvest demand, wood-product markets, and forest carbon dynamics implications. *IForest - Biogeosciences and Forestry*, *11*(2), 315. https://doi.org/10.3832/ifor2636-011

Jonsson, R., Camia, A., & Mubareka, S. (2021). *Analysis of wood resource balance gaps for the EU*. https://doi.org/10.2760/417678

JRC. (2018). *Renewable Energy – Recast to 2030 (RED II)*. https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en

JRC. (2019). *Wood Resource Balances of EU-28 and Member States*. https://core.ac.uk/download/pdf/186491016.pdf

JRC. (2022). *Sankey diagrams of woody biomass flows in the European Union | Knowledge for policy*. https://knowledge4policy.ec.europa.eu/publication/forestry-sankey_en

KKIENERM. (2019, September 1). *Wildlife, Forest & Fisheries Crime Module 1 Key Issues: Implications of Wildlife Trafficking*. //www.unodc.org

Klapwijk, M. J., Bylund, H., Schroeder, M., & Björkman, C. (2016). Forest management and natural biocontrol of insect pests. *Forestry: An International Journal of Forest Research*, *89*(3), 253–262. https://doi.org/10.1093/forestry/cpw019

Klein, A.-M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T. (2006). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences*, *274*(1608), 303–313. https://doi.org/10.1098/rspb.2006.3721

Kriegel, P., Matevski, D., & Schuldt, A. (2021). Monoculture and mixture-planting of non-native Douglas fir alters species composition, but promotes the diversity of ground beetles in a temperate forest system. *Biodiversity and Conservation*, *30*(5), 1479–1499. https://doi.org/10.1007/s10531-021-02155-1

Krishnan, S., Guerra, G., Bertrand, D., Wertz-Kanounnikoff, S., & Kettle, C. (2020). *The pollination services of forests – A review of forest and landscape interventions to enhance their cross-sectoral benefits. Forestry Working Paper No. 15. Rome, FAO & Bioversity International.*

Kulakowski, D., Seidl, R., Holeksa, J., Kuuluvainen, T., Nagel, T. A., Panayotov, M., Svoboda, M., Thorn, S., Vacchiano, G., Whitlock, C., Wohlgemuth, T., & Bebi, P. (2017). A walk on the wild side: Disturbance dynamics and the conservation and management of European mountain forest ecosystems. *Forest Ecology and Management*, *388*, 120–131. https://doi.org/10.1016/j.foreco.2016.07.037

Kurukulasuriya, P., & Rosenthal, S. (2013). *Climate Change and Agriculture: A Review of Impacts and Adaptations*. World Bank. https://openknowledge.worldbank.org/handle/10986/16616

Kuuluvainen, T., Angelstam, P., Frelich, L., Jõgiste, K., Koivula, M., Kubota, Y., Lafleur, B., & Macdonald, E. (2021). Natural Disturbance-Based Forest Management: Moving Beyond Retention and Continuous-Cover Forestry. *Frontiers in Forests and Global Change*, *4*. https://www.frontiersin.org/articles/10.3389/ffgc.2021.629020

Laganière, J., Paré, D., Thiffault, E., & Bernier, P. Y. (2017). Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests. *GCB Bioenergy*, *9*(2), 358–369. https://doi.org/10.1111/gcbb.12327

Letourneau, D. K., & Dyer, L. A. (1998). Density Patterns of Piper Ant-Plants and Associated Arthropods: Top-Predator Trophic Cascades in a Terrestrial System? *Biotropica*, *30*(2), 162–169.

Letourneau, D. K., & Dyer, L. A. (1998a). Density Patterns of Piper Ant-Plants and Associated Arthropods: Top-Predator Trophic Cascades in a Terrestrial System? *Biotropica*, *30*(2), 162–169.

Letourneau, D. K., & Dyer, L. A. (1998b). Experimental Test in Lowland Tropical Forest Shows Top-down Effects Through Four Trophic Levels. *Ecology*, *79*(5), 1678–1687. https://doi.org/10.1890/0012-9658(1998)079[1678:ETILTF]2.0.CO;2

Leverkus, A. B., Buma, B., Wagenbrenner, J., Burton, P. J., Lingua, E., Marzano, R., & Thorn, S. (2021). Tamm review: Does salvage logging mitigate subsequent forest disturbances? *Forest Ecology and Management*, *481*, 118721. https://doi.org/10.1016/j.foreco.2020.118721

Leverkus, A. B., Gustafsson, L., Rey Benayas, J. M., & Castro, J. (2015). Does post-disturbance salvage logging affect the provision of ecosystem services? A systematic review protocol. *Environmental Evidence*, *4*(1), 16. https://doi.org/10.1186/s13750-015-0042-7

Lucas-Borja, M. E., Ortega, R., Miralles, I., Plaza-Álvarez, P. A., González-Romero, J., Peña-Molina, E., Moya, D., Zema, D. A., Wagenbrenner, J. W., & de las Heras, J. (2020). Effects of wildfire and logging on soil functionality in the short-term in Pinus halepensis M. forests. *European Journal of Forest Research*, *139*(6), 935–945. https://doi.org/10.1007/s10342-020-01296-2

Ma, K., Dj, B., Eg, R., & Da, M. (2016). Local Plant Diversity Across Multiple Habitats Supports a Diverse Wild Bee Community in Pennsylvania Apple Orchards. *Environmental Entomology*, *45*(1). https://doi.org/10.1093/ee/nvv147

Mai-Moulin, T., Hoefnagels, R., Grundmann, P., & Junginger, M. (2021). Effective sustainability criteria for bioenergy: Towards the implementation of the european renewable directive II. *Renewable and Sustainable Energy Reviews*, *138*, 110645. https://doi.org/10.1016/j.rser.2020.110645

Mansuy, N., Thiffault, E., Lemieux, S., Manka, F., Paré, D., & Lebel, L. (2015). Sustainable biomass supply chains from salvage logging of fire-killed stands: A case study for wood pellet production in eastern Canada. *Applied Energy*, *154*, 62–73. https://doi.org/10.1016/j.apenergy.2015.04.048

Matthews, R., Hogan, G., & Mackie, E. (2018). *Carbon impacts of biomass consumed in the EU Supplementary analysis and interpretation for the European Climate Foundation*. https://europeanclimate.org/wp-content/uploads/2018/05/CIB-Summary-report-for-ECF-v10.5-May-20181.pdf

Maxim, A. (2014). Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis. *Energy Policy*, *65*, 284–297. https://doi.org/10.1016/j.enpol.2013.09.059

McKechnie, J., Colombo, S., Chen, J., Mabee, W., & MacLean, H. L. (2011). Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels. *Environmental Science & Technology*, *45*(2), 789–795. https://doi.org/10.1021/es1024004

McLaren, B. E., & Peterson, R. O. (1994). Wolves, Moose, and Tree Rings on Isle Royale. *Science*, *266*(5190), 1555–1558. https://doi.org/10.1126/science.266.5190.1555

Meyfroidt, P., de Bremond, A., Ryan, C. M., Archer, E., Aspinall, R., Chhabra, A., Camara, G., Corbera, E., DeFries, R., Díaz, S., Dong, J., Ellis, E. C., Erb, K.-H., Fisher, J. A., Garrett, R. D., Golubiewski, N. E., Grau, H. R., Grove, J. M., Haberl, H., … zu Ermgassen, E. K. H. J. (2022). Ten facts about land systems for sustainability. *Proceedings of the National Academy of Sciences*, *119*(7), e2109217118. https://doi.org/10.1073/pnas.2109217118

N. Wear, D., & Bartuska, A. (2020a). *Forest Bioenergy 101: Generation and Emissions*. Resources for the Future. https://media.rff.org/documents/Forest_Bioenergy_101.pdf

N. Wear, D., & Bartuska, A. (2020b). *Forest Bioenergy 102: Policy Approaches*. https://media.rff.org/documents/Forest_Bioenergy_102.pdf

New EU Forest Strategy for 2030, COM/2021/572 final (2021). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0572#footnote39

Newbold, T., Hudson, L. N., Arnell, A. P., Contu, S., De Palma, A., Ferrier, S., Hill, S. L. L., Hoskins, A. J., Lysenko, I., Phillips, H. R. P., Burton, V. J., Chng, C. W. T., Emerson, S., Gao, D., Pask-Hale, G., Hutton, J., Jung, M., Sanchez-Ortiz, K., Simmons, B. I., … Purvis, A. (2016). Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science (New York, N.Y.)*, *353*(6296), 288–291. https://doi.org/10.1126/science.aaf2201

Nowak, D. J., Hirabayashi, S., Bodine, A., & Greenfield, E. (2014). Tree and forest effects on air quality and human health in the United States. *Environmental Pollution*, *193*, 119–129. https://doi.org/10.1016/j.envpol.2014.05.028

Nowak, D. J., Hirabayashi, S., Bodine, A., & Greenfield, E. (2014). Tree and forest effects on air quality and human health in the United States. *Environmental Pollution. 193: 119-129.*, *193*, 119–129. https://doi.org/10.1016/j.envpol.2014.05.028

OECD (2021). A global analysis of the cost-efficiency of forest carbon sequestration. *OECD Environment Working Papers*.

Olagunju, T. (2015). *Impacts of Human-induced Deforestation, Forest Degradation and Fragmentation on Food Security*.

Oldfield, E. E., Felson, A. J., Wood, S. A., Hallett, R. A., Strickland, M. S., & Bradford, M. A. (2014). Positive effects of afforestation efforts on the health of urban soils. *Forest Ecology and Management*, *313*, 266–273. https://doi.org/10.1016/j.foreco.2013.11.027

Osborne, J. L., Williams, I. H., & Corbet, S. A. (1991). Bees, Pollination and Habitat Change in the European Community. *Bee World*, *72*(3), 99–116. https://doi.org/10.1080/0005772X.1991.11099088

Pace, M. L., Cole, J. J., Carpenter, S. R., & Kitchell, J. F. (1999). Trophic cascades revealed in diverse ecosystems. *Trends in Ecology & Evolution*, *14*(12), 483–488. https://doi.org/10.1016/S0169-5347(99)01723-1

Paquette, A., & Messier, C. (2011). The effect of biodiversity on tree productivity: From temperate to boreal forests. *Global Ecology and Biogeography*, *20*(1), 170–180. https://doi.org/10.1111/j.1466-8238.2010.00592.x

Pelkonen, P. (Ed.). (2014). *Forest bioenergy for Europe*. European Forest Institute.

Peter, D. H., & Harrington, T. B. (2018). Effects of forest harvesting, logging debris, and herbicides on the composition, diversity and assembly of a western Washington, USA plant community. *Forest Ecology and Management*, *417*, 18–30. https://doi.org/10.1016/j.foreco.2018.01.045

Pierre, S., Groffman, P. M., Killilea, M. E., & Oldfield, E. E. (2016). Soil microbial nitrogen cycling and nitrous oxide emissions from urban afforestation in the New York City Afforestation Project. *Urban Forestry & Urban Greening*, *15*, 149–154. https://doi.org/10.1016/j.ufug.2015.11.006

Pilli, R., Fiorese, G., & Grassi, G. (2015). EU mitigation potential of harvested wood products. *Carbon Balance and Management*, *10*(1), 6. https://doi.org/10.1186/s13021-015-0016-7

Pimentel, D., Wilson, C., McCullum, C., Huang, R., Dwen, P., Flack, J., Tran, Q., Saltman, T., & Cliff, B. (1997). Economic and Environmental Benefits of Biodiversity. *BioScience*, *47*(11), 747–757. https://doi.org/10.2307/1313097

Poorter, L., van der Sande, M. T., Thompson, J., Arets, E. J. M. M., Alarcón, A., Álvarez-Sánchez, J., Ascarrunz, N., Balvanera, P., Barajas-Guzmán, G., Boit, A., Bongers, F., Carvalho, F. A., Casanoves, F., Cornejo-Tenorio, G., Costa, F. R. C., de Castilho, C. V., Duivenvoorden, J. F., Dutrieux, L. P., Enquist, B. J., … Peña-Claros, M. (2015). Diversity enhances carbon storage in tropical forests. *Global Ecology and Biogeography*, *24*(11), 1314–1328. https://doi.org/10.1111/geb.12364

Pörtner, Hans-Otto, Scholes, Robert J., Agard, John, Archer, Emma, Bai, Xuemei, Barnes, David, Burrows, Michael, Chan, Lena, Cheung, Wai Lung (William), Diamond, Sarah, Donatti, Camila, Duarte, Carlos, Eisenhauer, Nico, Foden, Wendy, Gasalla, Maria A., Handa, Collins, Hickler, Thomas, Hoegh-Guldberg, Ove, Ichii, Kazuhito, … Ngo, Hien. (2021). *IPBES-IPCC co-sponsored workshop report on biodiversity and climate change* (Version 2). Zenodo. https://doi.org/10.5281/ZENODO.4782538

