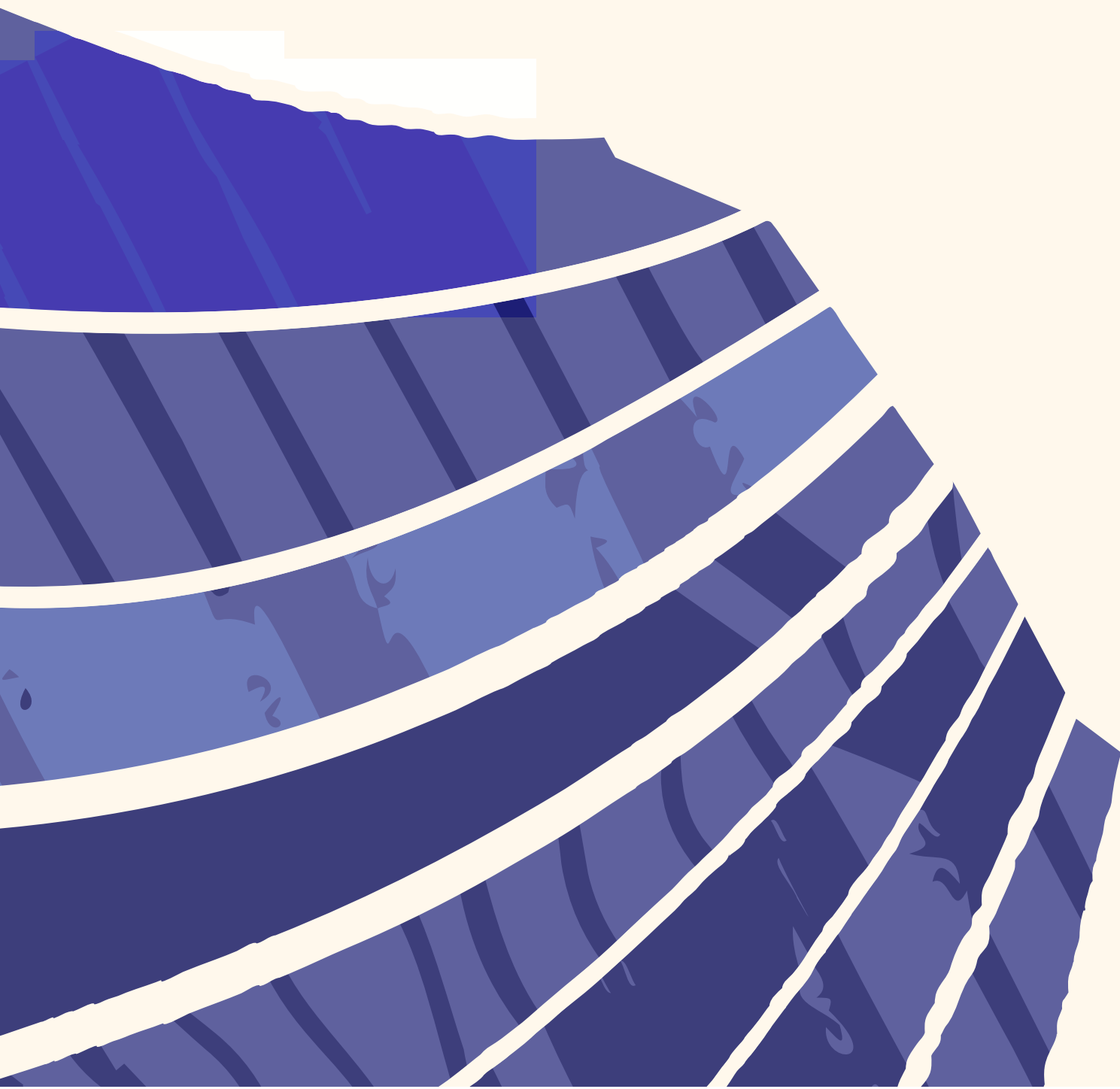


Chapter 2

Climate change, land use, ecosystem services and health



Second Austrian Assessment Report on Climate Change | AAR2

Chapter 2 Climate change, land use, ecosystem services and health

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EXECUTIVE SUMMARY

Land-related human activities that benefit from multiple ecosystem services constitute an important element of Austria's greenhouse gas (GHG) budget (*high confidence*). Agricultural activities, which are essential for food production, contributed 9.9 % to Austria's total GHG emissions during the most recent available 5-year average (2019–2023), dominated by CH₄ and N₂O (*high confidence*). For the same period, the sector land use, land use change and forestry, contributed 2.3 % of Austria's GHG emissions (*medium confidence*). This sector represented in the past a strong carbon sink, which decreased since the early 2000's and turned into a source around 2020, characterized by large year-to-year variations. {2.1.1}

The use of land for human livelihoods alters biogeochemical cycles and ecological patterns and processes, affecting the climate system, biodiversity and ecosystem services (*high confidence*). There are multiple trade-offs between different ecosystem services, mostly because the (global) land surface is limited. Rapid reductions in anthropogenic greenhouse gas (GHG) emissions that limit warming to 'well-below' 2°C would greatly alleviate, while warming above 2°C will exacerbate existing trade-offs. {Chapter 2}

