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A) Project data

Allgemeines zum Projekt	
Kurztitel:	UNRAVEL
Langtitel:	Towards enhancing the carbon stocks in forests: Unravelling the wood production potentials under sustainability conditions for Austria
Zitiervorschlag:	Roux, N., Matej, S., Seidl, R., Tappeiner, U., Tasser, E., Gingrich, S., Erb, K.-H. (2026): UNRAVEL, Endbericht. Klima- und Energiefonds
Programm inkl. Jahr:	ACRP 13th Call, 2021
Dauer:	1.11.2021 bis 31.10.2025
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Schlagwörter:	LULUCF, harvest allowance, potential, climate change mitigation, carbon opportunity costs, stock forgone, harvested wood products, substitution
Projektgesamtkosten:	299,963 €
Fördersumme:	299,963 €
Klimafonds-Nr:	KR20AC0K18081
Erstellt am:	31.01.2026

B) Project overview

1 Kurzfassung

UNRAVEL untersuchte nachhaltige Potenziale für Waldnutzung und Holzernte unter dem Gesichtspunkt der Wahrung von Waldkohlenstoffsenken, Biodiversität und weiteren Ökosystemleistungen. Anders als herkömmliche Ansätze, die die Kohlenstoffauswirkungen unterschiedlicher Waldbewirtschaftungsstrategien ex-post bewerten, stellte UNRAVEL Klimaziele und Ökosystemleistungen als Ausgangspunkt und entwickelte so Einsichten zu nachhaltigen Holznutzungsniveaus.

UNRAVEL konzentrierte sich auf Österreich, wo Wälder 48 % der Landesfläche bedecken und seit über zwei Jahrhunderten Waldfläche und Biomasse zunehmen. Trotz steigender Holzeinschläge stellten die Wälder historisch eine bedeutende Kohlenstoffsenke dar (2018: 4,3 Mio. t CO_2e in Waldbiomasse, 2.0 Mio. t CO_2e in Holzprodukten bei 88 % Bewirtschaftungsintensität). In jüngster Zeit kippte der Waldsektor in Österreich von einer Senke zu einer Kohlenstoffquelle, was die Relevanz des UNRAVEL-Ansatzes unterstreicht.

UNRAVEL integrierte biophysikalische Bilanzierung und dynamische Waldkohlenstoffmodellierung, um Wissenslücken zur Dynamik der Waldnutzung und ihrem Beitrag zum Klimaschutz zu schließen. Dabei zielt das Projekt ab auf (a) den Aufbau robuster Datenbanken zu Holzströmen, (b) die Quantifizierung von Kohlenstoff-Opportunitätskosten inländischen und importierten Holzes, (c) die Ableitung von Erntemengen im Einklang mit Kohlenstoffsenken und Ökosystemintegrität sowie (d) die Untersuchung von Zielkonflikten zwischen Holzbereitstellung, Kohlenstoffbindung und Ökosystemintegrität, insbesondere im Lichte der anhaltenden Wissenslücken zu natürlichen Störungen.

(a) Auf Basis einer Materialflussrechnung mit Fokus auf den Rohstoffeinsatz (RMI), konnten die Kohlenstoffflüsse im österreichischen Holzsystem quantifiziert werden. Dazu wurden Daten zu Österreichs nationalen und internationalen Lieferketten kombiniert um die geographischen Herkünfte der gesamten Holzmenge, die in Österreich verarbeitet oder konsumiert wird, zu ermitteln. Der durchschnittliche RMI lag 2015–2017 bei 9,7 Mio. t C/Jahr; der damit verbundene gesamte brutto-Holzeinschlag betrug 16,9 Mio. t C/Jahr. 52 % davon sind auf internationale Importe zurückzuführen, die überwiegend aus Europa stammen, allerdings bei Papier und Plattenwerkstoffe auch nicht-Europäische Länder einen signifikanten Anteil ausmachen. Österreich ist ein globales Zentrum der Holzverarbeitung: Der hinter Österreichs Holzwirtschaft stehende gesamt-Brutto-Holzeinschlag ist 2,1-mal größer als der heimische Einschlag, und 1,6-mal größer als der Einschlag, der hinter den im Inland konsumierten Holz steht.

(b) UNRAVEL hat das CRAFT-Waldkohlenstoffmodell weiterentwickelt, um die jährliche Dynamik der österreichischen Waldbiomasse (1992–2021) konsistent zu rekonstruieren, den Totholzbestand zu integrieren und die Opportunitätskosten der Ernte bezogen auf Kohlenstoffspeicherung zu quantifizieren. Die durchschnittliche Holznutzung in Österreich in den Jahren 2015–2017 reduziert den Gleichgewichts-Kohlenstoffvorrat in der lebenden Waldbiomasse um 66,2 Mio. t C (“equilibrium carbon gap‟, etwa „asymptotische Gleichgewichts-Kohlenstoff-Lücke‟). Dies entspricht einer durchschnittlichen Reduktion von 2,4 Mio. t CO_2/Jahr über 100 Jahre bei gleichbleibender Holznutzung und unverändertem Klima. Österreichs Bruttoimporte reduzieren den „equilibrium gap‟ in der Waldbiomasse der Herkunftsländer um 127,2 Mio. t C, was einem durchschnittlichen Verlust von 4,7 Mio. t CO_2/Jahr über die ersten 100 Jahre bei gleichbleibender Holznutzung und unverändertem Handel entspricht.

Diese Kohlenstoff-Opportunitätskosten werden maßgeblich von Mortalität, Störungen bestimmt. Trotz anhaltender Unsicherheiten konnte UNRAVEL Erkenntnisse zur Beziehung zwischen Kohlenstoff-Opportunitätskosten und veränderten Störungsregimen liefern: konzeptionelle Explorationen auf Basis des CRAFT Modells zeigen, dass der wesentliche Faktor die Differenz der Störungsanfälligkeit zwischen geernteten und nicht-geernteten Wälder ist, in Relation zu deren Biomassebestand. Werden geerntete und nicht-geerntete Wälder gleichermaßen betroffen, steigen die Kohlenstoff-Opportunitätskosten bei zunehmenden Störungseinflüssen. Nur wenn nicht geerntete Wälder deutlich überproportional (+25 bis +39%) von natürlichen Störungen betroffen sind als geerntete Wälder, werden die Kohlenstoff-Opportunitätskosten vernachlässigbar.

(c) In einer Szenarioanalyse leiteten wir Holznutzungsobergrenzen ab, die mit Österreichs LULUCF-Senken-verpflichtung kompatibel sind. Die Zielsetzungen implizieren eine kumulative Kohlenstoffsenke im Wald von −82,3 bis −91,6 MtC im Zeitraum 2018 bis 2050, bei konstanter HWP-Senke. Im Vergleich zu den durchschnittlichen Holznutzungsniveaus der Jahre 2016–2018 entspricht dies Reduktionen der jährlichen Ernte von 14–16 % bis 2030, 26–29 % bis 2040 und 35–42 % bis 2050. Die Erhöhung der HWP-Senke, indem langlebige Materialprodukte gegenüber energetischen Nutzungen priorisiert werden, verringert die Notwendigkeit die Ernte zu reduzieren. Eine Leitplanke zur Wahrung der Ökosystemintegrität, nach der höchstens 75% des Nettozuwachses geerntet werden, erfordert eine Reduktion der Ernte um 9% (bis 2030), 16% (bis 2040) und 22% (bis 2050).

(d) Wir zeigten, dass eine Reduktion der Holznutzung die Kohlenstoffspeicherung in Holzprodukten sowie zur Substitution fossiler Energieträger potentiell verringert. Dieser Verlust kompensiert jedoch nicht die Vorteile einer erhöhten Kohlenstoffspeicherung in Wäldern bei reduzierter Ernte. Selbst in der baulichen Nutzung von Holz, dem Anwendungsbereich mit dem größten Klimawandel Mitigationseffekt, übertreffen die Opportunitätskosten die kombinierten Effekte aus Materialsubstitution und Senken in Holzprodukten über typische Lebenszyklen hinweg.

Der Stakeholder-Prozess in UNRAVEL zeigte zunehmende Divergenzen zwischen Standpunkten bezogen auf den Zusammenhang von Waldnutzung und Klimaschutz. UNRAVEL adressierte Wissensbedarfe von Stakeholdern in kompakten Factsheets und trug in hochrangigen Prozessen dazu bei, divergierende Positionen zur Rolle der Waldnutzung in der Klimapolitik zu klären und Standpunkte zu nuancieren und zu differenzieren.

2 Executive Summary

UNRAVEL aimed at exploring how much wood can be sustainably produced in Austria while prioritizing the preservation and enhancement of forest carbon (C) sinks, biodiversity, and other ecosystem services. UNRAVEL reframed how forest-based climate strategies are assessed by reversing the analytical perspective of mainstream research: Rather than following conventional approaches that assess the carbon impacts of different forest management strategies ex post, UNRAVEL strived to develop approaches that take climate and ecosystem targets—especially forest carbon sequestration—as the starting point of assessing the resulting option space for wood production. Following such a framing aims to avoid methodological biases associated with defining acceptable reference levels or parity times and generates new insights into wood production levels compatible with sustainability goals.

UNRAVEL focusses on Austria, a forestry-intensive, globally connected processing hub. Forests cover 48% of its territory, and forest area and biomass have increased for over two centuries, making Austrian forests a substantial carbon sink despite rising harvest volumes. While in 2018 forests sequestered 4.3 Mt CO_2e annually and harvested wood products contributed an additional 2.0 Mt CO_2e sink with a relatively high forest management intensity of 88%, the forest sector has recently turned to a source of carbon emissions, underpinning the timeliness of UNRAVEL's approach. To fulfil its aims, UNRAVEL integrates biophysical accounting, trade tracing, and dynamic forest carbon modeling to quantify wood supply allowances that are compatible with ambitious climate and biodiversity targets.

UNRAVEL addresses key knowledge gaps in forest use dynamics and their role in climate change mitigation by: (a) Establishing robust, comprehensive databases on Austrian wood flows, (b) Quantifying carbon opportunity costs of domestic and imported wood use. (c) Deriving harvest volumes compatible with sink and ecosystem integrity targets and (d) Exploring trade-offs among wood provision, carbon sequestration, and ecosystem integrity in the light of persistent knowledge-gaps on natural disturbances.

(a) We built a material flow account, focused on the Raw Material Input (RMI) to quantify carbon flows in Austria's wood system. We combined data on Austria's national and international supply chains, to trace embodied gross harvest and its primary origins. Average 2015–2017 RMI was 9.7 Mt C/yr; embodied gross harvest was 16.9 Mt C/yr (62 Mt CO_2/yr), with 52% from imports. Primary origins of imports are predominantly European, though non-European inputs are significant for paper and panels once re-exports are accounted for. Austria is a wood processing hub: Input-based embodied harvest (16.9 Mt C/yr) is 2.1 times larger than domestic harvest and 1.6 times the consumption-based embodied harvest. An input-based account provides a complementary perspective on the responsibility of "processing-hub" countries such as Austria in preserving forests and increasing LULUCF sinks.

(b) We advanced the CRAFT forest carbon model to reconstruct Austrian yearly forest biomass dynamics (1992–2021), integrate a deadwood pool, and

conceptualize carbon opportunity costs. Average harvest of 2015-2017 in Austria reduces the equilibrium carbon stock in forest living biomass by 66.2 Mt C (hereafter equilibrium carbon gap), representing a carbon sink forgone of 2.4 Mt CO2/yr on average over 100 years assuming constant harvest and climate. Austria's gross imports reduce the equilibrium carbon stock in forest biomass in origin countries by 127.2 Mt C, or a carbon sink forgone of 4.7 Mt CO2/yr on average over the first 100 years of constant harvest and trade.

The relation between mortality and disturbance dynamics on the one hand, and harvest levels on the other hand, critically shapes these substantial carbon opportunity costs. The analyses have shown that, while it is elusive to assess the impact from disturbances in the future, UNRAVEL allowed to gather stringent insights into the relation of carbon opportunity costs under altered disturbance regimes: if harvested and non-harvested are affected similarly, in relation to their respective biomass stocks, carbon opportunity costs increase with increasing disturbance impacts. Carbon opportunity costs decline only if non-harvested forests are substantially more affected by natural disturbances than harvested forests. Exploratory quantifications for Austria indicate that opportunity costs become negligible when the rate of mortality and disturbances per biomass stock is approximately 25–39% higher in harvested than in non-harvested forests.

(c) We derived harvest allowances that meet Austria's LULUCF sink commitment, accounting for alternative scenarios of harvested wood product (HWP) sinks, the timing of target achievement (2030 or 2040), and developments until 2050. These objectives imply a cumulative carbon sink in forests of −86.3 to −91.6 MtC between 2018 and 2050 assuming a constant afforestation and HWP sink (harvest reductions affect only energy uses). This requires reducing yearly harvest by 14–16% (by 2030), 26–29% (by 2040), and 35–42% (by 2050) relative to average 2016–2018. Increasing the HWP sink by prioritizing long-lived materials over energy uses substantially lowers the necessity to reduce wood harvest. An ecosystem integrity guardrail of harvesting ≤75% of net increment requires reducing harvest by 9% (by 2030), 16% (by 2040), and 22% (by 2050).

(d) Reducing wood use reduces the potential for carbon storage in harvested wood products and for substituting fossil fuels and abiotic materials. However, results show unambiguously that these trade-offs do not outweigh the benefits of enhanced carbon storage in forests. Even in construction applications, the sector where wood use delivers the greatest climate mitigation benefits, foregone forest carbon sinks exceed the combined benefits of material substitution and harvested wood product sinks over typical life cycles.

Science platforms (APCC SRLU, AAR2) and stakeholder engagement processes revealed increasing divergence and conflict regarding the interrelation of forest and wood use in the context of climate protection. UNRAVEL assessed stakeholders' knowledge needs and addressed them through concise fact sheets. In addition, UNRAVEL engaged in high-level stakeholder processes, with impacts reflected, for example, in the Second Austrian Assessment Report, and contributed to clarifying and nuancing divergent positions on the role of forest use in climate change mitigation.

3 Background and objectives

Forests play a pivotal role in the global carbon cycle. By storing large amounts of carbon in biomass, deadwood, and soils, and sequestering large amounts of carbon each year, forests influence atmospheric CO_2 concentrations and thus climate (Arneth et al., 2019). Forests provide essential ecosystem services, including biodiversity conservation, water regulation, soil protection, and cultural values. The use of forest influences these dynamics, changing stocks and flows of carbon as well as the portfolio of ecosystem service provision (Erb et al., 2016). Changes in forest use represent strong "natural climate solutions", either by providing carbon sinks and storing carbon outside the atmosphere (Griscom et al., 2017), or by the provision of wood that can substitute for fossil fuels (Thees et al., 2020).

However, large disagreement prevails on forest-based mitigation strategies. Viewpoints that favour bioenergy and wood use are contrasted by positions that stress the biophysical, monetary and time-response advantages of forest conservation and restoration for carbon sequestration and biodiversity protection on the other (Ludvig et al., 2021; Norton et al., 2019). A central challenge is the inherent trade-off between wood harvest and forest carbon stocks. Harvesting wood reduces carbon stored in forest ecosystems (Erb et al., 2018; Soimakallio et al., 2022). At the same time, harvested wood can contribute to climate mitigation by storing carbon in products and by substituting more emission-intensive materials or fossil fuels. This dual role has been at the centre of scientific and policy debates for decades (Mather-Gratton et al., 2021).

Research has assessed the climate impacts of forest management and wood-use strategies, often focusing on changes in carbon stocks relative to a baseline trajectory and based on substitution effects of wood products. These mainstream approaches underpin national and international greenhouse gas accounting frameworks and have generated important insights into how emissions from forestry and wood use can be reduced. For countries with strong forest and wood-processing sectors, such as Austria, this research has supported narratives of climate-smart forestry and bioeconomy development.