Power, M. E., Tilman, D., Estes, J. A., Menge, B. A., Bond, W. J., Mills, L. S., Daily, G., Castilla, J. C., Lubchenco, J., & Paine, R. T. (1996). Challenges in the Quest for Keystones: Identifying keystone species is difficult—but essential to understanding how loss of species will affect ecosystems. *BioScience*, *46*(8), 609–620. https://doi.org/10.2307/1312990

Priess, J. A., Mimler, M., Klein, A.-M., Schwarze, S., Tscharntke, T., & Steffan-Dewenter, I. (2007). Linking Deforestation Scenarios to Pollination Services and Economic Returns in Coffee Agroforestry Systems. *Ecological Applications*, *17*(2), 407–417. https://doi.org/10.1890/05-1795

Proskurina, S., Junginger, M., Heinimö, J., Tekinel, B., & Vakkilainen, E. (2019). Global biomass trade for energy- Part 2: Production and trade streams of wood pellets, liquid biofuels, charcoal, industrial roundwood and emerging energy biomass. *Biofuels, Bioproducts and Biorefining*, *13*(2), 371–387. https://doi.org/10.1002/bbb.1858

Ranius, T., Hämäläinen, A., Egnell, G., Olsson, B., Eklöf, K., Stendahl, J., Rudolphi, J., Sténs, A., & Felton, A. (2018). The effects of logging residue extraction for energy on ecosystem services and biodiversity: A synthesis. *Journal of Environmental Management*, *209*, 409–425. https://doi.org/10.1016/j.jenvman.2017.12.048

Ratcliffe, S., Wirth, C., Jucker, T., van der Plas, F., Scherer-Lorenzen, M., Verheyen, K., Allan, E., Benavides, R., Bruelheide, H., Ohse, B., Paquette, A., Ampoorter, E., Bastias, C. C., Bauhus, J., Bonal, D., Bouriaud, O., Bussotti, F., Carnol, M., Castagneyrol, B., … Baeten, L. (2017). Biodiversity and ecosystem functioning relations in European forests depend on environmental context. *Ecology Letters*, *20*(11), 1414–1426. https://doi.org/10.1111/ele.12849

Ravenek, J., Bessler, H., Engels, C., Scherer-Lorenzen, M., Gessler, A., Jesch, A., De Luca, E., Temperton, V., Ebeling, A., Roscher, C., Schmid, B., Weisser, W., Wirth, C., Kroon, H., Weigelt, A., & Mommer, L. (2014). Long-term study of root biomass in a biodiversity experiment reveals shifts in diversity effects over time. *Oikos*, *123*. https://doi.org/10.1111/oik.01502

Reed, D. H., & Frankham, R. (2003). Correlation between Fitness and Genetic Diversity. *Conservation Biology*, *17*(1), 230–237. https://doi.org/10.1046/j.1523-1739.2003.01236.x

Ren, J. (Ed.). (2021). *Energy systems evaluation. (Volume 1), Sustainability assessment*. Springer.

Rickels, W., Proelß, A., Geden, O., Burhenne, J., & Fridahl, M. (2021). Integrating Carbon Dioxide Removal Into European Emissions Trading. *Frontiers in Climate*, *3*. https://doi.org/10.3389/fclim.2021.690023

Ripple, W., Beschta, R., & Painter, L. (2015). Trophic cascades from wolves to alders in Yellowstone. *Forest Ecology and Management*, *354*, 254–260. https://doi.org/10.1016/j.foreco.2015.06.007

Robert, N., Jonsson, R., Chudy, R., & Camia, A. (2020). The EU Bioeconomy: Supporting an Employment Shift Downstream in the Wood-Based Value Chains? *Sustainability*, *12*(3), 758. https://doi.org/10.3390/su12030758

Saarikoski, H., Mustajoki, J., Barton, D. N., Geneletti, D., Langemeyer, J., Gomez-Baggethun, E., Marttunen, M., Antunes, P., Keune, H., & Santos, R. (2016). Multi-Criteria Decision Analysis and Cost-Benefit Analysis: Comparing alternative frameworks for integrated valuation of ecosystem services. *Ecosystem Services*, *22*, 238–249. https://doi.org/10.1016/j.ecoser.2016.10.014

Sala, O. E., Stuart Chapin, F., III, Armesto, J. J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L. F., Jackson, R. B., Kinzig, A., Leemans, R., Lodge, D. M., Mooney, H. A., Oesterheld, M., Poff, N. L., Sykes, M. T., Walker, B. H., Walker, M., & Wall, D. H. (2000). Global Biodiversity Scenarios for the Year 2100. *Science*, *287*(5459), 1770–1774. https://doi.org/10.1126/science.287.5459.1770

Savaresi, A., Perugini, L., & Chiriacò, M. V. (2020). Making sense of the LULUCF Regulation: Much ado about nothing? *Review of European, Comparative & International Environmental Law*, *29*(2), 212–220. https://doi.org/10.1111/reel.12332

Savolainen, O., & Kärkkäinen, K. (1992). Effect of forest management on gene pools. In W. T. Adams, S. H. Strauss, D. L. Copes, & A. R. Griffin (Eds.), *Population Genetics of Forest Trees: Proceedings of the International Symposium on Population Genetics of Forest Trees Corvallis, Oregon, U.S.A., July 31–August 2,1990* (pp. 329–345). Springer Netherlands. https://doi.org/10.1007/978-94-011-2815-5_17

Secretariat of the Convention on Biological Diversity, & United Nations Environment Programme (Eds.). (2014). *Global biodiversity outlook 4: A mid-term assessment of progress towards the implementation of the strategic plan for biodiversity 2011-2020*. Secretariat for the Convention on Biological Diversity.

Sennet, S. (2018). *Clear-cut and Consequence: Trophic Cascades of Deforestation on Rapa Nui (Easter Island)*. https://doi.org/10.13140/RG.2.2.36680.26889

Silva, S. V., Andermann, T., Zizka, A., Kozlowski, G., & Silvestro, D. (2022). Global Estimation and Mapping of the Conservation Status of Tree Species Using Artificial Intelligence. *Frontiers in Plant Science*, *13*. https://www.frontiersin.org/articles/10.3389/fpls.2022.839792

Smith, P., Haberl, H., Popp, A., Erb, K., Lauk, C., Harper, R., Tubiello, F. N., de Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., Mbow, C., … Rose, S. (2013). How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology*, *19*(8), 2285–2302. https://doi.org/10.1111/gcb.12160

Soimakallio, S., Kalliokoski, T., Lehtonen, A., & Salminen, O. (2021). On the trade-offs and synergies between forest carbon sequestration and substitution. *Mitigation and Adaptation Strategies for Global Change*, *26*(1), 4. https://doi.org/10.1007/s11027-021-09942-9

Spracklen, B. D., Lane, J. V., Spracklen, D. V., Williams, N., & Kunin, W. E. (2013). Regeneration of native broadleaved species on clearfelled conifer plantations in upland Britain. *Forest Ecology and Management*, *310*, 204–212. https://doi.org/10.1016/j.foreco.2013.08.001

Thorn, S., Bässler, C., Brandl, R., Burton, P., Cahall, R., Campell, J., Castro, J., Choi, C.-Y., Cobb, T., Donato, D., Durska, E., Fontaine, J., Gauthier, S., Hébert, C., Hothorn, T., Hutto, R., Lee, E.-J., Leverkus, A., Lindenmayer, D., & Müller, J. (2018). Impacts of salvage logging on biodiversity: A meta-analysis. *Journal of Applied Ecology*, *55*. https://doi.org/10.1111/1365-2664.12945

Titus, B. D., Brown, K., Helmisaari, H.-S., Vanguelova, E., Stupak, I., Evans, A., Clarke, N., Guidi, C., Bruckman, V. J., Varnagiryte-Kabasinskiene, I., Armolaitis, K., de Vries, W., Hirai, K., Kaarakka, L., Hogg, K., & Reece, P. (2021). Sustainable forest biomass: A review of current residue harvesting guidelines. *Energy, Sustainability and Society*, *11*(1), 10. https://doi.org/10.1186/s13705-021-00281-w

Turkson, C., Acquaye, A., Liu, W., & Papadopoulos, T. (2020). Sustainability assessment of energy production: A critical review of methods, measures and issues. *Journal of Environmental Management*, *264*, 110464. https://doi.org/10.1016/j.jenvman.2020.110464

Vcmprimer.org (2022). Chapter 1: What is the voluntary carbon market? Retrieved from https://vcmprimer.org/chapter-1-what-is-the-voluntary-carbon-market%EF%BF%BC/

Vedavathy, S. (2003). Scope and importance of traditional medicine. *IJTK Vol.02(3) [July 2003]*. http://nopr.niscpr.res.in/handle/123456789/25928

Vellend, M., Verheyen, K., Flinn, K. M., Jacquemyn, H., Kolb, A., Van Calster, H., Peterken, G., Graae, B. J., Bellemare, J., Honnay, O., Brunet, J., Wulf, M., Gerhardt, F., & Hermy, M. (2007). Homogenization of forest plant communities and weakening of species–environment relationships via agricultural land use. *Journal of Ecology*, *95*(3), 565–573. https://doi.org/10.1111/j.1365-2745.2007.01233.x

Vera, I., Wicke, B., Lamers, P., Cowie, A., Repo, A., Heukels, B., Zumpf, C., Styles, D., Parish, E., Cherubini, F., Berndes, G., Jager, H., Schiesari, L., Junginger, M., Brandão, M., Bentsen, N. S., Daioglou, V., Harris, Z., & van der Hilst, F. (2022). Land use for bioenergy: Synergies and trade-offs between sustainable development goals. *Renewable and Sustainable Energy Reviews*, *161*, 112409. https://doi.org/10.1016/j.rser.2022.112409

Veresoglou, S. D., Halley, J. M., & Rillig, M. C. (2015). Extinction risk of soil biota. *Nature Communications*, *6*(1), Article 1. https://doi.org/10.1038/ncomms9862

Volkart, K., Weidmann, N., Bauer, C., & Hirschberg, S. (2017). Multi-criteria decision analysis of energy system transformation pathways: A case study for Switzerland. *Energy Policy*, *106*, 155–168. https://doi.org/10.1016/j.enpol.2017.03.026

Wang, S., Loreau, M., de Mazancourt, C., Isbell, F., Beierkuhnlein, C., Connolly, J., Deutschman, D. H., Doležal, J., Eisenhauer, N., Hector, A., Jentsch, A., Kreyling, J., Lanta, V., Lepš, J., Polley, H. W., Reich, P. B., van Ruijven, J., Schmid, B., Tilman, D., … Craven, D. (2021). Biotic homogenization destabilizes ecosystem functioning by decreasing spatial asynchrony. *Ecology*, *102*(6), e03332. https://doi.org/10.1002/ecy.3332

Watson, R. T., Zakri, A. H., Arico, S., Bridgewater, P., Mooney, H. A., & Cropper, A. (2005). *Millennium Ecosystem Assessment Panel*.

Weill, A. (2020, December 23). *12 Days of Conifers: Conifer Trees and How We Study Them | U.S. Geological Survey*. https://www.usgs.gov/news/12-days-conifers-conifer-trees-and-how-we-study-them

Wolfe, B. E., & Pringle, A. (2012). Geographically structured host specificity is caused by the range expansions and host shifts of a symbiotic fungus. *The ISME Journal*, *6*(4), 745–755. https://doi.org/10.1038/ismej.2011.155

Wood, A., Stedman-Edwards, P., & Mang, J. (2013). *The Root Causes of Biodiversity Loss*. Routledge. https://doi.org/10.4324/9781315071688

Worm, B., & Duffy, J. (2003). Worm B, Duffy JE.. Biodiversity, productivity, and stability in real food webs. Trends Ecol Evo 18: 628-632. *Trends in Ecology & Evolution*, *18*, 628–632. https://doi.org/10.1016/j.tree.2003.09.003

WWF. (2020). *Bending the curve of biodiversity loss*. WWF.