The future provision of agricultural crops for feed, food, fiber and fuel will be compromised by climate change, particularly regarding water availability (*medium confidence*). Among the wide range of temperature, precipitation and adaptation scenarios, impacts of climate change on agricultural yields show a high variance from negative to positive (*high confidence*). Impacts of extreme weather events, other disturbance factors (e.g., pests), the role and effect of CO₂ fertilization, adaptation measures (e.g., new crop types, plant breeding) still represent knowledge gaps. {2.2.1}

Forest-related disturbance regimes (drought, fire, windthrow, snow and ice breakage, bark beetle) are projected to increase with climate change, negatively affecting some important ecosystem services (*high confidence*). However, the extent of the resulting damage to forests and impacts on ecosystem services cannot yet be reliably quantified and assessed. Impacts on the protection function of forests against gravitational natural hazards and on the protection of drinking water resources can be assessed with *high confidence*, while impacts on the provision of wood for timber and ener-

gy or on carbon storage are difficult to quantify. {2.2.1, 2.2.2, Chapter Box 2.2}

Climate change threatens the extent and quality of services provided by ecosystems (*medium confidence*). In addition to provisioning and regulating services in agriculture and forestry, cultural ecosystem services are also affected. This includes impacts on certain recreational activities through reduced snow fall, increased rock fall, and reduced water quality. However, warmer temperatures also create opportunities, e.g., for bathing activities or summer tourism. {2.2.2, 2.2.3}

In limited situations, climate change improves ecosystem productivity due to increasing temperatures extending growing seasons (*medium confidence*). In both forestry and agriculture, observations show that a warmer climate increases plant productivity. These opportunities are jeopardized by the speed of change – in forestry, challenges are related to the long rotation periods in forest management, which limit the rapid adaption of tree species to take advantage of a different climate, while in agriculture, infrastructure changes are needed to allow for handling extreme weather situations (droughts, cold spells, heat waves). {2.2}

Irrigation needs will require new perspectives on water availability (*medium evidence, high agreement*). Provisioning of drinking water will be impaired in certain regions of northern and eastern Austria, whereas the increased need for agricultural irrigation will impact water resource planning significantly across Austria during drought events. {2.2.1}

Ongoing climate change will have regionally diverse impacts on the provision of ecosystem services due to complex biophysical conditions (*high confidence*). Notably, (1) a general decrease of all ecosystem services, particularly provisioning ecosystem services, is expected in the northern Alpine foothills and highlands, in the southern Alps with the Klagenfurt Basin and in the central Alps (*medium confidence*); (2) a spatial shift of dominant ecosystem services towards higher elevations will occur for regulating ecosystem services and towards low and peripheral areas for provisioning ecosystem services, depending on water availability and plant stress profiles (*medium confidence*). {2.2}

Some of Austria's international supply chains will become more vulnerable (*medium confidence*). Austria is a net importer of biomass, importing mainly raw materials and exporting mainly highly processed and manufactured final products. About 16 % of Austria's imports of food and feed and 5 % of Austria's imported wood products originate from regions that are moderately to highly vulnerable to climate change and do not yet appear to be ready to adapt, especially tropical and Mediterranean regions. {Chapter Box 2.1}

Technical and management measures in agriculture and forestry can reduce greenhouse gas emissions and increase sinks but their mitigation potential is limited (*high confidence*). Compared to a reference scenario, measures in agricultural management (e.g., increasing soil organic carbon, reducing emissions from agricultural inputs, optimizing livestock farming) show mitigation potentials of 0.4 to 2.5 MtCO₂eq/yr (*medium confidence*). Adaptive forest management like changing tree species shows a mitigation potential up to 1.9 MtCO₂eq/yr (*low confidence*), calculated over 2020–2150. This potential materializes only under a high global warming level (GWL; between GWL 4.0°C and GWL 5.0°C) and primarily beyond 2080. {2.3.1}

Tapping far-reaching mitigation potentials in agriculture and forestry requires structural measures reducing the use of biomass and changing current economic practices and consumption patterns (*high confidence*). Ambitious mitigation will require far-reaching measures with substantial costs, involving trade-offs and structural disruptions, such as loss of livelihoods for farmers or the need to deal with spillover effects (*high confidence*). Shifting towards healthy, plant-based diets shows mitigation potentials of 5.0 to 15.4 MtCO₂eq/yr, when agricultural production can be restructured to reduce agricultural emissions and increase sinks through afforestation on freed agricultural land (*medium confidence*). Halving food waste may reduce emissions by 2.1 to 4.7 MtCO₂eq/yr (*medium confidence*). Prioritizing long-lived harvested wood products over energy show mitigation potentials of 0.1 to 0.5 MtCO₂eq/yr (*low confidence*). In the currently only available set of model results for Austria, contrasting two scenarios shows that annual average wood harvest of 25 million Vfm/yr (15 million Efm/yr) compared to wood harvest levels of 30 million Vfm/yr (25 million Efm/yr) will yield a mitigation potential of 7 to 8.4 MtCO₂eq/yr until 2150. Current harvest levels (2016–2022) are 25 million Vfm/yr (20 million Efm/yr). To which

extent the realization of all these potentials is constrained by climate change induced disturbances (e.g., increases in windthrows, insect infestations, vegetation fires) remains a research gap. {2.3.2, 2.3.3, Chapter Box 2.2}