However, these approaches have significant limitations. By focusing on actual changes in carbon stocks relative to a chosen baseline, they often neglect what would happen to forest carbon stocks in the absence of harvest (Erb et al., 2022). Forests left unmanaged or harvested less intensively in general continue to accumulate carbon for decades, in the cases of abandonment of managed forests as well as of old-growth forests (Luyssaert et al., 2008, 2021). Ignoring this "sink forgone" leads to an underestimation of the opportunity costs of wood harvest (Peng et al., 2023). Moreover, because substitution benefits are frequently credited to wood use while lost sequestration potential is not fully accounted for, results tend to be biased towards increased harvesting.

Another key shortcoming is the narrow thematic focus on carbon. Forests provide multiple ecosystem services that are closely interlinked (IPBES, 2019). Biodiversity, in particular, depends on forest structure, age, deadwood availability, and disturbance regimes, all of which are affected by management intensity (Weber et al., 2025). Intensive harvesting can undermine habitat quality and other regulating services, while strategies aimed at reducing harvest pressure might enhance carbon stocks and generate synergies between climate protection and biodiversity conservation (Oettel and Lapin, 2021). However, such strategies constrain wood supply, rendering integrated assessments that jointly consider carbon, biodiversity, and other ecosystem services highly desirable (Erb et al., 2022).

Mainstream approaches are also limited by their spatial framing. Greenhouse gas accounting typically follows territorial boundaries, in line with international reporting obligations. While appropriate for inventories, this perspective is insufficient for sustainability evaluations in a globalised economy. Wood production, processing, and consumption are embedded in international trade networks, and forest use in one country can drive impacts on forests elsewhere (Pendrill et al., 2019; Roux et al., 2025; Wang et al., 2023). This is particularly relevant for Austria, which is highly integrated into global wood markets and among the world's largest importers of roundwood. Territorial assessments risk shifting environmental pressures abroad rather than reducing them overall.

And lastly, time dynamics are an often overlooked but crucial dimension. Reducing harvest pressure strengthens forest carbon sinks immediately, whereas afforestation or wood-based substitution typically requires decades to deliver net mitigation benefits, particularly where initial forest carbon losses must be compensated. Given the urgency of near-term CO_2 reductions, this temporal asymmetry is critical (Norton et al., 2022).

To summarize, the current mainstream framing implicitly treats harvesting as the default and forest carbon sinks as a constraint, leading to persistent problems with reference levels, opportunity costs, and the reconciliation of short-term mitigation needs with long-term dynamics. The project UNRAVEL aims to address these intricacies. Rather by starting from wood production and assessing environmental implications, it aims to take climate change mitigation targets as starting point. For this purpose, it establishes databases and furthers existing models to provide a robust knowledge base for Austria as a case study.

Austria provides a particularly relevant case for applying this perspective. Almost half of its territory is forested, and its forests have acted as significant carbon sinks for more than a century, despite high and increasing harvest levels. This sink function has since been lost during the project period, and forests currently act as net carbon sources, highlighting the timeliness and relevance of UNRAVEL. At the same time, Austrian forest economy relies on vast amounts of wood imports, highlighting the importance of approaches that goes beyond territorial perspectives and take the global dimension of wood use into account.

UNRAVEL quantified wood harvest allowances compatible with forest carbon sequestration targets and ecosystem services, accounting for global wood supply chains, through 5 WPs: (1) Biophysical accounting of wood flows, (2) Modelling forest carbon sequestration under climate change, (3) Carbon sequestration target scenarios for Austria, (4) Trade-offs between wood provision, carbon sequestration and ecosystem services, and (5) Knowledge co-production and integration.

4 Project Content und Results

WP1: Biophysical Accounting of Wood Production and Use

Austria‘s wood production 1992-2021

Forestry harvest increased by 53% from 1992 to 2021 and showed a distinct peak between 2006 and 2008. The strongest relative increases in harvest levels occurred in Vorarlberg (+94%), Tirol (+92%), and Kärnten (+69%). In absolute terms, Steiermark had the highest increase in harvest levels (+0.77MtC/yr). Decreasing harvest levels were mostly found in the East of Austria. Harvest from coniferous trees makes up around 80% of total harvest, with highest harvest intensities in Oberösterreich (Figure 1).

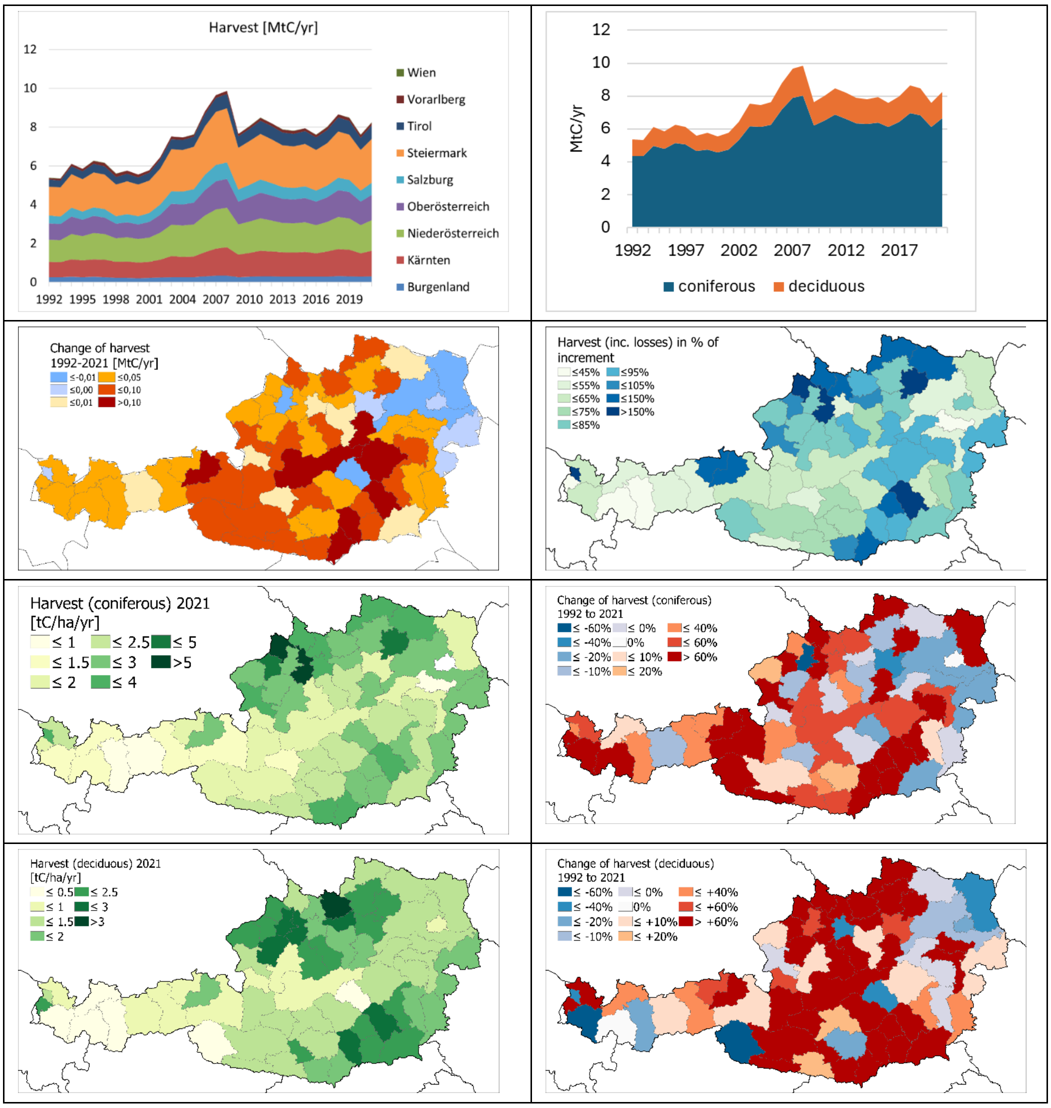

Figure 1: Forestry harvest development 1992-2021 per federal state (upper left) and per forest type (upper right), and spatial patterns of wood harvest and change from 1992 to 2021, on BFI level (maps; for content see plate-titles).

Input-based account of Austria's wood system and origins of AT wood processing industries

Global wood trade has more than quadrupled since 1970, with wood often exchanged multiple times between harvest and final consumption. Footprinting methods correct for these reexports and contrast production-based accounts (allocating impacts to producers/exporters) with consumption-based accounts (allocating impacts to importers/consumers), but both overlook intermediate processing countries, or "wood hubs", such as Austria. We hence quantified an input-based account centered on Raw Material Input (RMI), the sum of domestic extraction and gross imports in raw material equivalents (excluding harvest losses), using the global wood trade model FORBIO (Bruckner et al., 2019; Bruckner and Rosadio Cayllahua, in preparation). See methods. This reveals the scale of forest carbon flows moving through processing countries and distributes impacts along national supply chains. For Austria (2015–2017), wood RMI averaged 9.7 Mt C/yr; corresponding to an input-based account of embodied gross harvest of 16.9 Mt C/yr (62 Mt CO_2/yr), including 8.7 Mt C/yr of domestic material input. Austria's input-based embodied gross harvest was 2.1 times its production-based gross domestic harvest and 1.6 times its consumption-based embodied harvest, with imports contributing 52%.

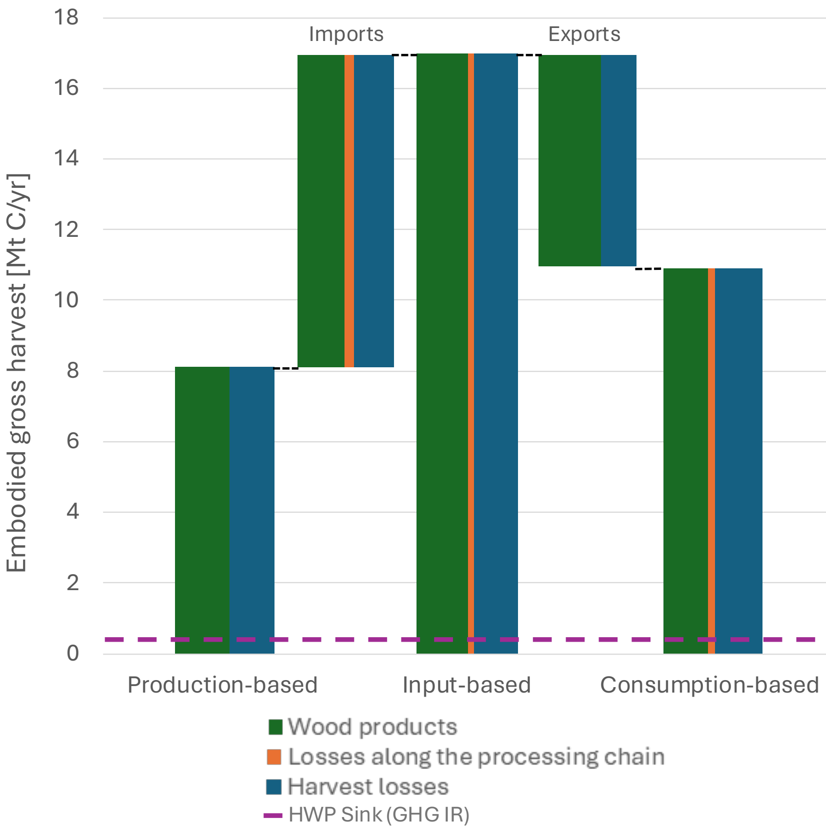

Figure 2: Comparison of production-based, input-based, and consumption-based accounts of gross harvest embodied in Austria's wood system (average 2015-2017). The dashed purple line represents the carbon sink in harvested wood products (HWP) reported in Austria's GHG inventory report (Anderl et al., 2025)*. Bar height indicates the amount of embodied gross harvest, the composition of the bars indicates the size of individual wood stages.*

Primary origins of Austrian wood

This input-based account was an important prerequisite for combining data on Austria's national and international wood supply chains. However, trade statistics account for countries of last added-value, and not countries of origin of biomass. Correcting these statistics for reexports, we found that the gross harvest embodied in Austria's imports originated mainly from neighboring countries: Czechia (1.74 Mt C/yr), Germany (1.67 Mt C/yr), Slovenia (0.82 Mt C/yr), Slovakia (0.78 Mt C/yr). The rest of the top 10 origins included other European countries (Sweden, Hungary, Croatia, Finland), Russia and Brazil (Figure 3A). 85% and 73% of the gross harvest embodied in imports of industrial roundwood and the aggregated category 'residues, briquettes, chips, pellets and other agglomerates' originated from neighboring countries (Czechia, Germany, Slovenia, Slovakia, Hungary, Croatia). Sweden, Brazil, Germany, and Finland were the major origins of 'paper, paperboard, and pulp', covering together half of the gross harvest embodied in Austria's imports of paper. More than half of the gross harvest embodied in imports of 'sawnwood, semi-finished products, and wood-based panels' came from Germany, Russia, and Czechia (Figure 3B). Figure 3C summarizes gross harvest embodied along Austrian wood-processing industries: sawmills 6.7 Mt C/yr (3.7 Mt throughput), pulp and paper 4.6 (2.9), further processing 3.1 (1.8), and particle board 1.1 (0.6). End uses include 7.1 Mt C/yr in energy (5.3 Mt wood), 3.8 in apparent consumption of material products (1.2), and 6.0 in exports (3.8); these stages cannot be summed without double counting. Domestic harvest sent directly to energy totals 2.5 Mt C/yr (31%), split between firewood and chips. With direct and indirect inputs, imports are substantial for all industries: non-Austrian shares are 41% in sawmills, 53% in particle board, and 66% in pulp, paper, and further processing; for end uses, 45% in energy, 49% in exports, and 75% in apparent consumption. Origins are mostly European, but non-European play a relatively larger role in the apparent consumption of material wood products: Latin America 11%, Asia 5%, North America 3%, Africa 1%. This is notably related to the paper and paperboard industry, with 7% of the embodied gross harvest coming from Latin America, 3% from Asia and 2% from North America.