Zanchi, G., Pena, N., & Bird, N. (2011). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, *4*(6), 761–772. https://doi.org/10.1111/j.1757-1707.2011.01149.x

Zimmerer, K. S., de Haan, S., Jones, A. D., Creed-Kanashiro, H., Tello, M., Carrasco, M., Meza, K., Plasencia Amaya, F., Cruz-Garcia, G. S., Tubbeh, R., & Jiménez Olivencia, Y. (2019). The biodiversity of food and agriculture (Agrobiodiversity) in the anthropocene: Research advances and conceptual framework. *Anthropocene*, *25*, 100192. https://doi.org/10.1016/j.ancene.2019.100192

APPENDIX

APPENDIX – A1

Harvest Scenarios / Vulnerability Factors	Existing managed Forest or Plantation				Salvage	Afforestation and transition to plantation	Uncategorized/ assumed Forest Clearing with or without replanting	
	Broadleaf Stem Wood (including coppice) [1]	Broadleaf Residue [2]	Conifer Stem Wood [3]	Conifer Residue [4]	Broadleaf, Conifer [5]	Broadleaf, Conifer [6]	Broadleaf [7]	Conifer [8]
Top-Down Trophic Cascades	Negative Impact	Negative Impact	Negative Impact	Negative Impact	Negative Impact	Positive Impact	Negative Impact	Negative Impact
Bottom-up trophic cascades	Negative Impact	Negative Impact	Negative Impact	Negative Impact	No Impact	Positive Impact	Negative Impact	Negative Impact
Increased likelihood of inbreeding	Negative Impact	No Impact	Negative Impact	No Impact	Negative Impact	Negative Impact	No Impact	No Impact
Increased risk of extinction of endangered species	Negative Impact	Negative Impact	Negative Impact	Negative Impact	No Impact	No Impact	Negative Impact	Negative Impact
Ecosystem Homogenization	Negative Impact	Positive Impact	Negative Impact	Positive Impact	Negative Impact	Negative Impact	No Impact	No Impact
Loss of complexity and increased risk of food-chain and nutrient-cycle homogenization	Negative Impact	Negative Impact	Negative Impact	Negative Impact	Negative Impact	Positive Impact	Negative Impact	Negative Impact
Loss of Habitat	Positive Impact	Negative Impact	Positive Impact	Negative Impact	Negative Impact	Positive Impact	Negative Impact	Negative Impact
Loss of treatment opportunities (traditional and modern medicine) and cures	No Impact	No Impact	No Impact	No Impact	No Impact	Positive Impact	Negative Impact	Negative Impact
Decrease in food security	Negative Impact	Negative Impact	Negative Impact	Negative Impact	No Impact	Positive Impact	Negative Impact	Negative Impact
Potential increase in Jaccard Index (>0.6)	Negative Impact	Negative Impact	No Impact	Negative Impact	No Impact	Negative Impact	Negative Impact	Negative Impact
Decreased air purification	Negative Impact	Negative Impact	Negative Impact	Negative Impact	No Impact	Positive Impact	Negative Impact	Negative Impact
Increase in carbon emissions due to potential sequestration loss	Negative Impact	Negative Impact	Negative Impact	Negative Impact	Negative Impact	Positive Impact	Negative Impact	Negative Impact
Reduction in pollination	Negative Impact	No Impact	Negative Impact	No Impact	No Impact	Positive Impact	Negative Impact	Negative Impact
Reduced maintenance of genetic resources as key inputs to crop varieties and livestock breeds, medicines, and other products	Positive Impact	Negative Impact	Positive Impact	Negative Impact	Negative Impact	No Impact	Negative Impact	Negative Impact
Endangerment of native species	Negative Impact	Negative Impact	Negative Impact	Negative Impact	Negative Impact	No Impact	Negative Impact	Negative Impact
Increased risk of deforestation	No Impact	No Impact	No Impact	No Impact	No Impact	Positive Impact	Negative Impact	Negative Impact
Increased risk of animal and plant trade	Negative Impact	Positive Impact	Negative Impact	Positive Impact	No Impact	Negative Impact	Negative Impact	Negative Impact
Creation of monocultured ecosystem	Negative Impact	No Impact	Negative Impact	Positive Impact	No Impact	Negative Impact	No Impact	No Impact
Proliferation of pests	Positive Impact	Positive Impact	Positive Impact	Positive Impact	Positive Impact	Negative Impact	Negative Impact	Negative Impact
Threats to food security of predators	Negative Impact	No Impact	Negative Impact	No Impact	Positive Impact	Positive Impact	Negative Impact	Negative Impact
Soil degradation	Negative Impact	Negative Impact	Negative Impact	Negative Impact	Negative Impact	Positive Impact	Negative Impact	Negative Impact
Damage to existing root structures	Positive Impact	No Impact	Positive Impact	No Impact	No Impact	Positive Impact	Negative Impact	Negative Impact

Table A1: Vulnerability factors exacerbated by biodiversity loss in each harvest scenario

APPENDIX – A2

Vulnerability Factors \ Harvest Scenarios	Existing managed Forest or Plantation				Salvage	Afforestation and transition to plantation	Uncategorized/ assumed Forest Clearing with or without replanting	
	Broadleaf Stem Wood (including coppice) [1]	Broadleaf Residue [2]	Conifer Stem Wood [3]	Conifer Residue [4]	Broadleaf, Conifer [5]	Broadleaf, Conifer [6]	Broadleaf [7]	Conifer [8]
Top-Down Trophic Cascades	-1	-1	-1	-1	-1	1	-1	-1
Bottom-up trophic cascades	-1	-1	-1	-1	0	1	-1	-1
Increased likelihood of inbreeding	-1	0	-1	0	-1	-1	0	0
Increased risk of extinction of endangered species	-1	-1	-1	-1	0	0	-1	-1
Ecosystem Homogenization	-1	1	-1	1	-1	-1	0	0
Loss of complexity and increased risk of food-chain and nutrient-cycle homogenization	-1	-1	-1	-1	-1	1	-1	-1
Loss of Habitat	1	-1	1	-1	-1	1	-1	-1
Loss of treatment opportunities (traditional and modern medicine) and cures	0	0	0	0	0	1	-1	-1
Decrease in food security	-1	-1	-1	-1	0	1	-1	-1
Potential increase in Jaccard Index (>0.6)	-1	-1	0	-1	0	-1	-1	-1
Decreased air purification	-1	-1	-1	-1	0	1	-1	-1
Increase in carbon emissions due to potential sequestration loss	-1	-1	-1	-1	-1	1	-1	-1
Reduction in pollination	-1	0	-1	0	0	1	-1	-1
Reduced maintenance of genetic resources as key inputs to crop varieties and livestock breeds, medicines, and other products	1	-1	1	-1	-1	0	-1	-1
Endangerment of native species	-1	-1	-1	-1	-1	0	-1	-1
Increased risk of deforestation	0	0	0	0	0	1	-1	-1
Increased risk of animal and plant trade	-1	1	-1	1	0	-1	-1	-1
Creation of monocultured ecosystem	-1	0	-1	1	0	-1	0	0
Proliferation of pests	1	1	1	1	1	-1	-1	-1
Threats to food security of predators	-1	0	-1	0	1	1	-1	-1
Soil degradation	-1	-1	-1	-1	-1	1	-1	-1
Damage to existing root structures	1	0	1	0	0	1	-1	-1
Total Score	**-12**	**-9**	**-11**	**-8**	**-7**	**7**	**-19**	**-19**
Normalized Score	**-0.63**	**-0.47**	**-0.58**	**-0.42**	**-0.37**	**0.37**	**-1.00**	**-1.00**
Ranking (Least-Most Harmful Harvest Scenario)	6	4	5	3	2	1	8	7

Table A2: Scoring based on above identified effects, and normalization for each harvest scenarios

Biodiversity Indexing	
Effects	**Score Assigned**
Positive Impact	1
No Impact	0
Negative Impact	-1

APPENDIX – A3

Vulnerability Factors \ Harvest Scenarios	Existing managed Forest or Plantation				Salvage	Afforestation and transition to plantation	Uncategorized/ assumed Forest Clearing with or without replanting	
	Broadleaf Stem Wood (including coppice) [1]	Broadleaf Residue [2]	Conifer Stem Wood [3]	Conifer Residue [4]	Broadleaf, Conifer [5]	Broadleaf, Conifer [6]	Broadleaf [7]	Conifer [8]
Top-Down Trophic Cascades	(Pace et al., 1999) (Letourneau & Dyer, 1998a)	(Camia et al., 2021)	(Pace et al., 1999)	(Camia et al., 2021)	(Camia et al., 2021)	Assumption	(Sennet, 2018)	(Sennet, 2018)
Bottom-up trophic cascades	(Pace et al., 1999) (Letourneau & Dyer, 1998b)	(Giuntoli et al., 2015)	(Pace et al., 1999) (McLaren & Peterson, 1994)	(Giuntoli et al., 2015)	Assumption	Assumption	(Sennet, 2018)	(Sennet, 2018)
Increased likelihood of inbreeding	(Savolainen & Kärkkäinen, 1992)	Assumption	(Savolainen & Kärkkäinen, 1992)	Assumption	(Camia et al., 2021)	(Jiang et al., 2016)	Assumption	Assumption
Increased risk of extinction of endangered species	(Abdallah & Lasserre, 2007)	(Peter & Harrington, 2018)	(Abdallah & Lasserre, 2007)	(Peter & Harrington, 2018)	Assumption	Assumption	(Camia et al., 2021)	(Camia et al., 2021)
Ecosystem Homogenization	(Vellend et al., 2007)	(Peter & Harrington, 2018)	(Vellend et al., 2007)	(Peter & Harrington, 2018)	(Camia et al., 2021)	(Jiang et al., 2016)	Assumption	Assumption
Loss of complexity and increased risk of food-chain and nutrient-cycle homogenization	(de Jong et al., 2022)	(Ranius et al., 2018)	(de Jong et al., 2022)	(Ranius et al., 2018)	(Leverkus et al., 2015)	(Pierre et al., 2016)	(Bringhurst & Jordan, 2015)	(Bringhurst & Jordan, 2015)
Loss of Habitat	(European Forest Institue, 2021)	(Ranius et al., 2018)	(European Forest Institue, 2021)	(Ranius et al., 2018)	(Camia et al., 2021)	(Bodo et al., 2021)	(Camia et al., 2021)	(Camia et al., 2021)
Loss of treatment opportunities (traditional and modern medicine) and cures	Assumption	Assumption	Assumption	Assumption	Assumption	(Vedavathy, 2003)	(Abba et al., 2020)2/27/23 2:56:00 PM	(Bhardwaj et al., 2021)
Decrease in food security	(FAO, 2013)	(Ranius et al., 2018)	(FAO, 2013)	(Ranius et al., 2018)	Assumption	(Smith et al., 2013)	(Olagunju, 2015)	(Demessie et al., 2015)
Potential increase in Jaccard Index (>0.6)	(Silva et al., 2022)	(Hao et al., 2019)	(Weill, 2020)	(Hao et al., 2019)	Assumption	(Jiang et al., 2016)	Assumption	Assumption
Decreased air purification	(Nowak et al., 2014)	(Ranius et al., 2018)	(Nowak et al., 2014)	(Ranius et al., 2018)	(Leverkus et al., 2015)	(Cerasoli et al., 2021)	(Camia et al., 2021)	(Camia et al., 2021)
Increase in carbon emissions due to potential sequestration loss	(Nowak et al., 2014)	(Ranius et al., 2018)	(Nowak et al., 2014)	(Ranius et al., 2018)	(Leverkus et al., 2015)	(Cerasoli et al., 2021)	(Camia et al., 2021)	(Camia et al., 2021)
Reduction in pollination	(Krishnan et al., 2020)	(Ranius et al., 2018)	(Krishnan et al., 2020)	(Ranius et al., 2018)	(Heil & Burkle, 2019)	(Krishnan et al., 2020)	(Priess et al., 2007)	(Osborne et al., 1991)
Reduced maintenance of genetic resources as key inputs to crop varieties and livestock breeds, medicines, and other products	(FAO, 2020)	(Aravanopoulos, 2018)	(FAO, 2020)	(Aravanopoulos, 2018)	(Thorn et al., 2018)	(FAO, 2020)	Assumption	Assumption
Endangerment of native species	(Kuuluvainen et al., 2021)	Assumption	(Kuuluvainen et al., 2021)	(Peter & Harrington, 2018)	(Thorn et al., 2018)	(Hoffmann, 2004)	(Camia et al., 2021)	(Camia et al., 2021)
Increased risk of deforestation	Assumption	Assumption	Assumption	Assumption	Assumption	Assumption	Assumption	Assumption
Increased risk of animal and plant trade	Assumption	(Ranius et al., 2018)	Assumption	(Ranius et al., 2018)	Assumption	(Jiang et al., 2016)	(Boekhout van Solinge, 2013)	(Boekhout van Solinge, 2013)
Creation of monocultured ecosystem	(Fischer, 2019)	Assumption	(Kriegel et al., 2021)	(Kriegel et al., 2021)	Assumption	(Jiang et al., 2016)	(Hossain et al., 2013)	(Egenolf et al., 2021)
Proliferation of pests	(Klapwijk et al., 2016)	(Ranius et al., 2018)	(Klapwijk et al., 2016)	(Ranius et al., 2018)	(Camia et al., 2021)	(Jiang et al., 2016)	(Kurukulasuriya & Rosenthal, 2013)	(Alba-Sánchez et al., 2019)
Threats to food security of predators	(Chaudhary et al., 2016)	Assumption	(Chaudhary et al., 2016)	Assumption	(Leverkus et al., 2021)	Assumption	(Camia et al., 2021)	(Camia et al., 2021)
Soil degradation	(Chaudhary et al., 2016)	(Ranius et al., 2018)	(Chaudhary et al., 2016)	(Ranius et al., 2018)	(Lucas-Borja et al., 2020)	(Oldfield et al., 2014)	(Camia et al., 2021)	(Camia et al., 2021)
Damage to existing root structures	(Ravenek et al., 2014)	(Ravenek et al., 2014)	(Ravenek et al., 2014)	(Ravenek et al., 2014)	(Ravenek et al., 2014)	(Ravenek et al., 2014)	(Ravenek et al., 2014)	(Ravenek et al., 2014)