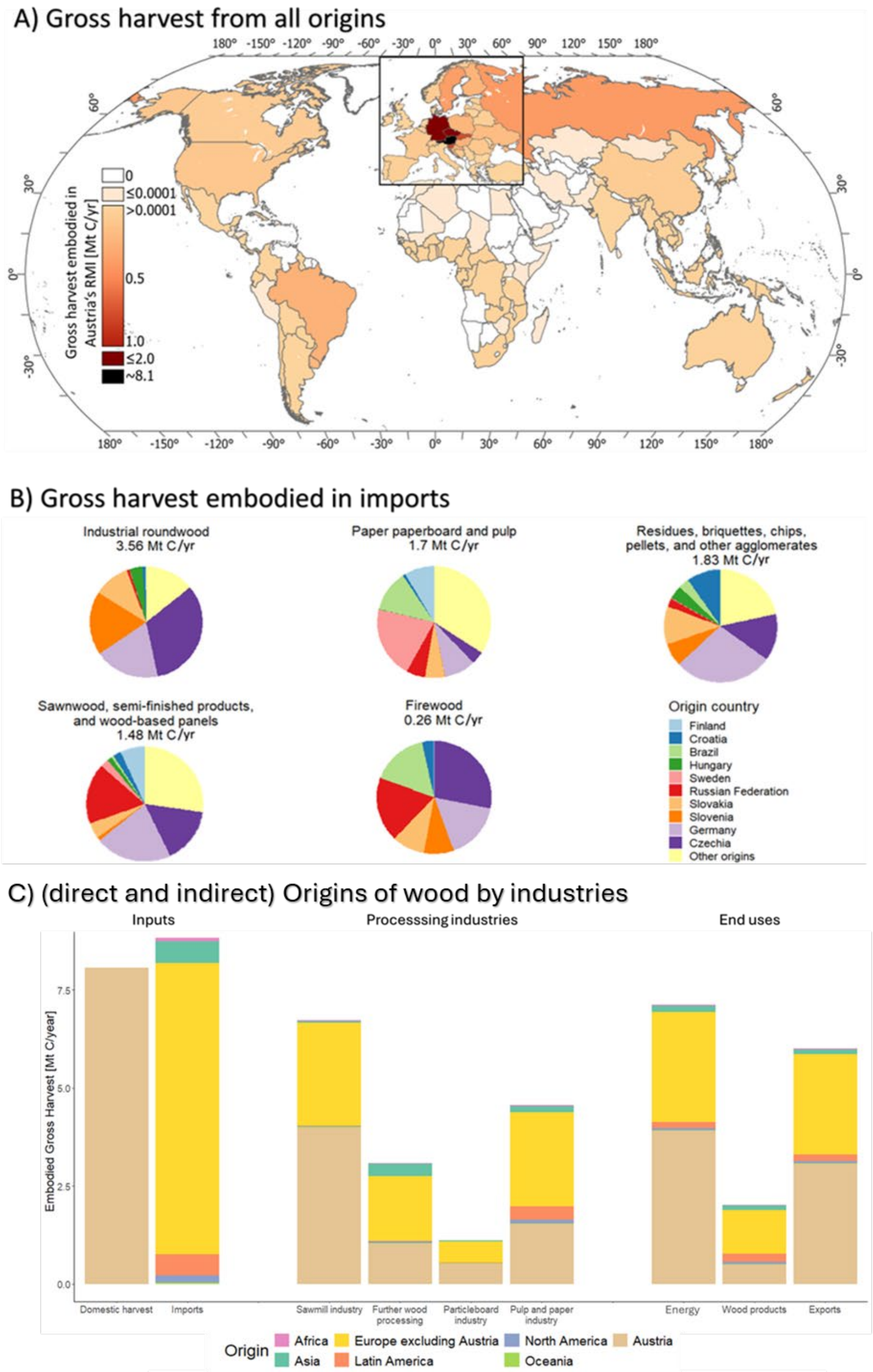

Figure 3: Gross harvest embodied in Austria's wood raw material input (average 2015-2017).

A) Map of origin countries

B) Major origins of imports by product categories.

C) Gross harvest embodied in Austria's domestic harvest, imports, processing industries, and end uses of wood, by origin continents. Bars should not be added, to avoid double counting processed products and used residues.

WP2: Modeling Forest Carbon Sequestration Potentials Under Climate Change

Austria’s carbon stocks in forests biomass 1992-2021

To understand future forest carbon sequestration potentials, we established databases on recent and ongoing forest carbon dynamics (Fig. 4) for further use in subsequent analyses. Based on CRAFT model runs, the role of change in growth conditions for forest dynamics could be assessed (Fig. 4, bottom row).

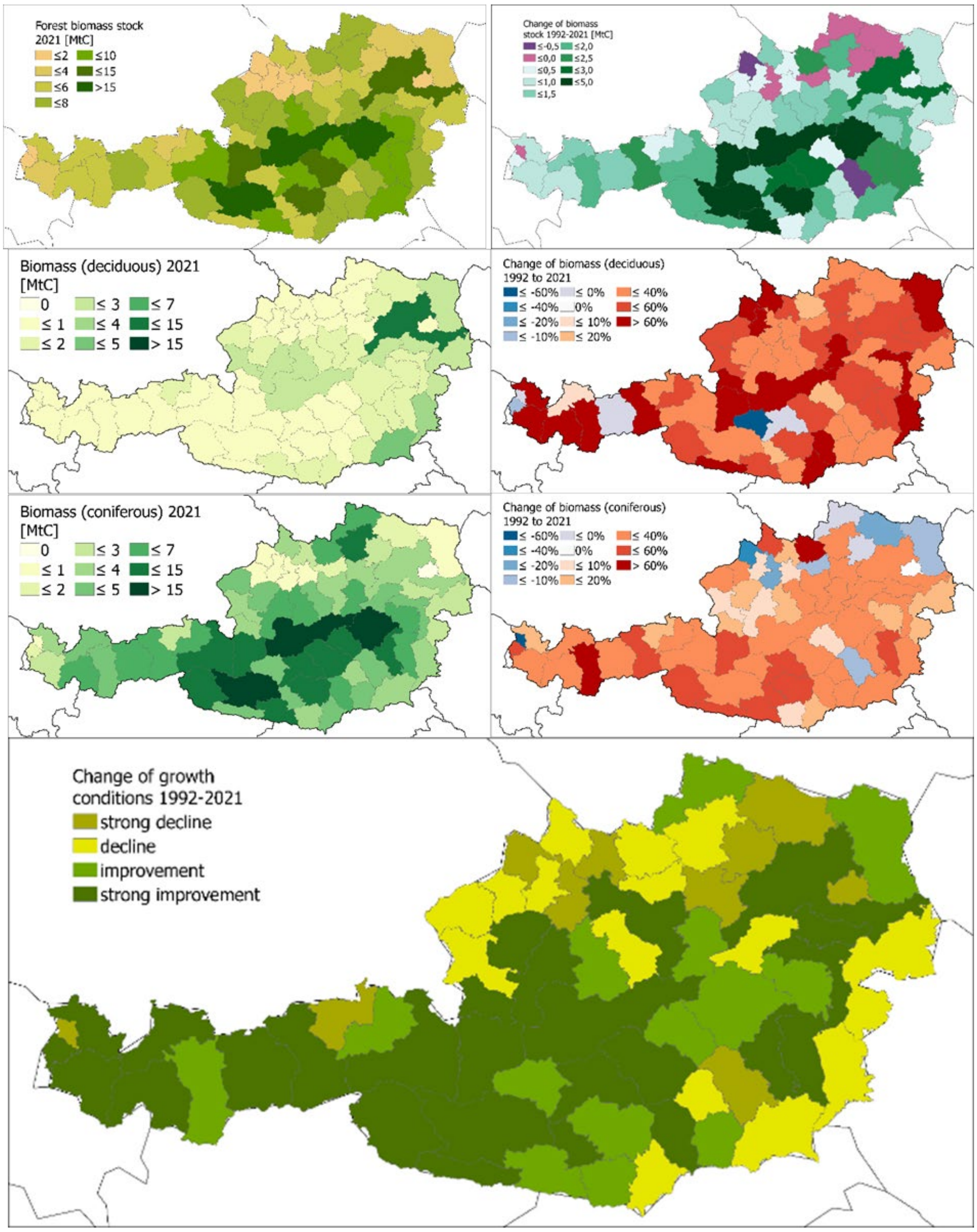

Figure 4: Forest biomass dynamics 1992-2021. Development of forest growth conditions 1992-2021. The change in growth condition (bottom row) was derived with the CRAFT model (see Le Noë *et al., 2021) and can be climate- or management induced.*

Forest carbon stocks forgone through wood harvest

The concept of Carbon Opportunity Costs of wood harvest, or carbon sink forgone was proposed in previous research (Bhan et al., 2021; Marques et al., 2019; Peng et al., 2023). Furthering this concept, we call Carbon Stock Forgone (CStF) the difference between the carbon stock with and without harvest, and Carbon Sink Forgone (CSiF) the difference between the carbon sink with and without harvest. The CStF and CSiF can be understood as opportunity costs, in terms of forest carbon stock and sink, of harvesting wood compared to letting the forest grow older. We assume that, at the national level, average forest carbon stocks saturate over time and reach a steady-state equilibrium where NPP equals the sum of mortality, and disturbances. Under these conditions carbon stocks without harvest saturate to the potential carbon stock. A constant harvest regime (hypothetical situation with constant harvest, climate and other forest growth conditions) creates a new, lower equilibrium, where annual harvest equals annual net increment. Therefore, while the CSiF converges to zero, the CStF converges to a positive long-term value. We call this long term CStF the Equilibrium Carbon Gap (ECG). We calculated the CSiF, CStF and ECG embodied in Austria's domestic harvest, gross imports and exports (Fig. 5) (see methods for details).

Average harvest of 2015-2017 in Austria reduces the equilibrium carbon stock in forest living biomass by 66.2 Mt C, representing a carbon sink forgone of 2.4 Mt CO_2/yr on average over 100 years of constant harvest regime. Austria's gross imports reduce the equilibrium carbon stock in forest living biomass in origin countries by 127.2 Mt C, or a carbon sink forgone of 4.7 Mt CO_2/yr on average over the first 100 years of constant harvest and trade.

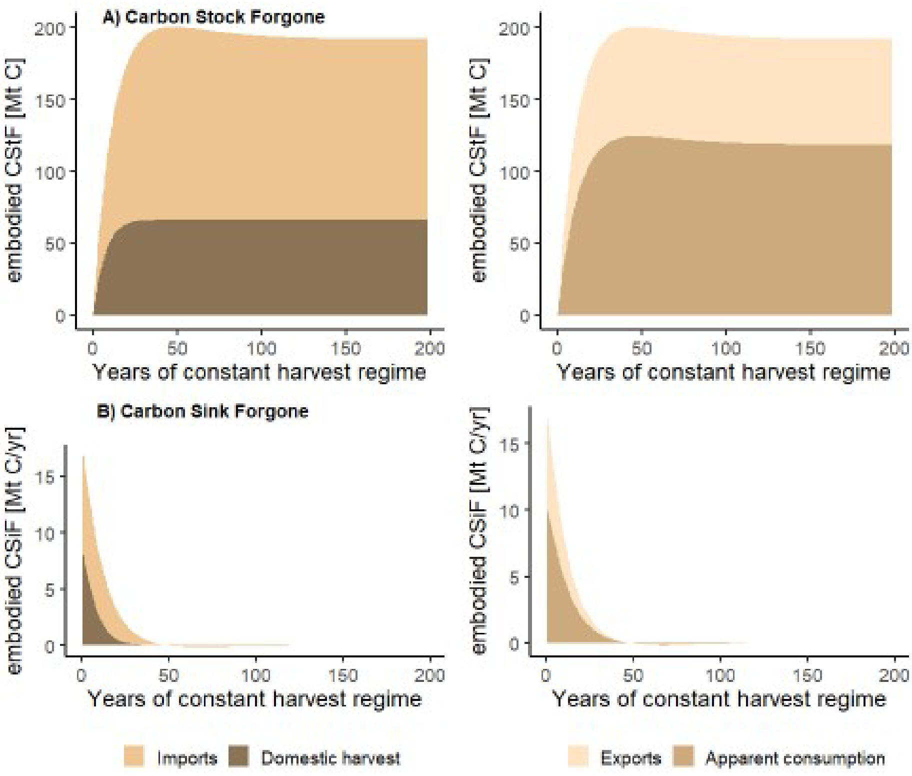

Figure 5: Carbon Stock (A) and Sink (B) Forgone embodied in Austria's domestic harvest, gross imports and exports, and apparent consumption of wood, under a constant harvest and trade regime, using average harvest and trade patterns of 2015-2017.

Equilibrium carbon gap under varying mortality and natural disturbances from climate change

In UNRAVEL, we conducted several studies on the impact of climate change on forest dynamics (Schirpke and Tasser, 2024; Marzini et al., 2025, Frank et al. under review; Marzini et al. under review). An important discussion emerged around the question of whether climate change affects mortality and disturbances stronger in non-harvested than in harvested forests, with ambiguous results. It is commonly assumed that climate change affects mortality and disturbances stronger in non-harvested than in harvested forest, albeit uncertainties are large and revoking evidence exist (Jandl et al., 2024b; Krüger et al., 2025). We conducted explorative analyses on the role of disturbances for the magnitude of carbon opportunity costs (COC) with the CRAFT model. This allowed us to isolate key variables that are decisive for the size and future of COC also in the light of the massive uncertainties related to future natural disturbances and their impact on forest dynamics.

We first explored the possibility that climate change would increase the rate of disturbances per biomass stock uniformly for harvested and non-harvested forests. Note that the absolute mortality still increases stronger in non-harvested forests, due to their higher carbon stocks. The rate of mortality and disturbances per biomass matters hence more than the absolute mortality and impact of disturbances.

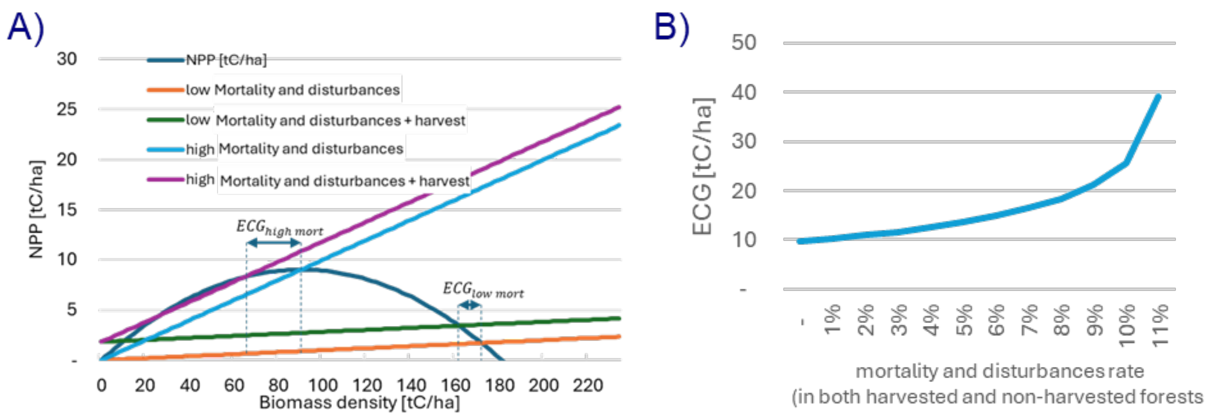

Figure 6: A) NPP, mortality+disturbances and harvest as a function of biomass density in Austria's forests. Equilibrium is achieved where mortality+disturbances intersect with NPP. Harvest lowers the equilibrium biomass, inducing an Equlibrium Carbon Gap (ECG). Increasing the rate of mortality and disturbances equally for harvested and non-harvested forests (steeper curves) increases the ECG until the point where mortality+disturbances+harvest does not intersect the NPP curve anymore, indicating a collapse of forest carbon stocks. B) ECG as a function of the rate of disturbances per biomass stock, uniformly between harvested and non-harvested forests in Austria.

Under these conditions, the rise in disturbances increases the equilibrium carbon gap (Fig. 6). In other words, climate change would exacerbate the harvest induced loss of forest biomass carbon and, reciprocally, increase the potential to increase carbon stocks in forests biomass by decreasing harvest. In Austria, the base rate of mortality and disturbances in CRAFT was 6.18% of the living tree biomass in forests. The ECG increases with the rate of mortality and disturbances, until a threshold of 10.97% beyond which forest carbon stocks would collapse.

We further explored the possibility that the rate of mortality and disturbances per biomass stock becomes higher in non-harvested forests than in harvested ones. Under this assumption, the equilibrium carbon gap progressively vanishes. For a rate of mortality and disturbances between 6 and 11% of total biomass stock in harvested forests, the equilibrium carbon gap vanishes if the rate of mortality and disturbances is more than 1.25 to 1.39 times higher in non-harvested forests than in harvested forests.

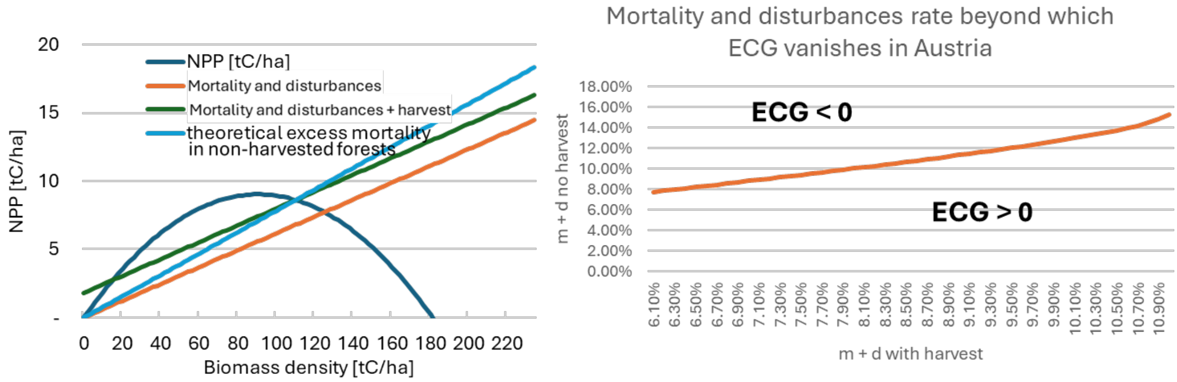

Figure 7: Equilibrium Carbon Gap under a differentiated climate change induced increase in mortality and disturbances between harvested and non-harvested forests.