Table A3: References for table A1

Appendix B - Matching Payback Periods to Harvest Scenarios

KEY MAPPING HARVEST SCENARIO TO FIGURES FROM LITERATURE							
Harvest Scenario as defined in this paper		**Description of Scenario from Literature**	**Source**	**Gas Payback Period**	**Coal Payback Period**	**AVG GAS**	**AVG COAL**
Existing Forest or Plantation	Broadleaf Stemwood	Payback period for coppice willows replacing natural gas for heating : 18-22 years [4]	Mckinney, et. al 2011	24	-	33.50	32.00
		Study of UK use in CHP, payback period slightly over 40 years for the whole powersystem [6]	(Agostini, 2014)	43	32		
	Broadleaf Residue	Harvest Residues weighted for broadleaf/conifer. Conterfactual: left on forest floor (20 yr power/coal ; 50yr heat /NG ; >100yr power/NG)[5]	(Laganière et al., 2017)	38	12	29.00	12.00
		11.5% residue decay rate replacing natural gas heat and power	(Giuntoli et. al. 2015)	20	-		
	Conifer Stemwood	Softwood high productive plantation with medium management intensity (including fertilization) biomass combustion efficiency 41%. Counterfactual: nor harvest of plantation [2]	(Jonker, 2013)	-	27	42.00	22.33
		Additional harvest of managed forests (20-30% MAI -> 60%) (22yr heat/coal ; 27 heat/NG ; 75 power/ng)	(Walker, 2010 ; Agostini, 2014)	42	22		
		Average of shortleaf loblolly pine and longleaf slash pine inj managed plantaions in the south central and southeastern US	(Rolls & Forster, 2020)	-	18		
	Conifer Residue	Harvest Residues weighted for broadleaf/conifer. Conterfactual: left on forest floor (12 yr power/coal ; 27yr heat /NG ; >100yr power/NG)	Lagniere et. al 2017	38	12	39.00	14.00
		Additional wood harvest. Counterfactual: BAU for wood products	(McKechnie, 2011)	-	16		
		3-6%/ year decay rate replacing natural gas heat and power [3]	(JRC, 2021)	40	-		
Afforestation	ALL	Short rotation plantation on Marginal Agricultural land with low carbon stock	(Zanchi, 2011)	0	0	0.00	0.00
		Afforesting post-agricultural land	(Mitchell, 2012)	0	0		
Salvage	ALL	Salvaged coniferous standing trees killed by natural disturbance counter factual left to decompose (85:15 - Heat:Power) [2]	(Laganière et al., 2017)	100	63	100.00	63.00
Forest Clearing	Conifer	Forest Clearing – Substitution with short high productivity plantation. Wood for bioenergy	(Zanchi, 2011)	15	17	85.75	68.50
		Forest Clearing – Substitution with short low productivity plantation (10 year rotation. Wood for bioenergy	(Zanchi, 2011)	108	114		
		Green Trees (living biomass Stemwood only) 45yr Mean Annual Increment (MAI) (85:15 Heat:Power)	(Laganière et al., 2017)	100	78		
		Oak-Hickory Clear cut and Converted to short leaf loblolly pine plantation	(Sterman et. al. 2018; JRC, 2021)	120	65		
	Broadleaf	Forest Clearing – Substitution with short low productivity plantation (20 yr rotation). Wood for bioenergy	(Zanchi, 2011)	108	114	114.00	89.50
		Oak-Hickory Clear cut and Converted to short leaf loblolly pine plantation	(Sterman et. al. 2018; JRC, 2021)	120	65		

(Footnotes on Page 79)

Appendix B - Matching Payback Periods to Harvest Scenarios

(Footnotes)

[1] (JRC, 2019)
[2] Softwood is considered analogous to Coniferous.
[3] Broadleaf residues generally have a higher decomposition rate than coniferous (Zhang, 2020)
[4] Payback period of natural gas for electricity assumed at 50 years following ratio of 1:2.5 (see Lagniere, 2017)
[5] Lower bounds on the likely range were taken to account for the much lower payback period of residues whose counterfactual is roadside burning. Little data is available on the extent of this practice in Europe.
[6] Overall payback period of slightly over 43 years has been disaggregated here for illustration of gas and coal contribution.

Appendix C - Full Synthesis of Carbon and Biodiversity Impacts with Normalized Impact Indices and Examples of Decision Weights

IMPACT SYNTHESIS

IMPACTS						2015						2030 BAU Silvicultural Practice / Low Rollout (RED I Targets) [5]						2030 High Mobilization / High Rollout (RED II Targets)				
Harvest Scenario		CARBON IMPACT INDEXED 10YR TH	CARBON IMPACT INDEXED 50YR TH	BIODIVERSITY IMPACT COUNT		Share of Primary Woody Sources (%)	Woody Biomass Flow for Energy (M m3)	Carbon Impact 10YR ***FLOW WEIGHTED*** [10]	Carbon Impact 50yr *FLOW WEIGHTED* [10]	BIODIVERSITY IMPACT *FLOW WEIGHTED*		Share of Primary Woody Sources (%)	Woody Biomass Flow for Energy (M m3)	Carbon Impact 10YR ***FLOW WEIGHTED*** [10]	Carbon Impact 50yr *FLOW WEIGHTED* [10]	BIODIVERSITY IMPACT *FLOW WEIGHTED*		Share of Primary Woody Sources (%)	Woody Biomass Flow for Energy (M m3)	Carbon Impact 10YR ***FLOW WEIGHTED*** [10]	Carbon Impact 50yr *FLOW WEIGHTED* [10]	BIODIVERSITY IMPACT *FLOW WEIGHTED*
Existing managed Forest or Plantation	Broadleaf Stemwood (including coppice) [2]	-0.33	0.4	-0.63		16.6	37	-12.33	14.8	-23.37		15.14	71.00	-23.67	28.40	-44.84		23.10	137.00	-45.67	54.80	-86.53
	Broadleaf Residue [3]	-0.17	0.6	-0.47		6.3	14	-2.33	8.4	-6.63		4.90	23.00	-3.83	13.80	-10.89		7.25	43.00	-7.17	25.80	-20.37
	Conifer Stemwood	-0.33	0.4	-0.58		16.6	37	-12.33	14.8	-21.42		14.93	70.00	-23.33	28.00	-40.53		23.10	137.00	-45.67	54.80	-79.32
	Conifer Residue	-0.33	0.4	-0.42		20.2	45	-15.00	18	-18.95		19.19	90.00	-30.00	36.00	-37.89		29.01	172.00	-57.33	68.80	-72.42
Salvage	Conifer, Broadleaf	-1.00	-0.4	-0.37		8.1	18	-18.00	-7.2	-6.63		20.26	95.00	-95.00	-38.00	-35.00		14.00	83.00	-83.00	-33.20	-30.58
Afforestation and transition to plantation [1,4]	Broadleaf, Conifer	0.17	1.0	0.37		9.4	21	3.50	21	7.74		4.48	21.00	3.50	21.00	7.74		3.54	21.00	3.50	21.00	7.74
Uncategorized/ assumed Forest Clearing with or without replanting	Conifer	-0.83	-0.2	-1.00		17.5	39	-32.50	-7.8	-39.00		16.84	79.00	-65.83	-15.80	-79.00		-	-	-	-	-
	Broadleaf	-1.00	-0.4	-1.00		5.4	12	-12.00	-4.8	-12.00		4.3	20	-20	-8	-20		-	-	-	-	-
					TOTAL	100.0	223	-	-	-		100	469					100.0	593			
					NORMALIZED AND Volume Weighted IMPACT			-101.00	57.2	-120.26				-258.17	65.40	-260.42				-235.33	192.00	-281.47
					Decision Weights			2	10	2.5				2	10	2.5				2	10	2.5
					THE "IMPORTANCE" OF EACH IMPACT (AS FOR DECISION MAKERS			-202	572	-300.6578947	69.3			-516.3333333	654	-651.0526316	-513			-470.6666667	1920	-703.6842105

1 Considered the amount of harvest deriving from area afforested in the last 5 years prior to harvest and a linear increase of 0.5 Mha/yr and 5.2 Mm3/Mha "used" forest (JRC, 2021 ; Forsell et al. 2016)

2 All coppice is considered broadleaf (JRC, 2021 ; Jonsson 2018)

3 Residual wood is broken up proportionally to the total blend of broadleaf and coniferous harvests

4 Afforested land 2015-2025 split between Broadleaf coppice and Coniferous Stemwood plantations at a ratio of 20:80

5 "Uncategorized" sources have been eliminated, with increased coppice harvests limited to a portion of afforested lands. The remaineder is left to coniferous harvests of stemwoods and residues.

REFERENCES

Abba, K., Umar, H., & Mohammed Abba, H. (2020). *Impact of Medicinal Plants and Deforestation on Communities in Wawa -Zange Forest Reserve, Gombe State, Nigeria*.

Abdallah, S. B., & Lasserre, P. (2007). Endangered species, real options, and forest management. *PAMM*, *7*(1), 1080803–1080804. https://doi.org/10.1002/pamm.200701097

Abdollahnejad, A., & Panagiotidis, D. (2020). Tree Species Classification and Health Status Assessment for a Mixed Broadleaf-Conifer Forest with UAS Multispectral Imaging. *Remote Sensing*, *12*(22), Article 22. https://doi.org/10.3390/rs12223722

Agostini, A., Giuntoli, J., Marelli, L., & Amaducci, S. (2020). Flaws in the interpretation phase of bioenergy LCA fuel the debate and mislead policymakers. *The International Journal of Life Cycle Assessment*, *25*(1), 17–35. https://doi.org/10.1007/s11367-019-01654-2

Agostini, A., Marelli, L., Giuntoli, J., & Boulamanti, A. (2014). *Carbon accounting of forest bioenergy: Conclusions and recommendations from a critical literature review*. Publications Office of the European Union. https://data.europa.eu/doi/10.2788/29442

Alba-Sánchez, F., López-Sáez, J. A., Abel-Schaad, D., Sabariego Ruiz, S., Pérez-Díaz, S., González-Hernández, A., & Linares, J. C. (2019). The impact of climate and land-use changes on the most southerly fir forests (Abies pinsapo) in Europe. *The Holocene*, *29*(7), 1176–1188. https://doi.org/10.1177/0959683619838043

Aljbory, Z., & Chen, M.-S. (2018). Indirect plant defense against insect herbivores: A review. *Insect Science*, *25*(1), 2–23. https://doi.org/10.1111/1744-7917.12436

Ameray, A., Bergeron, Y., Valeria, O., Montoro Girona, M., & Cavard, X. (2021). Forest Carbon Management: A Review of Silvicultural Practices and Management Strategies Across Boreal, Temperate and Tropical Forests. *Current Forestry Reports*, *7*(4), 245–266. https://doi.org/10.1007/s40725-021-00151-w

Applequist, W. L., Brinckmann, J. A., Cunningham, A. B., Hart, R. E., Heinrich, M., Katerere, D. R., & Andel, T. van. (2020). Scientists' Warning on Climate Change and Medicinal Plants. *Planta Medica*, *86*(1), 10–18. https://doi.org/10.1055/a-1041-3406