Our basic model and thought experiments hence suggest that the effect of wood harvest on forests carbon stocks considerably depends on how the rate of mortality and disturbances per biomass stocks differ between harvested and non-harvested forests, especially under climate change. We point towards the existence of a relative threshold value between the rate of mortality and disturbances in non-harvested compared to harvested forests, below which harvest reduces carbon stocks, and above which harvest increases carbon stocks in living forest biomass (due to reduced mortality and susceptibility to disturbances). A thorough quantification of this threshold under RCP scenarios of climate change is an important research perspective.

The dynamics in mortality, disturbances and biomass stocks are relatively well studied at the stand and landscape levels. For example, there is a high consensus that even-aged stands eventually collapse from natural mortality or disturbances, and that the assumption of an equilibrium carbon stock is unwarranted for a single stand (Jandl et al., 2024a). At the tree and stand level, multiple non-linear and threshold-dependent processes occur (stress, competition, age, disturbances, etc.). However, CRAFT models forest carbon dynamics as an average stand within each country. It is hence necessary to understand whether these non-linearities and thresholds hold on average at the regional or national level, or whether dynamics in stands of different ages and landscapes compensate each other.

Understanding this dynamic requires rethinking the so far assumed linearity between mortality-disturbances and biomass stock. Earlier versions of CRAFT used turnover rates from Liski et al. (2002) as a constant ratio between mortality and biomass stocks. In the latest version of CRAFT, the relation between mortality, disturbances and biomass stocks is estimated through a linear regression model between potential NPP and carbon stocks (Gingrich et al., 2025). In these linear approaches, mortality and disturbances increase with carbon stocks, but only in absolute terms and not in relative terms. Under the linearity assumptions, shifts in mortality correspond to entire shifts in the mortality rate (for any level of biomass). Other approaches could think of "bending" the mortality curve, instead of shifting it. We tested with an exponential function for mortality and disturbances, assuming that the mortality of the base year would be unchanged. The more the mortality curve is bent, the lower the ECG, until it is not possible anymore to achieve the mortality rates of 2016. Under this assumption, ECG converges to zero but is always positive.

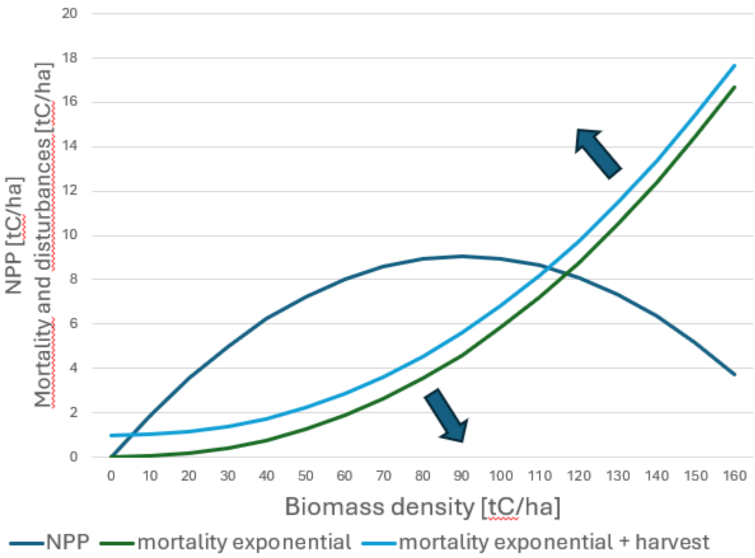

Figure 8: Equilibrium Carbon Gap in Austria assuming an exponential relation between mortality + disturbances and carbon stocks in forest living biomass. Arrows indicate that climate change might have a "bending" effect on mortality, with stands under high carbon stocks being exponentially affected more severely.

We further studied the relation between mortality, disturbances, biomass stocks, and harvest, based on theoretical and empirical knowledge. We notably calculated the Pearson correlation between harvest volumes ("EUFo", based on the BFW dataset) and disturbed area 1990-2021 from the The European Forest Disturbance Atlas (EFDA) (Viana-Soto and Senf, 2025). In Vorarlberg, we found a medium-strength negative correlation (-0.415), indicating lower harvest levels coinciding with larger disturbed areas. The positive correlation coefficients in the other regions ranged from 0.376 in Burgenland, to 0.730 in Salzburg, indicating lower harvest levels coinciding with lower disturbed areas. This analysis provides relevant but ambivalent insights for the incorporation of a stronger link between disturbance events, harvest and deadwood, requiring further investigation, linking tree-, stand-, landscape-, and national-level processes.

Integrating deadwood into CRAFT

Based on BFW data on "standing deadwood", a deadwood pool was integrated in CRAFT by accounting for biomass affected by mortality and for harvest losses while at the same time subtracting decomposing biomass (Fig. 9). In this adaptation of CRAFT the mortality rate determining the inflow to the deadwood pool was kept constant but the rate of decomposition and its change over time was optimized to match the input data on standing deadwood. CRAFT was able to reconstruct the standing deadwood with a median root mean square error of 11%. The median decomposition rate was modeled to be 79%, i.e. 79% of the current deadwood pool decomposes each year. The change of this rate between 1992 and 2021 was between -20% and +24%. It has to be noted that based on this input data and model structure, the decomposition rate also includes the conversion of standing deadwood to lying deadwood and further communicates with the assumed mortality rate. Next steps in model developments include the revision of the constant mortality rate and the modeling of the communication between disturbances such as windthrow or bark beetle infestations with harvest levels on the one hand and deadwood on the other hand.

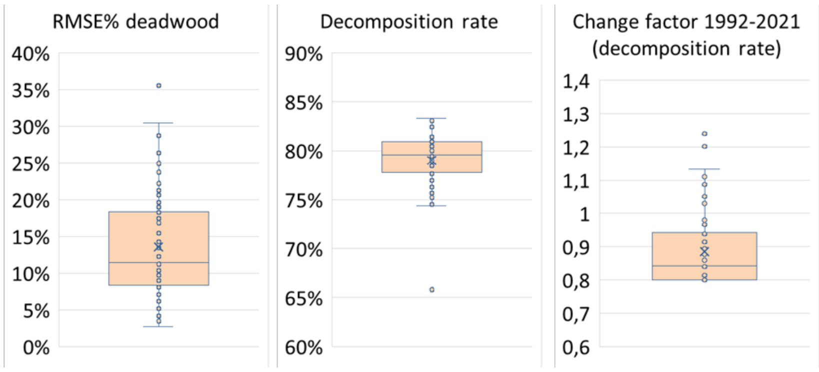

Figure 9: Results of CRAFT related to deadwood pool. Root mean square error between input data for standing deadwood and model results (left), modelled decomposition rate (middle), and change factor of decomposition rate (right).

WP3: Scenarios of Carbon Sequestration Targets for Austria

Conventionally, researchers have been deriving carbon sinks and climate change mitigation potentials from exogenous or market driven harvest levels combined with other measures in the forest-wood system. This is reflected in the first sub-section of WP3. The main goal of UNRAVEL was to reverse this logic, by starting with an exogenous objective of carbon sinks in forests and LULUCF sector and deduct the corresponding harvest allowance, as presented in the latter part of WP3 and in WP4.

Climate change mitigation potentials of measures in forest and wood use

We first assessed the mitigation potential of climate change mitigation measures related to forest and wood uses, following the conventional logic of starting with exogenous harvest levels and deducted carbon sinks and mitigation potentials, considering interactions with other measures. We considered the effect on forest sinks, net additions to harvested wood products (HWP), and the substitution of other energy sources and abiotic materials (Figure 10). See methods.

Compared to the respective scenarios under a reference harvest, decreased wood harvest:

- Enhances the forest sink by 8.8 Mt CO_2eq/yr in 2030-2050 and by 10.4 Mt CO_2eq/yr in 2060-2080.
- Reduces the HWP sink by -0.5 to -1.0 Mt CO_2eq/yr in 2030-2050 and -0.3 to -0.6 Mt CO_2eq/yr in 2060-2080, depending on whether the share of material uses is hold constant or increased (more cascading uses).
- Raises emissions from fossil fuels and abiotic materials by 0.3 to 1.8 Mt CO_2eq/yr in 2030-2050 and by 0.2 to 2.1 Mt CO_2eq/yr in 2060-2080, depending on the assumptions for substitution effects.

Overall, decreasing wood harvest reduces overall net GHG emissions by 6.2 to 8.0 Mt CO_2eq/yr in 2030-2050 and 7.9 to 9.9 Mt CO_2eq/yr in 2060-2080, compared to the respective scenarios under a reference harvest.

Compared to the respective scenarios under a reference harvest, increased wood harvest:

- Reduces the forest sink by 9.2 Mt CO_2eq/yr in 2030-2050 and by 12.7 Mt CO_2eq/yr in 2060-2080.
- Increases the HWP sink by 1.1 to 1.9 Mt CO_2eq/yr in 2030-2050 and 0.1 to 0.2 Mt CO_2eq/yr in 2060-2080, depending on whether the share of material uses is hold constant or increased (more cascading uses).
- rRduces emissions from fossil fuels and abiotic materials by 0.6 to 3.3 Mt CO_2eq/yr in 2030-2050 and by 0.2 to 2.0 Mt CO_2eq/yr in 2060-2080, depending on the assumptions for substitution effects.

Overall, increasing wood harvest raises net GHG emissions by 4.4 to 7.6 Mt CO_2eq/yr in 2030-2050 and 10.6 to 12.4 Mt CO_2eq/yr in 2060-2080, compared to the respective scenarios under a reference harvest.

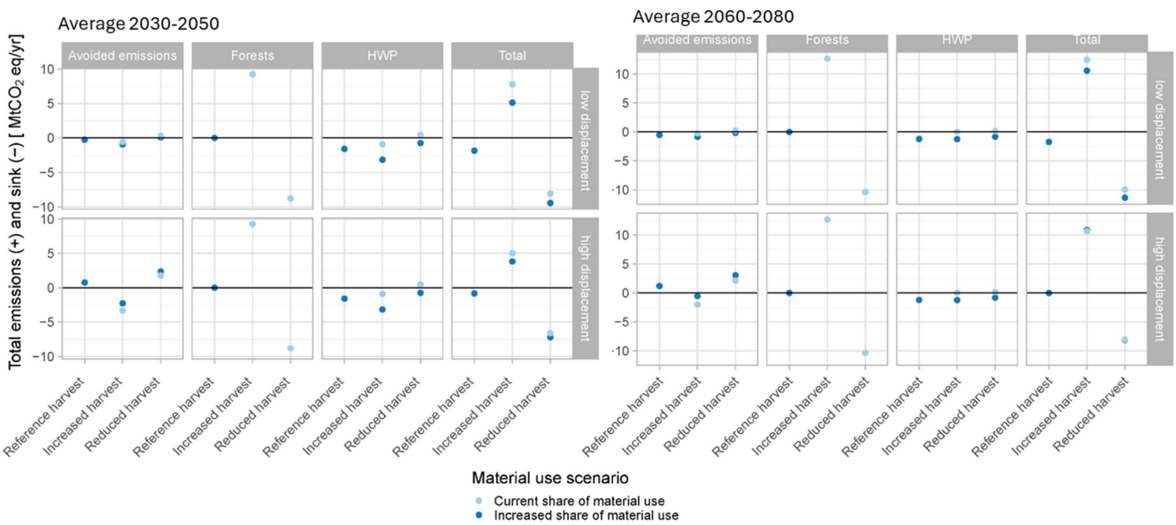

Figure 10: GHG emissions and sinks under combined climate change mitigation measures in the forest-wood system

Reverting the logic: quantifying wood harvest allowances under C sink constraints

A key goal of UNRAVEL was to quantify how much wood can be harvested, under various targets for carbon sinks in forests and other ecological constraints. Carbon sink obligations to stay or return below a global warming level of +1.5°C were first extracted for the global level from shared socio-economic pathways (SSPs) used in integrated assessment models (IAMs). This research revealed a wide option-space for land use, including afforestation and reforestation, and an immense heterogeneity of IAM results across scenario groups (Mayer et al. under review). Thus, the application of these results was impractical for UNRAVEL due to the wide range of options determined by covariates within (e.g. food system trajectories) and outside (e.g. energy system trajectories) the land system. Furthermore, IAM data is not available at the national scale, and would have required downscaling approaches which would have introduced another layer of uncertainty. And lastly, C sink obligations in IAMs are often mixed with objectives for Bioenergy with Carbon Capture and Storage (BECCS), which made it difficult to deduct independent objectives for wood harvest through this approach. Thus, the objective of WP3 was addressed by deriving the objective for forest C sinks from Austria's commitment in the EU LULUCF regulation. To avoid redundancies, the calculation of this target is described along with the resulting wood harvest allowances in WP4.

WP4: Exploring Interlinkages Between Wood Provision, Carbon Sequestration, and Ecosystem Services

Wood harvest allowances under sustainability conditions for Austria

In the EU LULUCF regulation, Austria committed to increasing the LULUCF sink from -4,771 kt CO_2 eq (average 2016-2018) by -879 kt CO_2eq to reach a value of -5,650 kt CO_2 eq by 2030. We used the CRAFT model and data from the UNFCC greenhouse gas inventory (Anderl et al 2025) to quantify how carbon sinks in forests could be increased to achieve the mandatory LULUCF sink.

We exogenously assumed various options for the sink in harvested wood products: a constant, doubled, and null HWP sink (implying corresponding adaptations of the wood used for energy). We assumed a continuation of past afforestation trends and calculated carbon density on afforested areas, assuming no harvest on these areas for the decades to come. We set non-forest land use changes as constant after 2023. The remaining carbon sink had to be achieved by forests remaining forests, by adjusting harvest levels. Note that we hereby only consider carbon flows in forest living biomass, omitting dynamics of deadwood and soils, due to related uncertainties that would habe blurred the results (Le Noë et al., 2023).. Because of the approaching deadline of the EU LULUCF Regulation (2030), we calculated various scenarios where the target is achieved in 2030 or in 2040, followed by either a constant sink or linear extrapolations of the target for following years (Figure 11).

Additionally, we also considered an ecosystem integrity target, that allowed harvest to be no higher than 75% of the net increment, reflecting that the more biomass is extracted from an ecosystem for societal use, the less remains for the needs of other species (Gingrich et al., 2025; Haberl et al., 2014; Running, 2012). Based on CRAFT model runs, an average of 76% of the net increment was harvested on the national level between 2016 and 2018. Note that we used the average of 2016-2018 as a base year, following the base year of the LULUCF regulation and because CRAFT could not be calibrated to the newest forest inventory, which was not yet available during the set-up of the model. The actual evolution of Austrian forest sinks into a source of carbon in the most recent years is hence not considered in the scenarios (Figure 11).

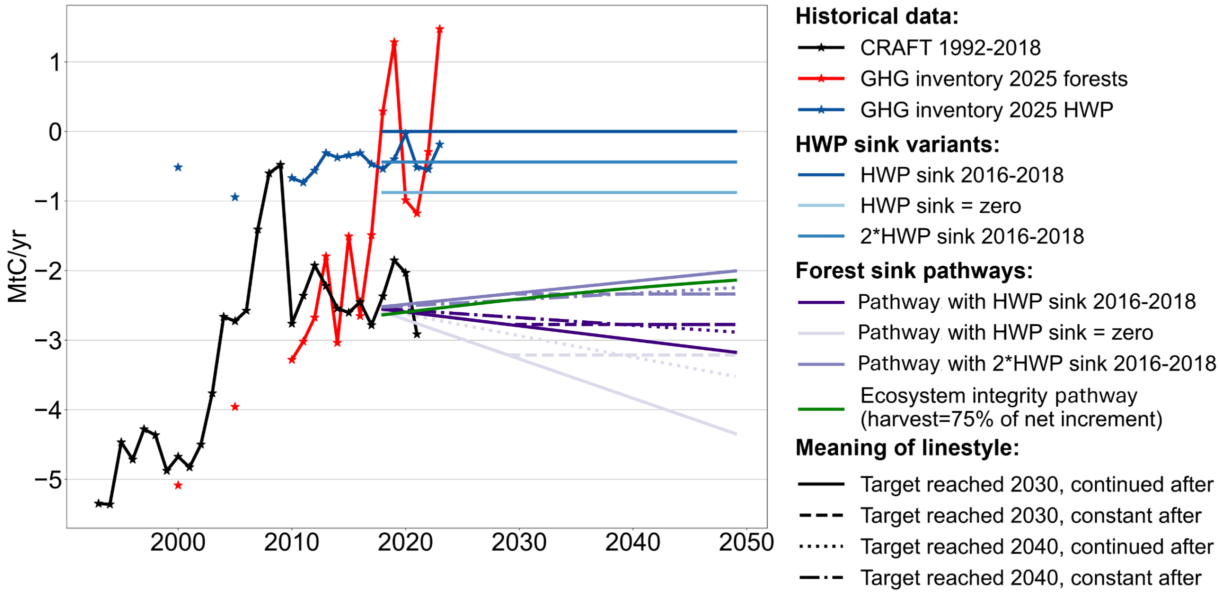

Figure 11: Carbon sinks in forests and HWPs before 2023 and scenarios for reaching the LULUCF sink targets 2018-2050. The LULUCF commitment allows for various forest sink pathways, depending on the level of HWP sink, when the commitment is to be achieved, and how sinks evolve afterwards. Doubling the HWP sink by prioritizing long-term material uses over energy and increasing the longevity of wood products strongly relaxes the pressure on increasing forest C sinks. Forests include forests remaining forests and afforestation.

Forest living biomass dynamics were assessed according to the derived carbon sink and ecosystem integrity targets for Austria. The CRAFT model was adapted to assess these constraints for the time frame 2018 to 2050: the growth parameters r and K were kept constant at their 2018 values, reflecting stable growth conditions until 2050 (see Method section); the forest area on which harvest can take place was kept constant at the 2018 forest area, however, in all scenarios, 2,333 ha of additional forest area were afforested per year, continuing the average net area change of 2016-2018.

To achieve the LULUCF commitment (either by 2030 or 2040) under a constant HWP sink, the cumulative forest biomass sink (incl. afforestation and forests remaining forests) for 2018–2050 must reach −86.3 Mt C (target 2040, constant after) to −91.6 Mt C (target 2030, trend continued after), i.e. -2.7 to -2.9 MtC/yr on average. Doubling the HWP sink by prioritizing long-lived material products over energy uses facilitates the achievement of the LULUCF commitment, lowering the cumulative forest sink requirement to −72.3 Mt C to −76.8 Mt C. Reversely, if the HWP sink shrinks to null (all wood used for energy), the cumulative forest sink requirement must reach −95.7 to −110.9 Mt C. Achieving the ecosystem integrity objective by stabilizing harvest levels at 75% of the net increment implies a cumulative sink of -75.6 MtC by 2050 in forest living biomass.

To achieve the LULUCF commitment under a constant HWP sink, cumulative gross harvest allowances over the period 2018-2050 range from 202.2 MtC to 209.5 MtC (including bark, aboveground harvest losses, and belowground biomass), corresponding to 656.2 to 679.9 Mm³, or 20.5 to 21.2 Mm³/yr on average (including bark, excluding losses and belowground biomass). This requires reducing yearly harvest by 14–16% (by 2030), 26–29% (by 2040), and 35–42% (by 2050) relative to average 2016–2018. Doubling the HWP sink by prioritizing long-lived material products over energy uses lowers the necessity to reduce wood harvest: the required reduction is then 9–10% (by 2030), 15–18% (by 2040), and 20–26% (by 2050). Under the ecosystem integrity constraint, the harvest allowance until 2050 is 223.7 MtC, which requires reducing yearly harvest by 9% (by 2030), 16% (by 2040), and 22% (by 2050). (Figure 12).

In the first 5 years of the scenarios, the ecosystem integrity target constrains harvest more tightly than most LULUCF pathways, and oppositely afterwards. If both constraints are to be achieved simultaneously over the entire period, the cumulative harvest allowance until 2050 is further reduced by 0.1% under constant HWP, and up to 2.2% under doubled HWP, slightly increasing the cumulative carbon sink in forest living biomass, compared to achieving each objective independently.

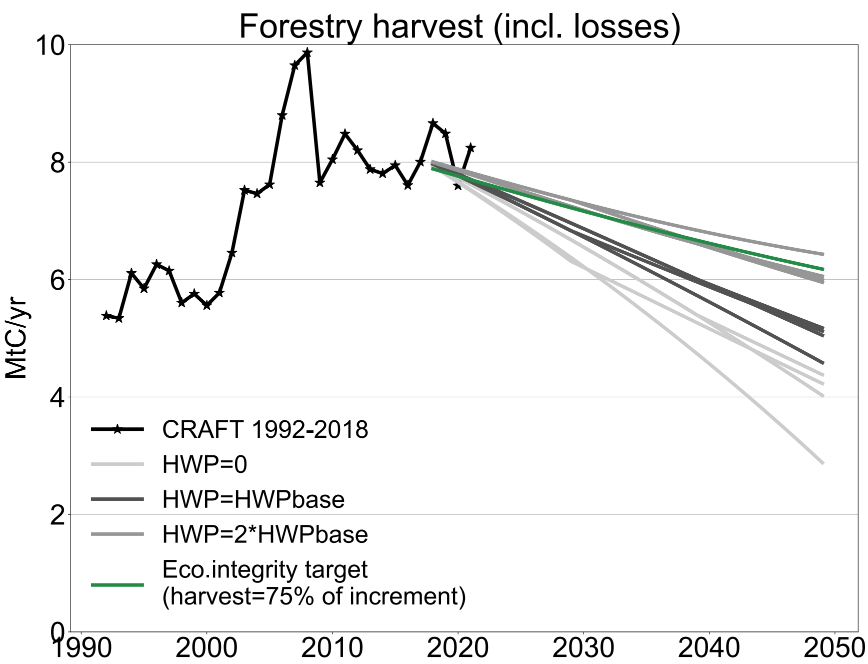

Figure 12: Wood harvest allowances under sustainability constraints for carbon sinks and ecosystem integrity. All pathways require a reduction of harvest, but the range is large, mostly depending on the level of the HWP sink (prioritizing long-term material uses over short term and energy uses).

Trade-offs between carbon sequestration, ecosystem integrity, and wood provision for the building sector

The relationship between wood provision, carbon sequestration and ecosystem integrity is subject to various trade-offs, which we explored from the global to the national level.

In Gingrich et al. 2025, we applied the "doughnut" metaphor to characterize sustainable resource use as constrained between supplying the necessary shelter for human wellbeing and planetary boundaries, delineating the option space for sustainable wood use at the global level. We calculated wood harvest allowances based on forest sequestration targets and assumptions for the development of forest growth conditions. Future forests were modeled for two extremes: 1) forest growth conditions continue to improve at the same rate where they have improved over the calibration period (e.g., 1992-2021 in Austria) and stay stable (i.e. stop declining) in other regions; 2) forest growth conditions continue to decline at the same rate where they have declined over the calibration period and stay stable (i.e. stop improving) in other regions. We developed an approach based on a global dataset on wood harvest and forest biomass for 1990 to 2020 and estimates of technical potentials for forest C-sinks through improved management as reported in Roe et al. (2021) and calculated the maximum annual harvest (including harvest losses) compatible with the given C-sequestration targets until 2050. In this adaptation annual harvest levels remained stable for the modeling period 2020-2050. We combined these wood supply potentials with quantifications of wood demand for buildings, creating an option space for providing sufficient wood for the building sector und ecological constraints.

In this analysis, forest growth conditions were found to make a considerable difference regarding harvest levels compatible with the set carbon and ecosystem targets. The analysis showed that none of the quantified scenarios was associated with net-negative emissions, despite varying growth conditions and floor space assumptions. Increasing the share of timber in construction under ecological sustainability constraints was found to be feasible only in a scenario with low floorspace demand and high circularity rates, but the sensitivity analysis revealed a low robustness of this finding. These results cast doubt on the effectiveness of global strategies that promote the use of wood in buildings as a powerful climate mitigation approach (Gingrich et al., 2025).

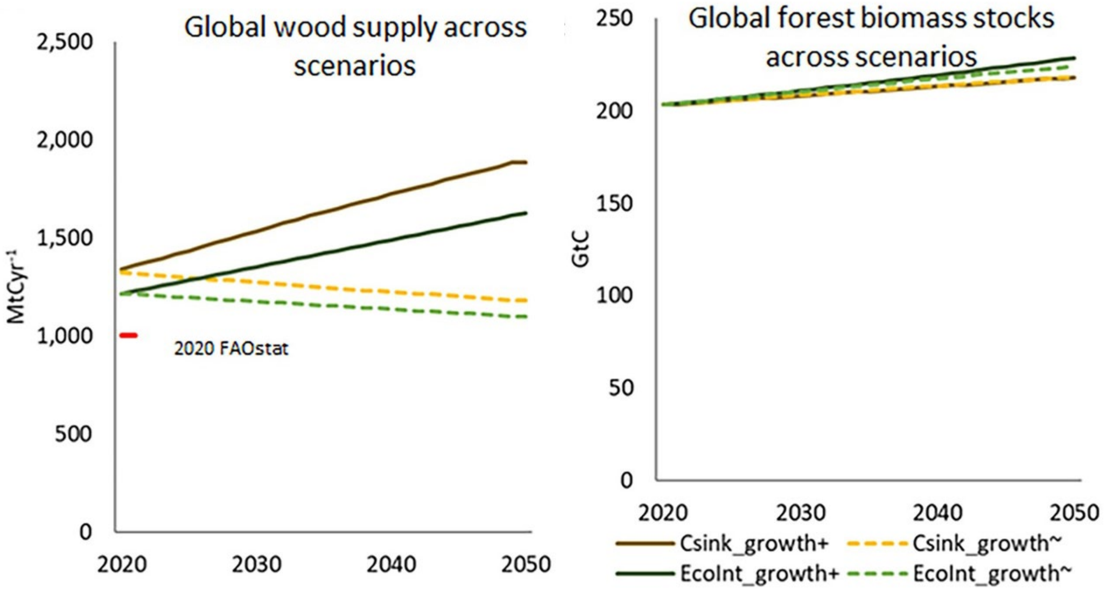

Figure 13: Comparison of wood harvest volumes and forest biomass stocks from Gingrich et al. (2025) modelled under improving (growth+) and declining (growth~) growth conditions and under consideration of C-sequestration targets (Csink) and safeguarding of ecosystem integrity (EcoInt).

In another study focusing on the Austrian context (Maierhofer et al. 2024), we contributed to linking forest carbon opportunity costs with greenhouse gas substitution from wood use in Austrian buildings by introducing a climate optimum concept that jointly evaluates emission substitution from wood and the unrealized forest carbon storage due to harvesting. We applied this concept to a representative Austrian single-family house and to Austrian forest scenarios to test whether wood use remains beneficial for climate mitigation once impacts on forest carbon sinks are included.

Over the life cycle, substitution of other construction materials reduced GHG emissions by 130.72 kg CO2eq/m2 GFA for wood-frame construction and 114.67 kg CO2eq/m2 GFA for wood-solid construction. By contrast, the carbon sink in forests and HWP was reduced by 540.26 kg CO2/m2 GFA for wood-frame options and 653.25 kg CO2/m2 GFA for wood-solid options, compared to the situation where the trees were not harvested. The analysis shows that the carbon sink which is foregone in forests due to harvesting outweighs the sink in HWP and GHG savings from substituting other construction materials with wood.

Governing trade-offs and synergies related to the reduction of wood harvest

Reducing carbon sequestration forgone requires a balanced portfolio across avoid–shift–improve measures, as the stakeholder processes in UNRAVEL have revealed at several instances. Improve measures focus on management changes that increase efficiency and resilience, such as diversifying tree species toward climate-resilient, site-appropriate mixes, applying selective thinning, and extending rotation where suitable. A direct trade-off appears between augmenting harvest to accelerate the change in tree species composition – hence increasing the resilience of stored carbon – and reducing harvest for increasing carbon stocks in forests. Future research should focus on quantifying this trade-off, to find the optimum level of harvest balancing the change in tree species composition and the increase in long-term carbon storage in forests.

Shift measures prioritize fuels and materials with the lowest impact per unit of service; once carbon sequestration forgone (CSF) is counted in the "rucksack" of wood, other renewables often outperform wood energy. Avoid measures aim at sufficiency—limiting wood along with overall resource and energy use—to preserve or increase forest carbon stocks. If Austria relies on forests as sinks in future decades, especially under declining sink strength due to climate change, sustainable wood supply is constrained.

Reducing wood use induces risks of fostering the dependence on fossil fuels and abiotic materials, known as substitution effects, displacement effects, or avoided emissions. However, including avoided emissions from wood substituting fossil fuels and abiotic materials in the carbon accounting of wood is contested. Indeed, avoided emissions correspond to a comparison between the emissions from wood and those from other fuels, not to a negative emission from wood use. For comparison, burning natural gas cannot be considered a negative emission technology, just because it emits less than petroleum. The choice to include avoided emissions hence depends on the research question: quantifying the carbon emissions of wood requires estimates without avoided emissions; however, quantifying the mitigation potential of successfully substituting fossil fuels with wood requires the inclusion of avoided emissions, considering the caveats described in WP3 and in the methods. In both cases, avoided emissions from substitution do not outweigh the carbon sink which is forgone in forests because of wood harvest. However, important uncertainties remain concerning the permanence of forest carbon stocks due to rising disturbances under climate change.

We studied the link between forest use, landscape patterns, and biodiversity (Tasser et al., 2024). This resulted also on a factsheet for the biodiversity hub, in which we argued that limiting wood extraction generally benefits biodiversity, as large, old, and dead trees form critical habitats, depending on site context (Weber et al., 2025). Preserving near-natural stands and retaining deadwood tends to enhance biodiversity (Oettel and Lapin, 2021). Converting spruce monocultures plantations that are not in their appropriate site and rejuvenating with diverse site-appropriate species can also promote diversity. An appropriate balance between limiting usage pressure and rejuvenating towards diverse site-appropriate species is necessary and requires further studies.

Social trade-offs of reducing wood extraction are substantial; calling for just transition strategies and compensations to manage conflicts among actor groups. Wood's versatility and local employment benefits make it socially and economically valuable. It accounts for about 10 percent of material consumption and 12 percent of energy use in Austria, with consumption up 160 percent since 1970 and most wood input used for energy. The processing sector is SME-dominated, export-oriented, and specialized in conifers. Austria is deeply embedded in global supply chains, being the second-largest roundwood importer worldwide. To secure net mitigation, reduced domestic harvest must be paired with reductions in total material and energy use and limitations on imports and exports or collaboration with origin countries to avoid leakage and unintended shifts to other high-carbon materials. Under reduced harvest, GDP contributions could decline by about 1.77 billion euros per year, for an average mitigation of 7 $MtCO_2/yr$, implying around 250 euros per tCO_2 (BFW, 2020; Erb et al., 2025). Justice-oriented support, including financial incentives and compensation, alternative income (e.g., disturbance monitoring), is crucial to manage dependencies and ensure no group is left behind (Erb et al., 2021). Reductions in domestic harvest also risk being offset by higher imports, while reductions in consumption may be offset by higher exports. Trade policies, international collaboration, and supply-chain due diligence could help limit such leakages.