Aravanopoulos, F. A. (Phil). (2018). Do Silviculture and Forest Management Affect the Genetic Diversity and Structure of Long-Impacted Forest Tree Populations? *Forests*, *9*(6), Article 6. https://doi.org/10.3390/f9060355

Ballogh, A. (2021, December 13). *The rise and fall of monoculture farming | Research and Innovation*. https://ec.europa.eu/research-and-innovation/en/horizon-magazine/rise-and-fall-monoculture-farming

Barlow, J., Ewers, R. M., Anderson, L., Aragao, L. E. O. C., Baker, T. R., Boyd, E., Feldpausch, T. R., Gloor, E., Hall, A., Malhi, Y., Milliken, W., Mulligan, M., Parry, L., Pennington, T., Peres, C. A., Phillips, O. L., Roman-Cuesta, R. M., Tobias, J. A., & Gardner, T. A. (2011). Using learning networks to understand complex systems: A case study of biological, geophysical and social research in the Amazon. *Biological Reviews*, *86*(2), 457–474. https://doi.org/10.1111/j.1469-185X.2010.00155.x

Bernards, D. M. (2022, December 7). *Adaptation or extinction: What climate change and land use mean for biodiversity*. Aktuelles aus der Goethe-Universität Frankfurt. https://aktuelles.uni-frankfurt.de/news-in-brief/adaptation-or-extinction-what-climate-change-and-land-use-mean-for-biodiversity/

Bhardwaj, K., Silva, A. S., Atanassova, M., Sharma, R., Nepovimova, E., Musilek, K., Sharma, R., Alghuthaymi, M. A., Dhanjal, D. S., Nicoletti, M., Sharma, B., Upadhyay, N. K., Cruz-Martins, N., Bhardwaj, P., & Kuča, K. (2021). Conifers Phytochemicals: A Valuable Forest with Therapeutic Potential. *Molecules*, *26*(10), 3005. https://doi.org/10.3390/molecules26103005

BioEnergy Europe. (2023). *About bioenergy*. https://bioenergyeurope.org/about-bioenergy.html

Bodo, T., Gimah, B. G., & Seomoni, K. J. (2021). Deforestation and Habitat Loss: Human Causes, Consequences and Possible Solutions. *Journal of Geographical Research*, *4*(2), Article 2. https://doi.org/10.30564/jgr.v4i2.3059

Boekhout van Solinge, T. (2013). Equatorial deforestation as a harmful practice and a criminological issue. In *Global Environmental Harm* (pp. 20–36). Willan. https://doi.org/10.4324/9781843927983-3

Bringhurst, K., & Jordan, P. (2015). The impact on nutrient cycles from tropical forest to pasture conversion in Costa Rica. *Sustainable Water Resources Management*, *1*(1), 3–13. https://doi.org/10.1007/s40899-015-0003-x

Brown, A. R., Hosken, D. J., Balloux, F., Bickley, L. K., LePage, G., Owen, S. F., Hetheridge, M. J., & Tyler, C. R. (2009). Genetic variation, inbreeding and chemical exposure—Combined effects in wildlife and critical considerations for ecotoxicology. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1534), 3377–3390. https://doi.org/10.1098/rstb.2009.0126

Camia, A., Giuntoli, J., Jonsson, K., Robert, N., Cazzaniga, N., Jasinevičius, G., Avitabile, V., Grassi, G., Barredo, C. J. I., & Mubareka, S. (2021, January 25). *The use of woody biomass for energy production in the EU*. JRC Publications Repository. https://doi.org/10.2760/831621

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., Narwani, A., Mace, G. M., Tilman, D., Wardle, D. A., Kinzig, A. P., Daily, G. C., Loreau, M., Grace, J. B., Larigauderie, A., Srivastava, D. S., & Naeem, S. (2012). Biodiversity loss and its impact on humanity. *Nature*, *486*(7401), Article 7401. https://doi.org/10.1038/nature11148

Cerasoli, S., Yin, J., & Porporato, A. (2021). Cloud cooling effects of afforestation and reforestation at midlatitudes. *Proceedings of the National Academy of Sciences*, *118*(33), e2026241118. https://doi.org/10.1073/pnas.2026241118

Chaudhary, A., Burivalova, Z., Koh, L. P., & Hellweg, S. (2016). Impact of Forest Management on Species Richness: Global Meta-Analysis and Economic Trade-Offs. *Scientific Reports*, *6*(1), Article 1. https://doi.org/10.1038/srep23954

Climate Action (2023a, February 23). European Climate Law. Retrieved from https://climate.ec.europa.eu/eu-action/european-green-deal/european-climate-law_en

Climate Action (2023b, February 24). 2020 climate & energy package. Retrieved from https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2020-climate-energy-package_en

Climate Action (2023c, February 24). 2030 climate & energy framework. Retrieved from https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2030-climate-energy-framework_en

Collins, K. (2021, July 28). Why Is The Amazon Rainforest So Important? *Medium*. https://karinacollins.medium.com/why-is-the-amazon-rainforest-so-important-895e8c0d55b7

Commisision Staff Working Document Impact Assessment. (2016). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52016SC0249&from=EN

Cox, P. A., Banack, S. A., Murch, S. J., Rasmussen, U., Tien, G., Bidigare, R. R., Metcalf, J. S., Morrison, L. F., Codd, G. A., & Bergman, B. (2005). Diverse taxa of cyanobacteria produce beta-N-methylamino-L-alanine, a neurotoxic amino acid. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(14), 5074–5078. https://doi.org/10.1073/pnas.0501526102

Crenna, E., Marques, A., La Notte, A., & Sala, S. (2020). Biodiversity Assessment of Value Chains: State of the Art and Emerging Challenges. *Environmental Science & Technology*, *54*(16), 9715–9728. https://doi.org/10.1021/acs.est.9b05153

Daily, G., Alexander, S., Ehrlich, P., Goulder, L., Lubchenco, J., Matson, P., Mooney, H., Postel, S., Schneider, S., Tilman, D., & Woodwell, G. (2007). *ECOSYSTEM SERVICES: Benefits Supplied to Human Societies by Natural Ecosystems*. https://www.semanticscholar.org/paper/ECOSYSTEM-SERVICES%3A-Benefits-Supplied-to-Human-by-Daily-Alexander/48273bf32f860b4350ed16164e602ba4c94a2de4

de Jong, A., de Vries, W., Kros, H., & Spijker, J. (2022). Impacts of harvesting methods on nutrient removal in Dutch forests exposed to high-nitrogen deposition. *Annals of Forest Science*, *79*(1), 33. https://doi.org/10.1186/s13595-022-01149-5

Demessie, A., Singh, B. R., & Lal, R. (2015). Land Degradation and Soil Carbon Pool in Different Land Uses and Their Implication for Food Security in Southern Ethiopia. In R. Lal, B. R. Singh, D. L. Mwaseba, D. Kraybill, D. O. Hansen, & L. O. Eik (Eds.), *Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa* (pp. 45–62). Springer International Publishing. https://doi.org/10.1007/978-3-319-09360-4_3

Díaz, S., Fargione, J., Iii, F. S. C., & Tilman, D. (2006). Biodiversity Loss Threatens Human Well-Being. *PLOS Biology*, *4*(8), e277. https://doi.org/10.1371/journal.pbio.0040277

Dornelas, M., Gotelli, N. J., McGill, B., Shimadzu, H., Moyes, F., Sievers, C., & Magurran, A. E. (2014). Assemblage Time Series Reveal Biodiversity Change but Not Systematic Loss. *Science*, *344*(6181), 296–299. https://doi.org/10.1126/science.1248484

Duncker, P., Raulund-Rasmussen, K., Gundersen, P., Katzensteiner, K., Jong, J., Ravn, H., Smith, M., Eckmüllner, O., Spiecker, H., Duncker, P., Raulund-Rasmussen, K., Gundersen, P., Katzensteiner, K., Jong, J., Ravn, H., Smith, M., Eckmüllner, O., & Spiecker, H. (2012). How Forest Management affects Ecosystem Services, including Timber Production and Economic Return: Synergies and Trade-Offs. *Ecology and Society*, *17*. https://doi.org/10.5751/ES-05066-170450

EC. (2018). *Biomass*. https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/biomass_en

Egenolf, V., Vita, G., Distelkamp, M., Schier, F., Hüfner, R., & Bringezu, S. (2021). The Timber Footprint of the German Bioeconomy—State of the Art and Past Development. *Sustainability*, *13*(7), Article 7. https://doi.org/10.3390/su13073878

Ellis, P. W., Gopalakrishna, T., Goodman, R. C., Putz, F. E., Roopsind, A., Umunay, P. M., Zalman, J., Ellis, E. A., Mo, K., Gregoire, T. G., & Griscom, B. W. (2019). Reduced-impact logging for climate change mitigation (RIL-C) can halve selective logging emissions from tropical forests. *Forest Ecology and Management*, *438*, 255–266. https://doi.org/10.1016/j.foreco.2019.02.004

Emmerson, M., Morales, M. B., Oñate, J. J., Batáry, P., Berendse, F., Liira, J., Aavik, T., Guerrero, I., Bommarco, R., Eggers, S., Pärt, T., Tscharntke, T., Weisser, W., Clement, L., & Bengtsson, J. (2016). How Agricultural Intensification Affects Biodiversity and Ecosystem Services. In *Advances in Ecological Research* (Vol. 55, pp. 43–97). Elsevier. https://doi.org/10.1016/bs.aecr.2016.08.005

Environment (2023, February 25). Biodiversity strategy for 2030. Retrieved from https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en

Estes, J. A., Terborgh, J., Brashares, J. S., Power, M. E., Berger, J., Bond, W. J., Carpenter, S. R., Essington, T. E., Holt, R. D., Jackson, J. B. C., Marquis, R. J., Oksanen, L., Oksanen, T., Paine, R. T., Pikitch, E. K., Ripple, W. J., Sandin, S. A., Scheffer, M., Schoener, T. W., … Wardle, D. A. (2011). Trophic downgrading of planet Earth. *Science (New York, N.Y.)*, *333*(6040), 301–306. https://doi.org/10.1126/science.1205106

Eugen, R., & Cojinovschi, A.-D. (2014). Structural Dynamics of Romanian Forests after 1990. *Present Environment and Sustainable Development*, *8*. https://doi.org/10.2478/pesd-2014-0002

European Comission. (n.d.). *Biodiversity strategy for 2030*. Environment. https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en

European Commission (2023, February 25). A European Green Deal. Retrieved from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

European Commission. (2021). *Energy systems evaluation. (Volume 1), Sustainability assessment*. Springer.

European Commission. (n.d.a). *2030 Climate Target Plan*. https://climate.ec.europa.eu/eu-action/european-green-deal/2030-climate-target-plan_en

European Commission. (n.d.b). *National action plans and annual progress reports (NREAPs)*. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/national-action-plans-and-annual-progress-reports_en

European Commission. Directorate General for Environment., Arcadis., IEEP., Birdlife., Stella., Niras., & Ecosystems Ltd. (2020). *Potential impacts of bioenergy developments on habitats and species protected under the birds and habitats directives: final report.* Publications Office. https://data.europa.eu/doi/10.2779/614742

European Commission. Joint Research Centre. (2019). *Brief on biomass for energy in the European Union.* Publications Office. https://data.europa.eu/doi/10.2760/546943

European Commission. Joint Research Centre. (2021a). *Environmental sustainability of energy generation from forest biomass*. https://joint-research-centre.ec.europa.eu/jrc-news/environmental-sustainability-energy-generation-forest-biomass-2021-01-26_en

European Commission. Joint Research Centre. (2021b). *The use of woody biomass for energy production in the EU.* Publications Office. https://data.europa.eu/doi/10.2760/831621

European Forest Institue. (2021). *What are the key factors affecting forest biodiversity? | European Forest Institute*. https://efi.int/forestbiodiversity/factors

European Union. (n.d.). *National energy and climate plans (NECPs)*. https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en

Eurostat. (n.d.). *Database*. https://ec.europa.eu/eurostat/web/main/data/database

Eurostat. (n.d.). *Shares (Renewables)*. Eurostat. https://ec.europa.eu/eurostat/web/energy/data/shares

Faith, D. P. (2021). Biodiversity. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy* (Spring 2021). Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/spr2021/entries/biodiversity/

FAO. (2013, May 15). *Forests and trees outside forests are essential for global food security and nutrition*. International Conference on Forests for Food Security and Nutrition, Rome, Italy. https://www.fao.org/3/aq110e/aq110e.pdf

FAO. (2015). *Climate change and food security: Risks and responses*.