Forests serve production, recreation, and conservation, creating frequent target conflicts. People ascribe different values—instrumental, intrinsic, relational—to land, and current land allocations reflect site conditions, histories, markets, technologies, and stakeholder interactions. Large-scale reforestation to maximize sinks can alter landscapes and affect food and water services, challenging livelihoods. Negotiating values among stakeholders and reducing demand for certain ecosystem services can mitigate trade-offs, but spatial planning often struggles to coordinate across sectors. Trade-offs tend to burden less powerful actors, highlighting equity concerns.

With the revised EU LULUCF, member-state reduction targets apply. Austria's Forest Act was amended in 2023 to embed climate change in sustainable forest management and clarify welfare functions related to carbon uptake and storage. Setting aside forests from use involves property rights and compensation; potential avenues include new protection categories or special-use definitions, but must be balanced with federal mandates for profitable management. For long-lived wood products, monetary incentives, owner awareness, and training in processing may be more effective than strict command-and-control. Renaturation will increasingly be governed by the EU Restoration Regulation, complementing existing state-level mitigation and compensation rules.

Effective policy requires co-developing pathways with land users (Erb et al., 2025). Stakeholder inclusion is a prerequisite for implementable climate policies, and firm-level implementation demands systemic, user-friendly program design. Many rules stem not only from government but also from private companies; governance must span entire value chains to ensure fair information exchange and balanced power. Payments for ecosystem services, improved monitoring, policy integration, and participatory learning can reduce conflicts and support a just transition across Austria's land and wood systems.

In sum, Austria's wood-related mitigation hinges on a balanced portfolio: avoid where feasible to protect carbon stocks and biodiversity, shift toward low-impact energy and materials with explicit accounting of carbon sequestration forgone, and improve forest management to increase resilience and reduce risk. Success depends on transparent carbon accounting, safeguards against leakage, careful treatment of substitution, and governance that recognizes rights, compensates public-good provision, and ensures a just transition.

WP5: Knowledge Co-Production and Knowledge Re-Integration

A key objective of UNRAVEL was to provide easily accessible knowledge on wood use – carbon dynamic interrelationships to stakeholders, in a first phase focusing on knowledge needs of environmental NGOs and in a second to a broader stakeholder audience. Unravel enabled extensive stakeholder engagement and science–society interaction, producing evidence syntheses and inputs for policy. A particular focus was on the stakeholder interactions within the APCC second assessment report, with strong involvement from scientific colleagues from other institutions and non-academic stakeholders. The AAR2 process was started after the commissioning of UNRAVEL and provided a perfect vehicle for pursuing the objectives of WP5 in UNRAVEL.

Knowledge needs of NGOs

In the beginning of the project, we conducted interviews with NGO representatives to identify their approach to forest C sequestration potentials and their role in climate change mitigation, understand relevant ongoing debates and processes and prevailing barriers in communication, and identify knowledge needs and perceived major barriers to forest conservation. The interview partners expressed knowledge needs on C dynamics under forest extensification (reduced harvest) and conservation (put areas out of use), co-benefits between carbon sequestration and biodiversity conservation, and the international "responsibility" of Austria for forest change abroad.

Factsheets

These knowledge needs have been covered in factsheets. Next to the factsheet on the limited wood energy potentials to contribute to climate change mitigation in Austria (Erb et al., 2023), we wrote a factsheet on Biodiversity-compatible mobilization of biomass for energy generation, for the Austrian Biodiversity Hub (Weber et al., 2025). The topic covered how biodiversity peaks across forest development phases, emphasized the role of protected forests, and deducted recommendations to enhance biodiversity related to wood bioenergy. In another factsheet, we assessed the potential of various measures for increasing C sinks in ecosystems (Roux et al, under review).

Assessment reports and stakeholder processes for the Austrian Panel for Climate Change

Topics and results from UNRAVEL were discussed with colleagues from various disciplines in the APCC special report land use (SRLU) and 2nd Austrian Assessment Report on Climate Change (AAR2). Important discussions in these processes identified and analysed the co-existing, of differing perspectives on the use of wood and forests for climate change mitigation prevailing in the scientific community.

‘Table 1.4: Comparison of two perspectives that lead to different assessments of the climate neutrality of forest use’ in the SRLU summarizes this discussion, comparing two points of view that arrive at different assessments of the climate neutrality of forest use. This discussion was continued in AAR2, resulting in ‘Chapter Box 2.2: Carbon sequestration potentials of forests’ as a main outcome.

UNRAVEL also contributed to the AAR2 transdisciplinary stakeholder process, communicating results and enabling discussions with companies, ministries, NGOs, and interest groups in the biomass sectors.

The team also extensively contributed to formal consultations (e.g., formulating statements to BMLUK and EU Commission related to the EU Deforestation Regulation - EUDR), supported the NECP measures assessment of organized by the CCCA in early 2025, and engaged with various stakeholder discussions around EU files such as EUDR and the Nature Restoration Law.

Stakeholder workshops – focus on Alpine forests

The UNRAVEL project supported Laura Barraclough's PhD thesis at the University of Innsbruck (main supervisor: Ulrike Tappeiner) entitled ‘Linking climate and social changes for identifying adaptation pathways in Alpine forests: stakeholder perspectives on Alpine Forest ecosystem-services’. Through semi-structured interviews of expert stakeholders, stakeholder workshops, Laura analyzed themes and connections between participants and identified stakeholder perceptions and thresholds for change. The central stakeholder workshop was held in December 2024 with 8 local stakeholders and experts. She utilized stakeholder participation methods to engage different types of forest users to instigate constructive dialogue on future forest management.

Understanding divides through bilateral discussions and mutual trust

The UNRAVEL project and related stakeholder processes revealed increasingly divergent perspectives in research on forests, wood use, and the bioeconomy, particularly regarding their role in climate change mitigation. Dialogue across viewpoints has become more difficult, often driven by strong normative positions, a tension also evident in science–policy platforms such as the APCC. While UNRAVEL sought to bridge these divides, their persistence after the project’s end highlights the limits of approaches focused solely on conventional and quantitative scientific insights. This points to the need for transformative formats that foster mutual understanding, transparency, and respectful exchange. Further research and social processes are needed to explore the roots of conflict, including emotional drivers, narratives, values, misunderstandings, and reinforcing social affiliations. Such work could help rebuild trust and improve scientific dialogue without aiming for consensus. As a first step, we initiated bilateral discussions with colleagues from BFW, IIASA, TU Munich, and BOKU, which supported trust-building and helped identify points of irritation and differing research perspectives.

5 Conclusions and recommendations

This section synthesizes UNRAVEL's key results and translates them into recommendations for Austria's forest, climate, and bioeconomy policy domains. The project reframed forest-based climate mitigation analyses by taking carbon sink and ecosystem integrity targets as starting points and assessing the compatible option space for wood production. It integrated (1) material flow accounting of Austria's wood system, (2) advanced in national forest carbon modeling and opportunity cost concepts, (3) assessed target-driven harvest allowances compatible with EU LULUCF commitments and ecosystem integrity, and (4) provided evidence on trade-offs and governance requirements, complemented by co-production of knowledge with stakeholders.

Key project results

- Austria represents an international wood-processing hub, with an average 2015–2017 Raw Material Input (RMI) of 9.7 Mt C/yr, corresponding to a global gross harvest (including bark, aboveground harvest losses, and belowground biomass) of 16.9 Mt C/yr (≈62 Mt CO_2/yr), 52% of which reaching Austria via imports. As Austria imports and exports a large share of its wood in- and throughput, the input-based account of embodied gross harvest is 2.1 times the production-based account and 1.6 times the consumption-based account. This provides a complementary perspective on the responsibility of wood-processing hubs such as Austria in global forest impacts and carbon sequestration.
- Carbon opportunity costs of wood use, quantified as sink foregone or stocks foregone, are large. Assuming a hypothetical constant harvest, climate and forest growth conditions, the domestic harvest (average 2015–2017) reduces the equilibrium forest living biomass by 66.2 Mt C, equivalent to a carbon sink forgone of 2.4 Mt CO_2/yr on average over the first 100 years. Gross imports reduce the equilibrium forest living biomass in origin countries by 127.2 Mt C, equivalent to a sink forgone of 4.7 Mt CO_2/yr over the first 100 years.
- The future of the carbon opportunity costs depends critically on how mortality and natural disturbance rates differ between harvested and non-harvested forests. Exploratory modelling in UNRAVEL revealed that, under current conditions, harvest reduces carbon stocks in forests. Under uniform increases of the rate of disturbances and mortality per biomass stocks across harvested and non-harvested forests, the equilibrium carbon gap (ECG) increases, exacerbating harvest-induced losses. Toy-model based quantifications, however, indicate that if climate change increases the rate of mortality and disturbances per biomass stock 1.25 to 1.39 times more in non-harvested forests than in harvested forests, non-harvested forests would eventually store less carbon than harvested ones. It remains for

future research to assess whether such rates and differences are plausible under different climate change scenarios.

- To meet Austria's EU LULUCF sink commitment (either by 2030 or 2040), the cumulative forest sink for 2018–2050 must reach −86.3 Mt C (target 2040, constant after) to −91.6 Mt C (target 2030, trend continued after), assuming a constant afforestation and HWP sink (harvest reductions assumed to affect only energy uses). This requires reducing yearly harvest by 14–16% (by 2030), 26–29% (by 2040), and 35–42% (by 2050) relative to average 2016–2018. Doubling the HWP sink by prioritizing long-lived material products over energy uses facilitates the achievement of the LULUCF commitment, lowering the necessity to reduce wood harvest: the required reduction is then 9–10% (by 2030), 15–18% (by 2040), and 20–26% (by 2050). An ecosystem integrity guardrail of harvesting ≤75% of net increment requires reducing yearly harvest by 9% (by 2030), 16% (by 2040), and 22% (by 2050).
- Unravel results, published in two high-rank journals, consistently indicate that carbon-related trade-offs favor in-forest carbon storage over harvested wood products (HWP) storage. Decreasing harvest substantially strengthens forest sinks, with smaller reductions in HWP sinks and material/energy substitution effects. Even in construction, i.e. the material application of wood's with the strongest mitigation effect, foregone forest sinks outweigh HWP storage and substitution benefits over typical life cycles (e.g., −540 to −653 kg CO_2/m^2 GFA foregone LULUCF sink versus 115–131 kg CO_2/m^2 substitution gains). Furthermore, avoided emissions are contingent on real substitution of fossil fuels and abiotic materials, which is often limited historically; This points to future research in which careful, comprehensive accounting that distinguishes emissions of wood from avoided emissions is required.
- Stakeholder engagement processes revealed increasing divergence and conflict regarding the interrelation of forest and wood use in the context of climate protection. UNRAVEL assessed stakeholders' knowledge needs and addressed them through concise fact sheets and contributed to sorting and nuancing the arguments from a scientific perspective, which found entry in the APCC special report on land use and the APCC Second Assessment Report (AAR2). A key factor fueling the discord may be that reducing harvest levels entails substantial distributional and transition challenges, estimated e.g. as GDP impacts of ca. €1.77 billion/yr for mitigation of about 7 Mt CO_2/yr). This underscores the need for clear and robust governance, including compensation mechanims, just transition policies and safeguards against leakage in order to sustainably harness the large mitigation potentials of the forest sector.

Conclusions

1) Starting from carbon sink and ecosystem integrity targets reveals the option space for sustainable wood harvest and use, complementing ex-post carbon accounting of exogenous assumptions on harvest levels. Under ambitious ecological objectives, moderate adaptations of wood supply helps maintaining and enhancing in-forest carbon stocks and biodiversity.

2) Austria's role as a processing hub is linked to carbon opportunity costs both domestically and abroad. An input-based accounting of embodied harvest is helpful to recognize the full responsibility of hub countries, design policies that avoid leakage and preserve global forest stocks.

3) Forest carbon opportunity costs—both Carbon Stock Forgone (CStF) and Carbon Sink Forgone (CSiF)—are substantial. For future developments, the determinant factor is the rate of mortality and disturbances relative to the biomass stock on harvested and unharvested forests, not the absolute impact of mortality and disturbances. Unless non-harvested forests face significantly higher rates of disturbances and mortality per biomass stock than harvested forests, harvesting reduces equilibrium stocks. Both these aspects, the future development of disturbances and their relative impact represent important research challenges.

4) Gains in forest sinks due to harvest reductions are immediate and outweigh HWP gains and substitution benefits of maintained or enhanced harvest levels. Even ambitious substitution portfolios and HWP storage, for example in buildings, do not offset foregone in-forest sinks within practical time horizons, under current supply chain conditions and technologies.

5) Biodiversity co-benefits align with reduced extraction and more natural forest structure (older trees, deadwood, mixed species), especially when replacing risk-prone monocultures with climate-resilient, site-appropriate species compositions.

6) Meeting LULUCF commitments while safeguarding ecosystem integrity requires coordinated action in forests, materials, energy, and trade. In all cases, achieving these objectives requires some reduction of wood harvest and use levels. However, the necessity to reduce harvest is substantially lowered if HWP sinks are increased by increasing product lifetimes, cascading use, and favoring long-lived products over short-term and energy uses of wood. Avoiding leakage via imports and exports is also essential to ensure the effectiveness of such strategies.

7) A just transition is essential to govern the socio-economic trade-offs of reducing wood use. Policy must support forest owners, SMEs, and regional economies through compensation, alternative income, market reforms, and democratic processes.

Recommendations

A) Carbon accounting and target-setting

- Regularly publish input-based along with production- and consumption-based accounts of embodied harvest and wood-related impacts, tracing back to countries of primary origin. Considering the responsibility of Austria as a processing-hub can have a strong influence on European forests and govern impacts on forest carbon stocks domestically and abroad.

- Distinguish and separately document emissions of wood from avoided emissions in all accounts. Use avoided emissions only in comparative mitigation assessments. Update models to reflect declining displacement factors over time and the limited historical substitution observed; avoid systematically presuming 1:1 displacement.

- Institutionalize and further research carbon opportunity cost metrics: Integrate CStF, CSiF, and ECG indicators into national forest and bioeconomy monitoring to reveal sink forgone under different harvest strategies and HWP portfolios.

- Increase research on the rate of mortality and natural disturbance per biomass stock, with a particular focus on separating effects on harvested and non-harvested (or less-harvested) forests.

B) Forest management and ecosystem integrity

- Reduce levels of wood harvest and use in line with LULUCF targets and ecosystem integrity.

- Prioritize forest and HWP sinks over energy uses.

- Weigh social benefits against options of reducing wood use and harvest for forest sink and stock protection and biosphere integrity. Foster research into "sustainable corridors" related to material wood use that achieve decent living standards within planetary boundaries of climate change mitigation and biosphere integrity, according to basic needs related to human wellbeing, especially through essential long-lasting materials (e.g. housing).

- Improve resilience while minimizing carbon losses. Accelerate the conversion from vulnerable species and monocultures to mixed, site-adapted species; extend rotations where ecologically suitable; favor selective thinning. Retain large trees and deadwood to support biodiversity. Pilot adaptive harvest strategies that balance species transition needs with carbon stock preservation; quantify trade-offs between accelerated transition and carbon stock goals. This is a particularly promising research field.

- Develop strong and robust governance that embeds compensation mechanisms for owners providing public-good sinks and habitat functions, as well as alternative income, market reforms, and just and democratic processes with multi-perspective stakeholders.

C) Project details

6 Methods

Tracing the national supply chain of wood in Austria

The data on wood and wood product flows was mostly extracted from the wood flow diagram (WFD) of the Austrian Ministry of Climate Action, Environment, Energy, Mobility, Innovation and Technology, for the years 2015 to 2017 (Strimitzer and Nemestothy, 2017, 2018, 2019). The WFD traces wood processing chains through six sectors and conversion processes: felling, sawmilling, pulp and paper, further wood processing, particle board manufacturing, and energy use. These diagrams provide the raw material equivalents of the flows in green and solid volume, resulting in balanced inputs and outputs for each node. Being absent from the WFD, data on domestic production, import and export of particleboards, and paper and paperboards products was added from FAOSTAT forestry data. For these added products, reexports were estimated and eliminated, to show only exports of goods that are produced in Austria. This was done by assuming that the share of exports and consumption is identical for domestically produced and imported products (Kastner et al., 2011b). Our resulting WFD covers flows of 15 wood products, aggregated into 7 categories.

Wood flows were converted into carbon mass using global IPCC 2019 carbon densities, distinguishing between coniferous and non-coniferous wood (Rüter et al., 2019). Used factors can be found in the Supplementary Material. The shares of coniferous and non-coniferous wood felled in and imported to Austria were computed from FAOSTAT forestry data, and used to estimate Austria-specific carbon densities for domestic and foreign wood, from standard carbon densities for coniferous and non-coniferous wood provided by the IPCC (IPCC, 2019). These carbon densities were then propagated from these wood sources to downstream industries, exports and final uses, assuming for each node equal shares of input flows in each output flow and keeping existing balances (see Appendix). This process was applied for data from 2015 to 2017, which were then used to compute yearly averages for the period.

Tracing Austria's wood imports to the countries of origin

To trace Austria's wood imports back to their primary origins, we employed the Forestry Biomass Input-Output (FORBIO) model (Bruckner et al., 2019; Bruckner and Rosadio Cayllahua, in preparation). FORBIO is a specialized Multi-Regional Input-Output (MRIO) database designed to track detailed flows of 23 FAO-classified wood products across 222 countries and territories, here calculated and averaged for the period 2015–2017. It provides physical input-output tables, covering key processes of the forestry, wood and paper industries such as industrial roundwood extraction, wood-based panel production, pulp and paper production, and wood fuel generation. The model estimates commodity balances by employing supply and use tables that link products and processes. These matrices quantify process inputs based on feedstock composition and technical conversion factors (FAO, ITTO and United Nations, 2020; UNECE and FAO, 2010), such as the conversion rate of 1.54 m³ of solid wood required to produce 1 m³ of particle board. Bilateral trade data from FAO and the BACI database (FAOSTAT; Gaulier and Zignago, 2010) are integrated into FORBIO to map the detailed flow of wood products. Where bilateral trade data are incomplete, gaps are filled using estimates derived from the differences between reported total imports/exports and available bilateral data, with adjustments made using the RAS method to ensure consistency with nationally reported totals. Corrections for re-exports are also implemented to avoid double-counting. FORBIO provides a strong product detail, allowing for analyzing trade flows in processed wood products, as opposed to other wood trade models, which usually aggregate all wood products into one or few categories of primary wood products (Kastner et al., 2011a; Roux et al., 2023; Zhang et al., 2020). More details about the FORBIO Model can be found in the appendix.

The key of our contribution is that we calculate the carbon flows embodied in the Raw Material Input (RMI) of wood for Austria. RMI denotes the sum of domestic extraction and gross imports (also equal to the sum of apparent consumption and gross exports), all in raw material equivalents. The benefit of this approach is that all wood entering socio-economic processing and use in the respective country is accounted for. This is necessary to quantify the origins of wood and associated carbon flows and to link it to the industry level. This is required because the origin of wood used by different processing industries may differ from the origin of wood embodied in final consumption. The composition of inputs across industries does not necessarily match the mix of products found in the final consumption basket, hence making it unwarranted to use the origins of final consumption for the processing industries.

To calculate Raw Material Imports and Exports, we used the method suggested by (Piñero et al., 2018).

To align FORBIO's estimates with Austria-specific data, we adapted FORBIO's import estimates to match the Wood Flow Diagram (WFD), which relies on Austrian-specific data. This involved aggregating products into common categories, calculating losses along international supply chains, and applying origin country shares from FORBIO to the WFD imports. This process yielded Austria's wood imports in raw material equivalents (RME) from their country of first origin. Similarly, Austria's exports were traced back to their origin countries, accounting for wood imported from other countries, processed in Austria, and re-exported. Loss factors and origin country shares from FORBIO were applied to WFD exports to calculate Austria's wood exports in RME. Recovered paper, recovered pulp, and post-consumer wood were excluded to avoid attributing gross harvest to these materials, as they do not represent new wood extraction (Kalcher et al., 2017). Adjusting for data gaps in the bilateral trade data and correcting for re-exports sometimes led to the situation that Raw Material Imports ended up being lower than actual imports for some products. For the products for which this was the case, we set the losses and upstream requirements to zero. The same applied to Raw Material Exports.

The shares of origin countries of domestic harvest and imports was then distributed along Austria's national wood supply chain through an iterative process. For each node of the Wood Flow Diagram (see previous section), the shares of origin countries of the incoming flows were allocated to the outgoing wood flows, yielding a wood flow diagram by origin countries.

Modeling forest biomass dynamics with CRAFT

The model CRAFT (Le Noë et al., 2020, 2021) reconstructs and quantifies dynamics in forest biomass carbon stocks and fluxes. Expanding simpler accounting models, it includes a place- and time-specific relationship between biomass C stocks and NPP to account for different forest growth conditions and their changes over time. The required input data on forest area, forestry harvest and some data points on forest biomass was collected from the national forest research center (BFW; https://www.bfw.gv.at/) at the subnational level of forest inspection districts (BFIs) in Austria and integrated in a reconciled (e.g., in regard to changing district boundaries) database covering the reporting periods 1992-1996, 2000-2002, 2007-2009, 2016-2021.

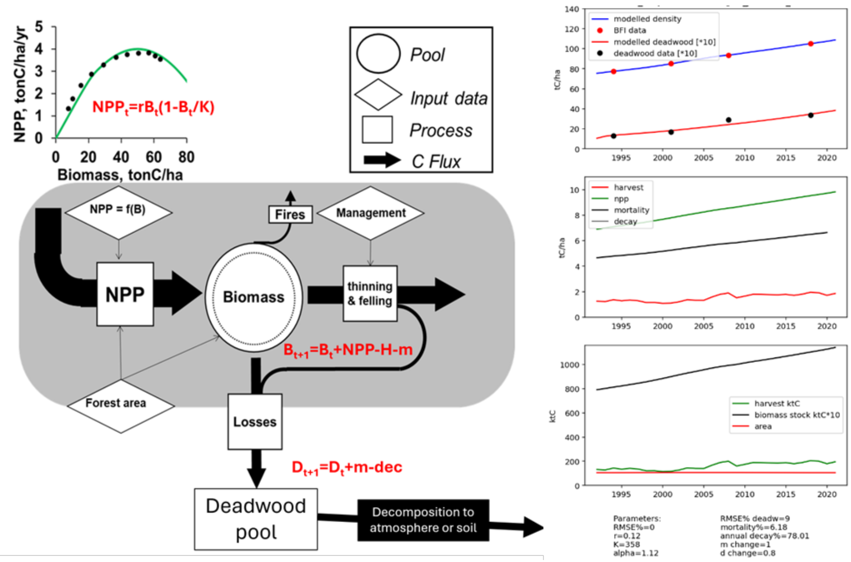

Figure: CRAFT model and its components. Inclusion of deadwood pool in CRAFT through accounting for mortality and decomposition of deadwood (left) and CRAFT model outputs for the example region St. Johann im Pongau (right).

As annual data on forest area and forestry harvest is required for modelling with CRAFT, we applied linear interpolation (for area) and as auxiliary information used the annual harvest time series from FAO which itself is based on the "Holzeinschlagsmeldung", albeit following different definitions than the forest inventories for harvest (Gschwantner, 2019). To reconcile FAO data with the NFI reports, the following approach was taken: The annual FAO values were adjusted based on the disparity apparent for the NFI reporting periods (NFI values were 103% to 116% higher than FAO values on the aggregated level). The distribution over BFIs was then also linearly interpolated between reporting periods and applied to the annual national values to arrive at annual harvest levels per BFI.

To harvest and biomass stocks we further applied biomass expansion and harvest loss factors to account for biomass compartments not reported in harvest statistics (e.g. branches, stumps, etc.) (Liski et al., 2002).

Based on these input data CRAFT calibrates the maximum theoretical carrying capacity K, the forest growth rate r and its change alpha within a range of possible values (Le Noë et al., 2021) to produce annual biomass stock and NPP estimates from 1992 to 2021 that best match the reported historical biomass stock dynamics.

This approach was used to produce annual, stock-flow consistent time series for Austrian forests as a total, as well as for coniferous and non-coniferous forests separately.

We also collected data on "standing deadwood" from BFW, which offered a starting point for the methodological development of the CRAFT model and the inclusion of a deadwood pool. For the reporting periods 1992-1994, 2000-2000, and 2007-2009 information is only available at the federal state-level ("Bundesländer"), but for the reporting period 2016-2021 values are reported at the level of 60+ forest inspection districts. Based on this information a deadwood pool was integrated in CRAFT by accounting for biomass affected by mortality and for harvest losses while at the same time subtracting decomposing biomass. In this adaptation of CRAFT, the mortality rate determining the inflow to the deadwood pool was kept constant but the rate of decomposition and its change over time was optimized to match the input data on standing deadwood. It has to be noted that based on this input data and model structure, the decomposition rate also includes the conversion of standing deadwood to lying deadwood and further communicates with the assumed mortality rate. Next steps in model developments include the modeling of the communication between disturbances such as windthrow or bark beetle infestations with harvest levels on the one hand and deadwood on the other hand.

Carbon Stock Forgone and Carbon Sink Forgone

The Carbon Opportunity Cost (COC) concept relies on the comparison of scenarios with and without harvest. In a given start year (yr0), we assume the forest carbon stock of harvest and no-harvest scenarios to be equal to C_0. Once wood is harvested, carbon stocks and sinks differ between the scenario with and without harvest. We call **Carbon Stock Forgone (CStF)** the difference between the carbon stock with and without harvest, and **Carbon Sink Forgone (CSiF)** the difference between the carbon sink with and without harvest. The CSiF is also the annual change in CStF. The CStF and CSiF can be understood as opportunity costs, in terms of forest carbon stock and sink, of harvesting wood compared to letting the forest grow older. We use **Carbon Opportunity Cost (COC)** when referring to both CStF and CSiF.

Constant harvest regime and Equilibrium Carbon Gap

In this study, COC values are calculated as the difference in carbon stocks and sinks between the no-harvest scenario and a hypothetical constant harvest regime scenario, assuming that wood harvest, climate and forest growth curves would remain unchanged over time (here 200 years). This approach allows us to analyze the dynamics of the COC and allocate it to harvest practices and supply chains, while excluding future changes in harvest, climate, and forest growth conditions. Constant harvest regime values of COC are not scenarios about actual future carbon stocks and sinks. Instead, they are estimates of a hypothetical carbon gap that would occur under constant current conditions, agnostic of future changes. The suggested indicators of COC are hence considering hypothetical forest dynamics under unchanged conditions, while being time-agnostic as all parameters and values are specific to the year of the analysis (here average 2015-17). If performing such analysis for other start years, each start year would be subject to its own carbon stock dynamics and hence potential carbon stock, due to changes in the initial biomass stock, as well as different climate or other growth conditions that can change in the course of time.

As forest carbon stocks saturate over time and reach a steady-state equilibrium between growth and mortality, carbon stocks without harvest saturate to the **potential carbon stock**. We call **actual carbon gap** the difference between the actual carbon stock in the moment of harvest, and the potential carbon stock. A constant harvest regime creates a new, lower equilibrium, where annual harvest equals annual net increment. Therefore, while the CSiF converges to zero, the CStF converges to a positive long-term value (Figure M2). We call this long term CStF the **Equilibrium Carbon Gap (ECG).** Note that at the stand level, this potential carbon stock would not be constant due to mortality and disturbances, as well as maintained growth of few very old trees, but that the dynamics of the potential carbon stock, on average at the national level, requires further investigation.

Note that if forest carbon stocks are being depleted (gross harvest > increment), carbon stocks under a constant harvest regime will fall to zero and the equilibrium ECG is equal to the entire potential carbon stock. Note that, even if forests carbon stocks follow a logistic form, the CStF can decrease slightly after having first increased, when in the first years, harvest < net increment with harvest < net increment without harvest, especially for small harvest values around the inflection point.

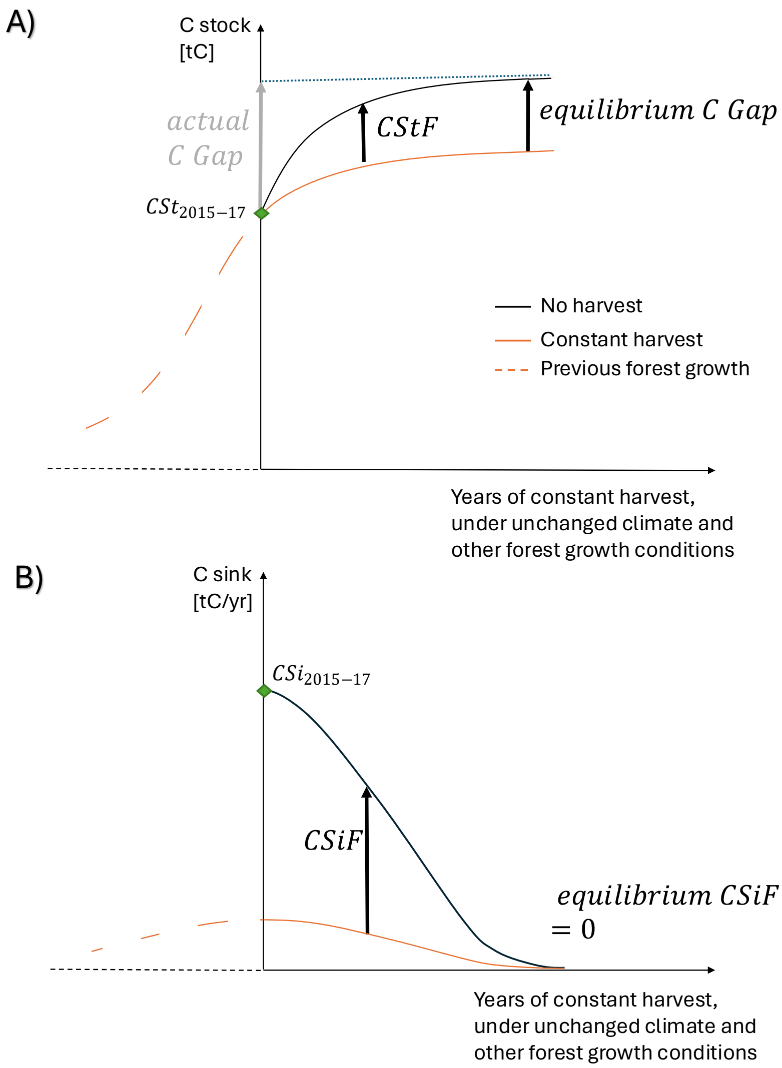

Figure M2: Illustration of the A) Carbon Stock Forgone (CStF) and B) Carbon Sink Forgone (CSiF) under a constant harvest regime. A) The logistic curve represents a carbon stock curve in the absence of harvest, converging towards a potential carbon stock (dotted line). If harvest occurs in year 0, when carbons stocks are C_0 and is maintained constant from there on, the CStF, i.e., the difference between the carbon stock with (black line) and without (orange line) harvest converges to an equilibrium carbon gap. B) Meanwhile, the CSiF, i.e. the difference between the carbon sink with (black line) and without (orange line) harvest converges to 0.