FAO. (2020). *Global Forest Resources Assessment 2020: Main report*. FAO. https://doi.org/10.4060/ca9825en

FAO. (2020). *Indicators of the genetic diversity of trees – State, pressure, benefit and response. The State of the World's Forest Genetic Resources – Thematic study |Policy Support and Governance| Food and Agriculture Organization of the United Nations*. http://www.fao.org/3/cb2492en/CB2492EN.pdf

Favero, A., Daigneault, A., & Sohngen, B. (2020). Forests: Carbon sequestration, biomass energy, or both? *Science Advances*, *6*(13), eaay6792. https://doi.org/10.1126/sciadv.aay6792

FDA. (2022). New Report Shows Biomass Industry Is Lighting Facts on Fire With Sustainability Claims. *Forest Defenders Alliance*. https://forestdefenders.eu/new-report-shows-biomass-industry-is-lighting-facts-on-fire-with-sustainability-claims/

Fischer, M. (2019, April 18). Mixed forests are more productive. *Naturwald Akademie*. https://naturwald-akademie.org/studies/mixed-forests-are-more-productive/

Fit for 55 (2023a, February 25). Retrieved from https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

Fit for 55: how the EU plans to boost renewable energy (2023b, February 25). Retrieved from https://www.consilium.europa.eu/en/infographics/fit-for-55-how-the-eu-plans-to-boost-renewable-energy/

Fit for 55: reaching climate goals in the land use and forestry sectors (2023c, February 25). Retrieved from https://www.consilium.europa.eu/en/infographics/fit-for-55-lulucf-land-use-land-use-change-and-forestry/

Fit for 55: reform of the EU emissions trading system (2023d, February 25). Retrieved from https://www.consilium.europa.eu/en/infographics/fit-for-55-eu-emissions-trading-system/

Fletcher, S., & Islam, M. Z. (2018). Comparing sets of patterns with the Jaccard index. *Australasian Journal of Information Systems*, *22*. https://doi.org/10.3127/ajis.v22i0.1538

Forest Europe. (n.d.). *Sustainable Forest Management*. Forest Europe Growing Life. https://foresteurope.org/workstreams/sustainable-forest-management/

Forsell, N., Korosuo, A., Havlik, P., & Valin, H. (2016). *Study on impacts on resource efficiency of future EU demand for bioenergy*. https://pure.iiasa.ac.at/id/eprint/14009/1/Task%203.pdf

Frank, S., Böttcher, H., Gusti, M., Havlík, P., Klaassen, G., Kindermann, G., & Obersteiner, M. (2016). Dynamics of the land use, land use change, and forestry sink in the European Union: The impacts of energy and climate targets for 2030. *Climatic Change*, *138*(1), 253–266. https://doi.org/10.1007/s10584-016-1729-7

Fuller, R. J. (1992). Effects of coppice management on woodland breeding birds. In G. P. Buckley (Ed.), *Ecology and Management of Coppice Woodlands* (pp. 169–192). Springer Netherlands. https://doi.org/10.1007/978-94-011-2362-4_9

Gardner, T. A., Ferreira, J., Barlow, J., Lees, A. C., Parry, L., Vieira, I. C. G., Berenguer, E., Abramovay, R., Aleixo, A., Andretti, C., Aragão, L. E. O. C., Araújo, I., de Ávila, W. S., Bardgett, R. D., Batistella, M., Begotti, R. A., Beldini, T., de Blas, D. E., Braga, R. F., … Zuanon, J. (2013). A social and ecological assessment of tropical land uses at multiple scales: The Sustainable Amazon Network. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *368*(1619), 20120166. https://doi.org/10.1098/rstb.2012.0166

Giuntoli, J., & Searle, S. (2019). *Does Bioenergy Demand Improve Forest Management?* https://theicct.org/sites/default/files/publications/ICCT_bioenergy_demand_20190719.pdf

Giuntoli, J., Agostini, A., Caserini, S., Lugato, E., Baxter, D., & Marelli, L. (2016). Climate change impacts of power generation from residual biomass. *Biomass and Bioenergy*, *89*, 146–158. https://doi.org/10.1016/j.biombioe.2016.02.024

Giuntoli, J., Barredo, J. I., Avitabile, V., Camia, A., Cazzaniga, N. E., Grassi, G., Jasinevičius, G., Jonsson, R., Marelli, L., Robert, N., Agostini, A., & Mubareka, S. (2022). The quest for sustainable forest bioenergy: win-win solutions for climate and biodiversity. *Renewable and Sustainable Energy Reviews*, *159*, 112180. https://doi.org/10.1016/j.rser.2022.112180

Giuntoli, J., Caserini, S., Marelli, L., Baxter, D., & Agostini, A. (2015). Domestic heating from forest logging residues: Environmental risks and benefits. *Journal of Cleaner Production*, *99*, 206–216. https://doi.org/10.1016/j.jclepro.2015.03.025

Goodale, C. L., Apps, M. J., Birdsey, R. A., Field, C. B., Heath, L. S., Houghton, R. A., Jenkins, J. C., Kohlmaier, G. H., Kurz, W., Liu, S., Nabuurs, G.-J., Nilsson, S., & Shvidenko, A. Z. (2002). Forest Carbon Sinks in the Northern Hemisphere. *Ecological Applications*, *12*(3), 891–899. https://doi.org/10.1890/1051-0761(2002)012[0891:FCSITN]2.0.CO;2

Haase, M., Baumann, M., Wulf, C., Rösch, C., & Zapp, P. (2021). 4.3 Multikriterielle Analysen zur Entscheidungsunterstützung in der Technikfolgenabschätzung. In S. Böschen, A. Grunwald, B.-J. Krings, & C. Rösch (Eds.), *Technikfolgenabschätzung* (pp. 306–320). Nomos Verlagsgesellschaft mbH & Co. KG. https://doi.org/10.5771/9783748901990-306

Halewood, M., Chiurugwi, T., Sackville Hamilton, R., Kurtz, B., Marden, E., Welch, E., Michiels, F., Mozafari, J., Sabran, M., Patron, N., Kersey, P., Bastow, R., Dorius, S., Dias, S., McCouch, S., & Powell, W. (2018). Plant genetic resources for food and agriculture:

Opportunities and challenges emerging from the science and information technology revolution. *New Phytologist*, *217*(4), 1407–1419. https://doi.org/10.1111/nph.14993

Hao, M., Corral-Rivas, J. J., González-Elizondo, M. S., Ganeshaiah, K. N., Nava-Miranda, M. G., Zhang, C., Zhao, X., & von Gadow, K. (2019). Assessing biological dissimilarities between five forest communities. *Forest Ecosystems*, *6*(1), 30. https://doi.org/10.1186/s40663-019-0188-9

Harfoot, M., Glaser, S. A. M., Tittensor, D. P., Britten, G. L., McLardy, C., Malsch, K., & Burgess, N. D. (2018). Unveiling the patterns and trends in 40 years of global trade in CITES-listed wildlife. *Biological Conservation*, *223*, 47–57. https://doi.org/10.1016/j.biocon.2018.04.017

Hassani, N. J. M. (2018, June 3). Coppice System—Everything You Need to Know about Silvicultural System. *Forestrypedia*. https://forestrypedia.com/coppice-system-detailed-note/

Hebblewhite, M., White, C. A., Nietvelt, C. G., McKenzie, J. A., Hurd, T. E., Fryxell, J. M., Bayley, S. E., & Paquet, P. C. (2005). Human Activity Mediates a Trophic Cascade Caused by Wolves. *Ecology*, *86*(8), 2135–2144. https://doi.org/10.1890/04-1269

Hedrick, P. W. (2005). A standardized genetic differentiation measure. *Evolution; International Journal of Organic Evolution*, *59*(8), 1633–1638.

Heil, L. J., & Burkle, L. A. (2019). The effects of post-wildfire salvage logging on plant reproductive success and pollination in Symphoricarpos albus, a fire-tolerant shrub. *Forest Ecology and Management*, *432*, 157–163. https://doi.org/10.1016/j.foreco.2018.09.013

Helmholtz Working Group MCDA for Sustainability Assessment. (2022). *MCDA for sustainability assessment – insights to Helmholtz Association activities*. https://elib.dlr.de/192296/1/HGF%20-%20MCDA%20for%20sustainability%20assessment%20-%20insights%20to%20Helmholtz%20Association%20activities%20-%202022-11-02.pdf

Hoffmann, J. P. (2004). Social and Environmental Influences on Endangered Species: A Cross-National Study. *Sociological Perspectives*, *47*(1), 79–107. https://doi.org/10.1525/sop.2004.47.1.79

Holtsmark, B. (2012). Harvesting in boreal forests and the biofuel carbon debt. *Climatic Change*, *112*(2), 415–428. https://doi.org/10.1007/s10584-011-0222-6

Hooper, D. U., Chapin III, F. S., Ewel, J. J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J. H., Lodge, D. M., Loreau, M., Naeem, S., Schmid, B., Setälä, H., Symstad, A. J., Vandermeer, J., & Wardle, D. A. (2005). Effects of Biodiversity on Ecosystem Functioning: A Consensus of Current Knowledge. *Ecological Monographs*, *75*(1), 3–35. https://doi.org/10.1890/04-0922

Hossain, M. N., Rokanuzzaman, M., Rahman, M. A., Bodiuzzaman, M., & Miah, M. A. (2013). Causes of Deforestation and Conservation of Madhupur Sal Forest in Tangail Region. *Journal of Environmental Science and Natural Resources*, *6*(2), Article 2. https://doi.org/10.3329/jesnr.v6i2.22105

IEA Bioenergy. (2018). *Is energy from woody biomass positive for the climate?* https://www.ieabioenergy.com/wp-content/uploads/2018/01/FAQ_WoodyBiomass-Climate_final-1.pdf

IEA Bioenergy. (2022). *Annual Report 2021*. https://www.ieabioenergy.com/wp-content/uploads/2022/04/IEA-Bioenergy-Annual-Report-2021.pdf

IEA. (2021). *Implementation of bioenergy in the European Union – 2021 update*. https://www.ieabioenergy.com/wp-content/uploads/2021/11/CountryReport2021_EU28_final.pdf

IPCC. (2014). *Annex III Technology-specific Cost and Performance Parameters*. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf

IPCC. (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

IRENA. (2018). *Renewable Energy Prospects for the European Union*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Feb/IRENA_REmap_EU_2018.pdf

Jetz, W., Wilcove, D. S., & Dobson, A. P. (2007). Projected Impacts of Climate and Land-Use Change on the Global Diversity of Birds. *PLOS Biology*, *5*(6), e157. https://doi.org/10.1371/journal.pbio.0050157

Jiang, W., Yang, S., Yang, X., & Gu, N. (2016). Negative impacts of afforestation and economic forestry on the Chinese Loess Plateau and proposed solutions. *Quaternary International*, *399*, 165–173. https://doi.org/10.1016/j.quaint.2015.04.011

Jochem, D., Weimar, H., Bösch, M., Mantau, U., & Dieter, M. (2015). Estimation of wood removals and fellings in Germany: A calculation approach based on the amount of used roundwood. *European Journal of Forest Research*, *134*(5), 869–888. https://doi.org/10.1007/s10342-015-0896-9

Johnson, W. E., Onorato, D. P., Roelke, M. E., Land, E. D., Cunningham, M., Belden, R. C., McBride, R., Jansen, D., Lotz, M., Shindle, D., Howard, J., Wildt, D. E., Penfold, L. M., Hostetler, J. A., Oli, M. K., & O'Brien, S. J. (2010). Genetic restoration of the Florida panther. *Science (New York, N.Y.)*, *329*(5999), 1641–1645. https://doi.org/10.1126/science.1192891

Jonker, J. G. G., Junginger, M., & Faaij, A. (2014). Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States. *GCB Bioenergy*, *6*(4), 371–389. https://doi.org/10.1111/gcbb.12056

Jonsell, M. (2007). Effects on biodiversity of forest fuel extraction, governed by processes working on a large scale. *Biomass and Bioenergy*, *31*, 726–732. https://doi.org/10.1016/j.biombioe.2007.06.018

Jonsson, R., Blujdea, V. N. B., Fiorese, G., Pilli, R., Rinaldi, F., Baranzelli, C., & Camia, A. (2018). Outlook of the European forest-based sector: Forest growth, harvest demand, wood-product markets, and forest carbon dynamics implications. *IForest - Biogeosciences and Forestry*, *11*(2), 315. https://doi.org/10.3832/ifor2636-011

Jonsson, R., Camia, A., & Mubareka, S. (2021). *Analysis of wood resource balance gaps for the EU*. https://doi.org/10.2760/417678

JRC. (2018). *Renewable Energy – Recast to 2030 (RED II)*. https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en

JRC. (2019). *Wood Resource Balances of EU-28 and Member States*. https://core.ac.uk/download/pdf/186491016.pdf

JRC. (2022). *Sankey diagrams of woody biomass flows in the European Union | Knowledge for policy*. https://knowledge4policy.ec.europa.eu/publication/forestry-sankey_en

KKIENERM. (2019, September 1). *Wildlife, Forest & Fisheries Crime Module 1 Key Issues: Implications of Wildlife Trafficking*. //www.unodc.org

Klapwijk, M. J., Bylund, H., Schroeder, M., & Björkman, C. (2016). Forest management and natural biocontrol of insect pests. *Forestry: An International Journal of Forest Research*, *89*(3), 253–262. https://doi.org/10.1093/forestry/cpw019

Klein, A.-M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T. (2006). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences*, *274*(1608), 303–313. https://doi.org/10.1098/rspb.2006.3721

Kriegel, P., Matevski, D., & Schuldt, A. (2021). Monoculture and mixture-planting of non-native Douglas fir alters species composition, but promotes the diversity of ground beetles in a temperate forest system. *Biodiversity and Conservation*, *30*(5), 1479–1499. https://doi.org/10.1007/s10531-021-02155-1

Krishnan, S., Guerra, G., Bertrand, D., Wertz-Kanounnikoff, S., & Kettle, C. (2020). *The pollination services of forests – A review of forest and landscape interventions to enhance their cross-sectoral benefits. Forestry Working Paper No. 15. Rome, FAO & Bioversity International.*

Kulakowski, D., Seidl, R., Holeksa, J., Kuuluvainen, T., Nagel, T. A., Panayotov, M., Svoboda, M., Thorn, S., Vacchiano, G., Whitlock, C., Wohlgemuth, T., & Bebi, P. (2017). A walk on the wild side: Disturbance dynamics and the conservation and management of European mountain forest ecosystems. *Forest Ecology and Management*, *388*, 120–131. https://doi.org/10.1016/j.foreco.2016.07.037

Kurukulasuriya, P., & Rosenthal, S. (2013). *Climate Change and Agriculture: A Review of Impacts and Adaptations*. World Bank. https://openknowledge.worldbank.org/handle/10986/16616

Kuuluvainen, T., Angelstam, P., Frelich, L., Jõgiste, K., Koivula, M., Kubota, Y., Lafleur, B., & Macdonald, E. (2021). Natural Disturbance-Based Forest Management: Moving Beyond Retention and Continuous-Cover Forestry. *Frontiers in Forests and Global Change*, *4*. https://www.frontiersin.org/articles/10.3389/ffgc.2021.629020

Laganière, J., Paré, D., Thiffault, E., & Bernier, P. Y. (2017). Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests. *GCB Bioenergy*, *9*(2), 358–369. https://doi.org/10.1111/gcbb.12327

Letourneau, D. K., & Dyer, L. A. (1998). Density Patterns of Piper Ant-Plants and Associated Arthropods: Top-Predator Trophic Cascades in a Terrestrial System? *Biotropica*, *30*(2), 162–169.

Letourneau, D. K., & Dyer, L. A. (1998a). Density Patterns of Piper Ant-Plants and Associated Arthropods: Top-Predator Trophic Cascades in a Terrestrial System? *Biotropica*, *30*(2), 162–169.

Letourneau, D. K., & Dyer, L. A. (1998b). Experimental Test in Lowland Tropical Forest Shows Top-down Effects Through Four Trophic Levels. *Ecology*, *79*(5), 1678–1687. https://doi.org/10.1890/0012-9658(1998)079[1678:ETILTF]2.0.CO;2

Leverkus, A. B., Buma, B., Wagenbrenner, J., Burton, P. J., Lingua, E., Marzano, R., & Thorn, S. (2021). Tamm review: Does salvage logging mitigate subsequent forest disturbances? *Forest Ecology and Management*, *481*, 118721. https://doi.org/10.1016/j.foreco.2020.118721

Leverkus, A. B., Gustafsson, L., Rey Benayas, J. M., & Castro, J. (2015). Does post-disturbance salvage logging affect the provision of ecosystem services? A systematic review protocol. *Environmental Evidence*, *4*(1), 16. https://doi.org/10.1186/s13750-015-0042-7

Lucas-Borja, M. E., Ortega, R., Miralles, I., Plaza-Álvarez, P. A., González-Romero, J., Peña-Molina, E., Moya, D., Zema, D. A., Wagenbrenner, J. W., & de las Heras, J. (2020). Effects of wildfire and logging on soil functionality in the short-term in Pinus halepensis M. forests. *European Journal of Forest Research*, *139*(6), 935–945. https://doi.org/10.1007/s10342-020-01296-2

Ma, K., Dj, B., Eg, R., & Da, M. (2016). Local Plant Diversity Across Multiple Habitats Supports a Diverse Wild Bee Community in Pennsylvania Apple Orchards. *Environmental Entomology*, *45*(1). https://doi.org/10.1093/ee/nvv147

Mai-Moulin, T., Hoefnagels, R., Grundmann, P., & Junginger, M. (2021). Effective sustainability criteria for bioenergy: Towards the implementation of the european renewable directive II. *Renewable and Sustainable Energy Reviews*, *138*, 110645. https://doi.org/10.1016/j.rser.2020.110645

Mansuy, N., Thiffault, E., Lemieux, S., Manka, F., Paré, D., & Lebel, L. (2015). Sustainable biomass supply chains from salvage logging of fire-killed stands: A case study for wood pellet production in eastern Canada. *Applied Energy*, *154*, 62–73. https://doi.org/10.1016/j.apenergy.2015.04.048

Matthews, R., Hogan, G., & Mackie, E. (2018). *Carbon impacts of biomass consumed in the EU Supplementary analysis and interpretation for the European Climate Foundation*. https://europeanclimate.org/wp-content/uploads/2018/05/CIB-Summary-report-for-ECF-v10.5-May-20181.pdf

Maxim, A. (2014). Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis. *Energy Policy*, *65*, 284–297. https://doi.org/10.1016/j.enpol.2013.09.059

McKechnie, J., Colombo, S., Chen, J., Mabee, W., & MacLean, H. L. (2011). Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels. *Environmental Science & Technology*, *45*(2), 789–795. https://doi.org/10.1021/es1024004

McLaren, B. E., & Peterson, R. O. (1994). Wolves, Moose, and Tree Rings on Isle Royale. *Science*, *266*(5190), 1555–1558. https://doi.org/10.1126/science.266.5190.1555

Meyfroidt, P., de Bremond, A., Ryan, C. M., Archer, E., Aspinall, R., Chhabra, A., Camara, G., Corbera, E., DeFries, R., Díaz, S., Dong, J., Ellis, E. C., Erb, K.-H., Fisher, J. A., Garrett, R. D., Golubiewski, N. E., Grau, H. R., Grove, J. M., Haberl, H., … zu Ermgassen, E. K. H. J. (2022). Ten facts about land systems for sustainability. *Proceedings of the National Academy of Sciences*, *119*(7), e2109217118. https://doi.org/10.1073/pnas.2109217118

N. Wear, D., & Bartuska, A. (2020a). *Forest Bioenergy 101: Generation and Emissions*. Resources for the Future. https://media.rff.org/documents/Forest_Bioenergy_101.pdf

N. Wear, D., & Bartuska, A. (2020b). *Forest Bioenergy 102: Policy Approaches*. https://media.rff.org/documents/Forest_Bioenergy_102.pdf

New EU Forest Strategy for 2030, COM/2021/572 final (2021). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0572#footnote39

Newbold, T., Hudson, L. N., Arnell, A. P., Contu, S., De Palma, A., Ferrier, S., Hill, S. L. L., Hoskins, A. J., Lysenko, I., Phillips, H. R. P., Burton, V. J., Chng, C. W. T., Emerson, S., Gao, D., Pask-Hale, G., Hutton, J., Jung, M., Sanchez-Ortiz, K., Simmons, B. I., … Purvis, A. (2016). Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science (New York, N.Y.)*, *353*(6296), 288–291. https://doi.org/10.1126/science.aaf2201

Nowak, D. J., Hirabayashi, S., Bodine, A., & Greenfield, E. (2014). Tree and forest effects on air quality and human health in the United States. *Environmental Pollution*, *193*, 119–129. https://doi.org/10.1016/j.envpol.2014.05.028

Nowak, D. J., Hirabayashi, S., Bodine, A., & Greenfield, E. (2014). Tree and forest effects on air quality and human health in the United States. *Environmental Pollution. 193: 119-129.*, *193*, 119–129. https://doi.org/10.1016/j.envpol.2014.05.028

OECD (2021). A global analysis of the cost-efficiency of forest carbon sequestration. *OECD Environment Working Papers*.

Olagunju, T. (2015). *Impacts of Human-induced Deforestation, Forest Degradation and Fragmentation on Food Security.*

Oldfield, E. E., Felson, A. J., Wood, S. A., Hallett, R. A., Strickland, M. S., & Bradford, M. A. (2014). Positive effects of afforestation efforts on the health of urban soils. *Forest Ecology and Management*, *313*, 266–273. https://doi.org/10.1016/j.foreco.2013.11.027

Osborne, J. L., Williams, I. H., & Corbet, S. A. (1991). Bees, Pollination and Habitat Change in the European Community. *Bee World*, *72*(3), 99–116. https://doi.org/10.1080/0005772X.1991.11099088

Pace, M. L., Cole, J. J., Carpenter, S. R., & Kitchell, J. F. (1999). Trophic cascades revealed in diverse ecosystems. *Trends in Ecology & Evolution*, *14*(12), 483–488. https://doi.org/10.1016/S0169-5347(99)01723-1

Paquette, A., & Messier, C. (2011). The effect of biodiversity on tree productivity: From temperate to boreal forests. *Global Ecology and Biogeography*, *20*(1), 170–180. https://doi.org/10.1111/j.1466-8238.2010.00592.x

Pelkonen, P. (Ed.). (2014). *Forest bioenergy for Europe*. European Forest Institute.

Peter, D. H., & Harrington, T. B. (2018). Effects of forest harvesting, logging debris, and herbicides on the composition, diversity and assembly of a western Washington, USA plant community. *Forest Ecology and Management*, *417*, 18–30. https://doi.org/10.1016/j.foreco.2018.01.045

Pierre, S., Groffman, P. M., Killilea, M. E., & Oldfield, E. E. (2016). Soil microbial nitrogen cycling and nitrous oxide emissions from urban afforestation in the New York City Afforestation Project. *Urban Forestry & Urban Greening*, *15*, 149–154. https://doi.org/10.1016/j.ufug.2015.11.006

Pilli, R., Fiorese, G., & Grassi, G. (2015). EU mitigation potential of harvested wood products. *Carbon Balance and Management*, *10*(1), 6. https://doi.org/10.1186/s13021-015-0016-7

Pimentel, D., Wilson, C., McCullum, C., Huang, R., Dwen, P., Flack, J., Tran, Q., Saltman, T., & Cliff, B. (1997). Economic and Environmental Benefits of Biodiversity. *BioScience*, *47*(11), 747–757. https://doi.org/10.2307/1313097

Poorter, L., van der Sande, M. T., Thompson, J., Arets, E. J. M. M., Alarcón, A., Álvarez-Sánchez, J., Ascarrunz, N., Balvanera, P., Barajas-Guzmán, G., Boit, A., Bongers, F., Carvalho, F. A., Casanoves, F., Cornejo-Tenorio, G., Costa, F. R. C., de Castilho, C. V., Duivenvoorden, J. F., Dutrieux, L. P., Enquist, B. J., … Peña-Claros, M. (2015). Diversity enhances carbon storage in tropical forests. *Global Ecology and Biogeography*, *24*(11), 1314–1328. https://doi.org/10.1111/geb.12364

Pörtner, Hans-Otto, Scholes, Robert J., Agard, John, Archer, Emma, Bai, Xuemei, Barnes, David, Burrows, Michael, Chan, Lena, Cheung, Wai Lung (William), Diamond, Sarah, Donatti, Camila, Duarte, Carlos, Eisenhauer, Nico, Foden, Wendy, Gasalla, Maria A., Handa, Collins, Hickler, Thomas, Hoegh-Guldberg, Ove, Ichii, Kazuhito, … Ngo, Hien. (2021). *IPBES-IPCC co-sponsored workshop report on biodiversity and climate change* (Version 2). Zenodo. https://doi.org/10.5281/ZENODO.4782538