In CRAFT, forests fluxes are modeled as a national average stand

$$NPP = rB\left(1 - \frac{B}{K}\right)$$

$$mortality\ and\ disturbances = mB$$

$$net\ growth: NG = rB\left(1 - \frac{B}{K}\right) - mB - hB$$

With

r: forest growth rate

B: forest carbon density (biomass stock per area)

K: carrying capacity

m: rate of mortality and disturbances per biomass stock

h: rate of harvest per biomass stock

The equilibrium carbon density B^* is the density which satisfies:
NPP = mortality + fire + harvest

$$rB(1-\frac{B}{K}) = B(m+f)+h$$

Whose only meaningful solution is:

$$B^* = \frac{K}{2r}\left[(r-m-f)+\sqrt{(r-m-f)^2-\frac{4rh}{K}}\right]$$

Let:

- B_H^*: equilibrium carbon density with harvest (h>0)
- $B_{NH}^* = \frac{K}{r}(r-m-f)$ the equilibrium carbon density without harvest (h=0)

The Equilibrium Carbon Gap is defined as

$$\mathrm{ECG} = B_{NH}^* - B_H^*$$

Substituting the expressions gives:

$$\mathrm{ECG} = \frac{K}{2r}\left[(r-m-f)-\sqrt{(r-m-f)^2-\frac{4rh}{K}}\right]$$

Since $\sqrt{(r-m-f)^2-\frac{4rh}{K}} < (r-m-f)$ when h >0, it follows that

$$\mathrm{ECG} = B_{NH}^* - B_H^* > 0$$

Hence, under these conditions, harvesting (h>0) always reduces the equilibrium carbon density, for any positive forest growth rate r and mortality and fire rates m and f.

If the average rate of mortality and disturbances per biomass stock differs between between harvested and non-harvested forests (either already nowadays or under future climate change), then the equilibrium carbon gap vanishes ($\mathrm{ECG} \leq 0$) if:

$$m_{NH}+f_{NH} \geq \frac{1}{2}\times\left[(r+m_H+f_H)-\sqrt{(r-m_H-f_H)^2-\frac{4rh}{K}}\right]$$

In the latest version of the CRAFT model, mortality and disturbances are considered as a fixed factor of 6.2% for Austria, based on the turnover rate

(NPP/biomass stock) in the potential vegetation (Erb et al., 2018; Gingrich et al., 2025).
Future research will test this linearity assumption between mortality+disturbances and biomass stocks and better understand the effect of non-linear processes and thresholds, due to competition, stress, self-thinning, and disturbances, on average at the national level.

Climate change mitigation potentials of measures in forest and wood use

Harvest levels (Table M1) and corresponding forest carbon sinks for above-/belowground biomass, deadwood, and soils under RCP8.5 were taken from Care for Paris (BFW Praxisinfo51, Weiss et al., 2020).

Table M1: Wood harvest by scenarios

harvest (Efm - excluding harvest residues)	Average 2030-2050		Average 2060-2080	
Reference harvest	4.8	MtC/yr	5.0	MtC/yr
	19.0	Mm³/yr	20.1	Mm³/yr
Reduced harvest	3.8	MtC/yr	3.8	MtC/yr
	15.0	Mm³/yr	15.3	Mm³/yr
Increased harvest	6.6	MtC/yr	6.2	MtC/yr
	26.5	Mm³/yr	24.7	Mm³/yr

The sink in harvested wood products (HWP) and emissions avoided through substitution were computed by allocating Austrian harvest to end uses – energy, building, shaping construction, furniture, packaging, other (Pölz et al., 2015; Strimitzer et al., 2021). The initial share of energy use in total wood use was set to 54%. In the scenarios with constant material and energy use, this share was hold constant over the entire period. In the scenarios with increased material use (or cascading use), the share of energy use was halved to 27% by 2050, mirroring the evolution assumed in the transition scenario from Umweltbundesamt (Krutzler et al., 2023). The decrease is assumed to be linear between 2020 and 2050. After 2050, the share of energy in total wood use was assumed to be constant.

To calculate substitution effects, we used end-use-specific displacement factors. In the higher-bound energy displacement variants, we assumed that each kWh from wood-energy displaces a kWh from fossil fuels over the entire period. In lower-bound displacement variants, we assumed that wood-energy displaces the

Austrian energy mix, which decarbonizes over time using the UBA Transition pathway to approach zero by 2110 (Table M2).

Table M2: Decarbonized displacement factor of wood energy use

	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110
Displacement factor with transition decarbonization (tC / tC)	0.48	0.34	0.10	0.09	0.07	0.06	0.04	0.03	0.01	0.00

The concept of avoided emissions through substitution is highly contested. The assumption that wood use actually substitutes other fuels and materials indeed contrasts with historical evidence. Studies find a degree of substitution close to 0% for wood used for energy, meaning that historically, increased wood use has mostly accumulated on top of other fuels and materials rather than substituting them. Reversely, the assumption of substitution implies that reducing the use of wood is automatically compensated by an increased use of other fuels and materials, which ignores the possibility of reducing wood through sufficiency measures (i.e., producing and consuming less materials and energy overall). To account for these limitations, we multiply our lower bound estimate of avoided emissions (both for energy and material uses) by 50%, assuming a "moderate degree of substitution". This moderate degree of substitution implies that only 50% of wood actually substitutes other fuels and materials (while the other 50% increase the overall use of materials and energy). It also implies that 50% of the reduction in wood harvest and use is achieved through sufficiency measures and energy savings, hence without increasing the use of other fuels and materials. For the upper-bound estimate of avoided emissions, we assume an "ambitious degree of substitution" of 100% (Table M3).

Table M3 Assumptions for the upper and lower bound displacement factors for energy uses of wood.

Displacement factors in kg C [emissions] / kg C [wood]	Initial factor (year 2020)	Replaces	Decarbonization of the energy system	Degree of substitution
Upper bound	0.67 kg C / kg C	Only fossil fuels	No decarbonization of the energy system (fossil fuels can be substituted eternally)	Ambitious degree of substitution: every unit of wood-energy substitutes a unit of fossil fuels, and every reduction of wood-energy is compensated by an increase in fossil fuels.
Lower bound	0.48 kg C / kg C	The Austrian energy mix	Decarbonization of the energy mix, based on UBA Transition scenario, extrapolated after 2050	Moderate degree of substitution: only 50% of wood actually substitutes other energy sources. 50% of the reduction in wood harvest and use is achieved through sufficiency measures.

Material use displacement factors (Pölzl et al., 2015; Maierhofer et al., 2024) follow the decarbonization pathways from Care for Paris (Table M4).

Table M4: Decarbonized displacement factors by decades, by wood material uses

Displacement factors in kg C [emissions] / kg C [wood]	2020	2030	2040	2050
Building construction	-0.54	-0.47	-0.39	-0.31
Shaping construction	-0.82	-0.74	-0.65	-0.58
Furniture	-0.44	-0.39	-0.33	-0.29
Packaging	-0.33	-0.30	-0.27	-0.24
Other products	-0.17	-0.14	-0.11	-0.10

As for energy uses, we calculate a lower bound of avoided emissions of 50%, assuming a "moderate degree of substitution" and wood reductions achieved through material savings.

Harvested Wood Products were modeled via the IPCC production approach (2019 Refinement, Tier 2), splitting inputs into sawnwood, panels, and paper, applying default half-lives (35, 25, 2 years), and calculating net additions to stock annually.

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8 Publications und Dissemination Activities

Scientific publications

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- Baraclough L, Ebner M, Tappeiner U: Stakeholder expectations forfuture mountain forests: synergies, trade-offs, and tipping points in ecosystem service supply, in revision
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- Erb, K.-H., & Gingrich, S. (2022). How can forests help us? In G. Thunberg, The Climate Book (pp. 230–232). Random House. (without specific acknowledgement)
- Erb, K.-H., & Gingrich, S. (2022). Wie können Wälder uns helfen? In G. Thunberg, Das Klima Buch (pp. 252–254). S. Fischer. (without specific acknowledgement)

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- Tappeiner, U., Schirpke, U., Tasser, E. (2024) Linking ecological and socio-economic changes to assess impacts of global change on landscape and ecosystem services in the European Alps. EGU 2024, 14.-19.04.2024, Vienna, Austria.
- Tasser, E. (2024) Heimische Biodiversität: Wie und warum sie sich verändert hat. Colloquium der Plattform Biodiversität - Colloquio Piattaforma Biodiversità, 10.01.2024, Bozen, Italy.
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- Tasser, E. (2025) Unsere Gemeinde, unsere Verantwortung. Impulse für eine biodiversitätsfördernde (naturnahe) Raum- und Bauordnung. KLAR region Stansertal, 19.03.2025, St. Anton am Arlberg (invited presentation).
- Tasser, E. (2025) Unsere Gemeinde, unsere Verantwortung: Impulse für eine biodiversitätsfördernde (naturnahe) Raum- und Bauordnung. Remise/Arlberg Wellcom, 19.03.2025, , St. Anton am Arlberg, Austria (invited talk).
- Tasser, E. (2025) Raum und Boden in Zeiten des Klimawandels: Chancen und Risiken: Veränderungen in der Landwirtschaft und Folgen für den Tourismus. Sonnenterrasse KLAR!, Raum und Boden Workshop, 11.04.2025, Fiss, Austria (invited talk).
- Tasser, E. (2025) Erneuerbare Energien: Auswirkung auf Lebensräume und Artenvielfalt. Annual meeting of the Order „Der Silberne Bruch", 28.03.2025, Mils, Austria (invited talk).
- Tasser, E. (2025) Wie verändert sich der Alpenraum für Mensch und Wildtiere? Wildökologisches Forum 2025, 22.-12.05.2025, Salzburg, Austria (invited talk).
- Tasser, E. (2025) Folgen des Klima- und Landnutzungswandels auf die Gebirgsregion. Alpenvereins-Akademie: Modul 1: Naturschutz im Alpenverein, Alpenvereinshaus Innsbruck, 22.11.2025, Innsbruck (invited presentation).
- Roux N. (2025) Measures in Austrian land and biomass use to mitigate climate change - potentials, limits and controverses. Seminar of the BOKU Institute of Meteorology and

Climatology

- Roux, N; Maguet, M; Bruckner, M; Matej, S; Gingrich, S; Erb, K (2024) The global carbon sink forgone linked to Austrian wood supply chains, 10th International Degrowth Conference and 15th Conference of the European Society for Ecological Economics
- Nicolas Roux, Christian Lauk, Andreas Magerl, Dominik Maierhofer, Simone Gingrich, Karl-Heinz Erb (2025) Robustly assessing potentials for AFOLU climate change mitigation requires an integrated accounting framework. The case of Austria; Poster presentation at the 25. Österreichischer Klimatag
- Bioeconomy dialogues, BOKU energy and bioeconomy clusters
- Simone Gingrich, Nicolas Roux, Karlheinz Erb - Uni Graz-Joanneum Research event on nature-based CO2 sequestration, represented by Karl Steininger, https://www.joanneum.at/co2-bindung-land-und-forstwirtin-klimaretter/
- Erb, Karl Heinz. „Biomasse als limitierte Ressource“. Kick-off Event des Energieclusters: Energie aus Biomasse, 06.06.2023, Wien, Austria. 6. Juni 2023.
- Erb, Karl Heinz. „Scrutinizing the Role of Land Management for the Carbon State of Ecosystems“. Keynote at Anthromes, CO2 and terrestrial carbon: From the deep past to net-zero, 27.03.2023 - 30.03.2023, Pontomac, Maryland, USA. 27. März 2023.
- Erb, Karl Heinz, Sarah Matej, Nicolas Roux, und Simone Gingrich. „The Current Situation of Wood Use in Austria: A Detailed MEFA Analysis [Poster]“. In Tagungsband 23. Klimatag: Ressourcen Im Wandel, herausgegeben von CCCA Climate Change Centre Austria. 2023. https://ccca.ac.at/fileadmin/00_DokumenteHauptmenue/03_Aktivitaeten/Dialogveranstaltungen/OEsterreichischer_Klimatag/2023_Tagungsband_final.pdf.
- Gaube, Veronika, und Simone Gingrich. „Habitat Erde. Biodiversität Landwirtschaft Landnutzung“. S4F Akademie, [online], 21. Januar 2022.
- Gingrich, Simone. „Der Wald als nachhaltige Rohstoffquelle – Multifunktionalität des Waldes“. BioBASE Webinar, [online], 1. Februar 2022. https://biobase.at/pressemeldungen/biobase-webinar-der-wald-als-nachhaltige-rohstoffquelle/.
- Gingrich, Simone. „Landnutzung und Klimawandel in Österreich 1830-2020. Historische Entwicklungen und heutige Herausforderungen“. Woche der Nachhaltigkeit 2024: Gemeinsam. Zukunft, 11.11.2024 - 15.11.2024, Innsbruck, Austria. 11. November 2024.
- Gingrich, Simone. „Wie man in den Wald hineinruft...“ Vortragsreihe Akademie.ALPIN.arium, Galtür, Austria, 19. September 2022.
- Gingrich, Simone, und Karl Heinz Erb. „The Global Land Squeeze - A Socio-Ecological Perspective on Providing Biomass While Safeguarding Biosphere Integrity“. The Global Land Squeeze: An interdisciplinary symposium, 28.–31. Oktober 2025, Aarhus, Denmark [online]. 28. Oktober 2025.
- Erb, Karl-Heinz. 2022.The RED’s incentives to use forest biomass are damaging EU forests...and damaging the climate. Presentation at the Expert briefing on Bioenergy, hosted by the European Commission - DG Energy, 8.6.2022
- Gingrich, S. 2023. Die Nutzung von Biomasse durch Menschen und was für andere Arten übrig bleibt. Vortrag. Veranstaltung "Pflanzliche Biomasse in Österreich Teil 2 - Nutzung 2050". 29.2.2024, Boku University
- Erb, K.-H. 2023. Auch Biomasse ist endlich. Vortrag. Veranstaltung „Pflanzliche Biomasse in Österreich Teil 1 – Verfügbarkeit“, 28.11.2023, Boku University.
- Tasser, E. (2023) Wildtiere als Indikatoren für die Qualität einer Landschaft (Divje zivece zivali kot indikator kakovosti pokrajine; Animali selvatici, indicatori di qualitàbdel territorio). Tagungsband zur 69. Tagung der AGJSO, Arbeitsgemeinschaft der Jagdverbände des Südostalpenraumes: 13-22.

Lectures:

- Tappeiner., Tasser, E.: Struktur und Funktion von Gebirgsökosystemen. 743156, EU 2, SS24, Universität Innsbruck.
- Tappeiner, U., Tasser, E.: Struktur und Funktion ausgewählter Ökosysteme. 743156, VO 1, WS24/25, Universität Innsbruck.
- Tasser, E. (2025) Bunte Vielfalt vor Ort: Die Bedeutung und Förderung von Biodiversität in Gemeinden und Betrieben. Klimaschutzlehrgang, Klimabüdnis Österreich, 31.01.2025, Vill, Innsbruck, Austria.
- Simon, A., Tasser, E., Vitecek, S.: Grundlagen der angewandten Ökologie. 743407, VO 1, SS25, Universität Innsbruck.
- Simon, A., Tasser, E.: Angewandte Ökologie – terrestrische Systeme. 743418, VO 2, SS25, Universität Innsbruck.
- Tappeiner, U., Tasser, E.: Struktur und Funktion von Gebirgsökosystemen. 743155, VO 1, WS25/26, Universität Innsbruck.
- Tappeiner, U., Tasser, E.: Struktur und Funktion ausgewählter Ökosysteme. 743516, VO 1, WS25/26, Universität Innsbruck.
- Karlheinz Erb, Helmut Haberl: Land use and Global Change, WISO300754, VS 2, WS24/25, WS25/26, Boku University
- Karlheinz Erb, Brady Mattsson, Peter Hietz: Land use, climate change and biodiversity (in Eng.), WISO300770, VS 2, WS2024/25, WS2025/26, Boku University

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