Power, M. E., Tilman, D., Estes, J. A., Menge, B. A., Bond, W. J., Mills, L. S., Daily, G., Castilla, J. C., Lubchenco, J., & Paine, R. T. (1996). Challenges in the Quest for Keystones: Identifying keystone species is difficult—but essential to understanding how loss of species will affect ecosystems. *BioScience*, *46*(8), 609–620. https://doi.org/10.2307/1312990

Priess, J. A., Mimler, M., Klein, A.-M., Schwarze, S., Tscharntke, T., & Steffan-Dewenter, I. (2007). Linking Deforestation Scenarios to Pollination Services and Economic Returns in Coffee Agroforestry Systems. *Ecological Applications*, *17*(2), 407–417. https://doi.org/10.1890/05-1795

Proskurina, S., Junginger, M., Heinimö, J., Tekinel, B., & Vakkilainen, E. (2019). Global biomass trade for energy- Part 2: Production and trade streams of wood pellets, liquid biofuels, charcoal, industrial roundwood and emerging energy biomass. *Biofuels, Bioproducts and Biorefining*, *13*(2), 371–387. https://doi.org/10.1002/bbb.1858

Ranius, T., Hämäläinen, A., Egnell, G., Olsson, B., Eklöf, K., Stendahl, J., Rudolphi, J., Sténs, A., & Felton, A. (2018). The effects of logging residue extraction for energy on ecosystem services and biodiversity: A synthesis. *Journal of Environmental Management*, *209*, 409–425. https://doi.org/10.1016/j.jenvman.2017.12.048

Ratcliffe, S., Wirth, C., Jucker, T., van der Plas, F., Scherer-Lorenzen, M., Verheyen, K., Allan, E., Benavides, R., Bruelheide, H., Ohse, B., Paquette, A., Ampoorter, E., Bastias, C. C., Bauhus, J., Bonal, D., Bouriaud, O., Bussotti, F., Carnol, M., Castagneyrol, B., … Baeten, L. (2017). Biodiversity and ecosystem functioning relations in European forests depend on environmental context. *Ecology Letters*, *20*(11), 1414–1426. https://doi.org/10.1111/ele.12849

Ravenek, J., Bessler, H., Engels, C., Scherer-Lorenzen, M., Gessler, A., Jesch, A., De Luca, E., Temperton, V., Ebeling, A., Roscher, C., Schmid, B., Weisser, W., Wirth, C., Kroon, H., Weigelt, A., & Mommer, L. (2014). Long-term study of root biomass in a biodiversity experiment reveals shifts in diversity effects over time. *Oikos*, *123*. https://doi.org/10.1111/oik.01502

Reed, D. H., & Frankham, R. (2003). Correlation between Fitness and Genetic Diversity. *Conservation Biology*, *17*(1), 230–237. https://doi.org/10.1046/j.1523-1739.2003.01236.x

Ren, J. (Ed.). (2021). *Energy systems evaluation. (Volume 1), Sustainability assessment*. Springer.

Rickels, W., Proelß, A., Geden, O., Burhenne, J., & Fridahl, M. (2021). Integrating Carbon Dioxide Removal Into European Emissions Trading. *Frontiers in Climate*, *3*. https://doi.org/10.3389/fclim.2021.690023

Ripple, W., Beschta, R., & Painter, L. (2015). Trophic cascades from wolves to alders in Yellowstone. *Forest Ecology and Management*, *354*, 254–260. https://doi.org/10.1016/j.foreco.2015.06.007

Robert, N., Jonsson, R., Chudy, R., & Camia, A. (2020). The EU Bioeconomy: Supporting an Employment Shift Downstream in the Wood-Based Value Chains? *Sustainability*, *12*(3), 758. https://doi.org/10.3390/su12030758

Saarikoski, H., Mustajoki, J., Barton, D. N., Geneletti, D., Langemeyer, J., Gomez-Baggethun, E., Marttunen, M., Antunes, P., Keune, H., & Santos, R. (2016). Multi-Criteria Decision Analysis and Cost-Benefit Analysis: Comparing alternative frameworks for integrated valuation of ecosystem services. *Ecosystem Services*, *22*, 238–249. https://doi.org/10.1016/j.ecoser.2016.10.014

Sala, O. E., Stuart Chapin, F., III, Armesto, J. J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L. F., Jackson, R. B., Kinzig, A., Leemans, R., Lodge, D. M., Mooney, H. A., Oesterheld, M., Poff, N. L., Sykes, M. T., Walker, B. H., Walker, M., & Wall, D. H. (2000). Global Biodiversity Scenarios for the Year 2100. *Science*, *287*(5459), 1770–1774. https://doi.org/10.1126/science.287.5459.1770

Savaresi, A., Perugini, L., & Chiriacò, M. V. (2020). Making sense of the LULUCF Regulation: Much ado about nothing? *Review of European, Comparative & International Environmental Law*, *29*(2), 212–220. https://doi.org/10.1111/reel.12332

Savolainen, O., & Kärkkäinen, K. (1992). Effect of forest management on gene pools. In W. T. Adams, S. H. Strauss, D. L. Copes, & A. R. Griffin (Eds.), *Population Genetics of Forest Trees: Proceedings of the International Symposium on Population Genetics of Forest Trees Corvallis, Oregon, U.S.A., July 31–August 2,1990* (pp. 329–345). Springer Netherlands. https://doi.org/10.1007/978-94-011-2815-5_17

Secretariat of the Convention on Biological Diversity, & United Nations Environment Programme (Eds.). (2014). *Global biodiversity outlook 4: A mid-term assessment of progress towards the implementation of the strategic plan for biodiversity 2011-2020*. Secretariat for the Convention on Biological Diversity.

Sennet, S. (2018). *Clear-cut and Consequence: Trophic Cascades of Deforestation on Rapa Nui (Easter Island)*. https://doi.org/10.13140/RG.2.2.36680.26889

Silva, S. V., Andermann, T., Zizka, A., Kozlowski, G., & Silvestro, D. (2022). Global Estimation and Mapping of the Conservation Status of Tree Species Using Artificial Intelligence. *Frontiers in Plant Science*, *13*. https://www.frontiersin.org/articles/10.3389/fpls.2022.839792

Smith, P., Haberl, H., Popp, A., Erb, K., Lauk, C., Harper, R., Tubiello, F. N., de Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., Mbow, C., … Rose, S. (2013). How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology*, *19*(8), 2285–2302. https://doi.org/10.1111/gcb.12160

Soimakallio, S., Kalliokoski, T., Lehtonen, A., & Salminen, O. (2021). On the trade-offs and synergies between forest carbon sequestration and substitution. *Mitigation and*

Adaptation Strategies for Global Change, *26*(1), 4. https://doi.org/10.1007/s11027-021-09942-9

Spracklen, B. D., Lane, J. V., Spracklen, D. V., Williams, N., & Kunin, W. E. (2013). Regeneration of native broadleaved species on clearfelled conifer plantations in upland Britain. *Forest Ecology and Management*, *310*, 204–212. https://doi.org/10.1016/j.foreco.2013.08.001

Thorn, S., Bässler, C., Brandl, R., Burton, P., Cahall, R., Campell, J., Castro, J., Choi, C.-Y., Cobb, T., Donato, D., Durska, E., Fontaine, J., Gauthier, S., Hébert, C., Hothorn, T., Hutto, R., Lee, E.-J., Leverkus, A., Lindenmayer, D., & Müller, J. (2018). Impacts of salvage logging on biodiversity: A meta-analysis. *Journal of Applied Ecology*, *55*. https://doi.org/10.1111/1365-2664.12945

Titus, B. D., Brown, K., Helmisaari, H.-S., Vanguelova, E., Stupak, I., Evans, A., Clarke, N., Guidi, C., Bruckman, V. J., Varnagiryte-Kabasinskiene, I., Armolaitis, K., de Vries, W., Hirai, K., Kaarakka, L., Hogg, K., & Reece, P. (2021). Sustainable forest biomass: A review of current residue harvesting guidelines. *Energy, Sustainability and Society*, *11*(1), 10. https://doi.org/10.1186/s13705-021-00281-w

Turkson, C., Acquaye, A., Liu, W., & Papadopoulos, T. (2020). Sustainability assessment of energy production: A critical review of methods, measures and issues. *Journal of Environmental Management*, *264*, 110464. https://doi.org/10.1016/j.jenvman.2020.110464

Vcmprimer.org (2022). Chapter 1: What is the voluntary carbon market? Retrieved from https://vcmprimer.org/chapter-1-what-is-the-voluntary-carbon-market%EF%BF%BC/

Vedavathy, S. (2003). Scope and importance of traditional medicine. *IJTK Vol.02(3) [July 2003]*. http://nopr.niscpr.res.in/handle/123456789/25928

Vellend, M., Verheyen, K., Flinn, K. M., Jacquemyn, H., Kolb, A., Van Calster, H., Peterken, G., Graae, B. J., Bellemare, J., Honnay, O., Brunet, J., Wulf, M., Gerhardt, F., & Hermy, M. (2007). Homogenization of forest plant communities and weakening of species–environment relationships via agricultural land use. *Journal of Ecology*, *95*(3), 565–573. https://doi.org/10.1111/j.1365-2745.2007.01233.x

Vera, I., Wicke, B., Lamers, P., Cowie, A., Repo, A., Heukels, B., Zumpf, C., Styles, D., Parish, E., Cherubini, F., Berndes, G., Jager, H., Schiesari, L., Junginger, M., Brandão, M., Bentsen, N. S., Daioglou, V., Harris, Z., & van der Hilst, F. (2022). Land use for bioenergy: Synergies and trade-offs between sustainable development goals. *Renewable and Sustainable Energy Reviews*, *161*, 112409. https://doi.org/10.1016/j.rser.2022.112409

Veresoglou, S. D., Halley, J. M., & Rillig, M. C. (2015). Extinction risk of soil biota. *Nature Communications*, *6*(1), Article 1. https://doi.org/10.1038/ncomms9862

Volkart, K., Weidmann, N., Bauer, C., & Hirschberg, S. (2017). Multi-criteria decision analysis of energy system transformation pathways: A case study for Switzerland. *Energy Policy*, *106*, 155–168. https://doi.org/10.1016/j.enpol.2017.03.026

Wang, S., Loreau, M., de Mazancourt, C., Isbell, F., Beierkuhnlein, C., Connolly, J., Deutschman, D. H., Doležal, J., Eisenhauer, N., Hector, A., Jentsch, A., Kreyling, J., Lanta, V., Lepš, J., Polley, H. W., Reich, P. B., van Ruijven, J., Schmid, B., Tilman, D., … Craven, D. (2021). Biotic homogenization destabilizes ecosystem functioning by decreasing spatial asynchrony. *Ecology*, *102*(6), e03332. https://doi.org/10.1002/ecy.3332

Watson, R. T., Zakri, A. H., Arico, S., Bridgewater, P., Mooney, H. A., & Cropper, A. (2005). *Millennium Ecosystem Assessment Panel*.

Weill, A. (2020, December 23). *12 Days of Conifers: Conifer Trees and How We Study Them | U.S. Geological Survey*. https://www.usgs.gov/news/12-days-conifers-conifer-trees-and-how-we-study-them

Wolfe, B. E., & Pringle, A. (2012). Geographically structured host specificity is caused by the range expansions and host shifts of a symbiotic fungus. *The ISME Journal*, *6*(4), 745–755. https://doi.org/10.1038/ismej.2011.155

Wood, A., Stedman-Edwards, P., & Mang, J. (2013). *The Root Causes of Biodiversity Loss*. Routledge. https://doi.org/10.4324/9781315071688

Worm, B., & Duffy, J. (2003). Worm B, Duffy JE.. Biodiversity, productivity, and stability in real food webs. Trends Ecol Evo 18: 628-632. *Trends in Ecology & Evolution*, *18*, 628–632. https://doi.org/10.1016/j.tree.2003.09.003

WWF. (2020). *Bending the curve of biodiversity loss*. WWF.

Zanchi, G., Pena, N., & Bird, N. (2011). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, *4*(6), 761–772. https://doi.org/10.1111/j.1757-1707.2011.01149.x

Zimmerer, K. S., de Haan, S., Jones, A. D., Creed-Kanashiro, H., Tello, M., Carrasco, M., Meza, K., Plasencia Amaya, F., Cruz-Garcia, G. S., Tubbeh, R., & Jiménez Olivencia, Y. (2019). The biodiversity of food and agriculture (Agrobiodiversity) in the anthropocene: Research advances and conceptual framework. *Anthropocene*, *25*, 100192. https://doi.org/10.1016/j.ancene.2019.100192