Implementing mitigation measures along the entire value chain, including production, processing, trade and consumption, is crucial to avoid leakage or spillovers (*high confidence*). Shifting emissions and environmental pressures to other regions through increased imports and exports negates any climate benefit, but trade measures can mitigate leakage. Research gaps exist for mitigation strategies that consider the total food system, encompassing more than just emissions from agricultural production. {2.1.1, 2.3.3, 2.A.9, 2.A.11}

Various land users compete for the resources, services and benefits they derive from land, inducing conflicts of objectives and interests (*high confidence*). A major conflict exists between biomass extraction on the one hand and carbon storage, biodiversity and nature conservation (with their associated social benefits and costs) on the other hand. There are also potential conflicts between agricultural uses and renewable energy, e.g., in the case of agriphotovoltaics, wind and water energy. Ambitious mitigation measures entail important challenges and conflicts. Transparent and democratic negotiation of trade-offs between values and stakeholders is essential to overcome barriers to the transformations of the land use system, counteracting path dependencies and unequal power relations among actors, while supporting vulnerable land users. {2.4}

A fundamental conflict unfolds between economic growth and environmental conservation (*high confidence*). Economic growth, in its current form, drives increased production and consumption and thus land demand, making it a key driver of climate change and biodiversity loss, e.g., due to land-use intensification and land-conversions. Technological improvements that increase yields partly offset land demand, but rebound effects in the land system often annihilate the efficiency gains. {2.4}

Adverse effects on the health of the Austrian population due to climate change are visible already, and these effects are expected to increase, as climate change continues (*high confidence*). In particular, extreme weather events such as heat waves pose serious health threats including prema-

ture death, but also non-fatal disease, reduced well-being and productivity. These impacts affect different population groups in different ways, raising the issue of environmental justice. The poor, elderly and chronically ill, those with physically or mentally demanding jobs, and members of ethnic minorities are and will be most affected. Geographical differences must also be considered, both at the small (e.g., urban heat island, poor neighborhoods) and larger scale (e.g., mountain regions). {Cross-Chapter Box 2}

Local mitigation measures, while benefiting the climate globally, can also exert remarkable beneficial effects on public health locally, e.g., regarding healthy diets or sustainable (pollution-free) modes of transport (*high confidence*). Nevertheless, poor implementation of measures (both mitigation and adaptation) could also have negative effects on health. Evaluating measures from a health perspective (health in all policies concept) allows to avoid such implementation failures. {Cross-Chapter Box 2}

The health care system contributes to climate change with its own carbon footprint (*limited evidence, high agreement*) and could also contribute substantially to the mitigation efforts. {Cross-Chapter Box 2}

Human health is highly dependent on functioning provisioning systems, which include global supply systems, local infrastructure and many ecosystem services. These are threatened by ongoing climate change (*medium evidence, high agreement*). Both ongoing long-term changes and acute extreme events can have long-lasting negative consequences for physical and mental health and social well-being. Pressures from climate change elsewhere in the world could affect health and the health care system in Austria. Chronic effects, especially on mental health, of extreme events and climate change have been documented elsewhere but are still heavily understudied in Austria. The interplay between ecosystems and human health, together with animal health, is an important aspect of One Health. {2.2, 2.3, Cross-Chapter Box 2}

2.1. Chapter Introduction

The impact of climate change on life is far-reaching. Rising temperatures, altered precipitation patterns, and different wind exposure influence the way land is used by humans and covered by vegetation. Changes in land use and vegetation also influence animal husbandry as well as wildlife. Human livelihood and health are affected by climate, climate change and the ecosystems around them.

Land ecosystems provide a wide range of essential, partly irreplaceable services to human society (*high confidence*). They support production of crops and livestock serving as food to nourish our global population (IPCC, 2019a). Ecosystems also produce fibers and energy resources, contributing to various industries and ensuring our energy needs

are met, and they are hosts to biodiversity (IPBES, 2019). Freshwater, an essential resource, is regulated by land ecosystems through processes such as filtration and groundwater recharge (Reid et al., 2005; IPCC, 2019a), securing a vital supply for drinking, agriculture, and industry. Moreover, these ecosystems actively participate in climate regulation by sequestering carbon, mitigating climate change, and influencing local weather patterns (IPCC, 2019b; Erb et al., 2023a).

This chapter assesses the current state of scientific knowledge for Austria on the interlinkages between climate change, ecosystems, and the services they provide to human society, including human health (see also [Cross-Chapter Box 2](#)). Here we use the concept of ecosystem services as a classification scheme that describes the benefits humans

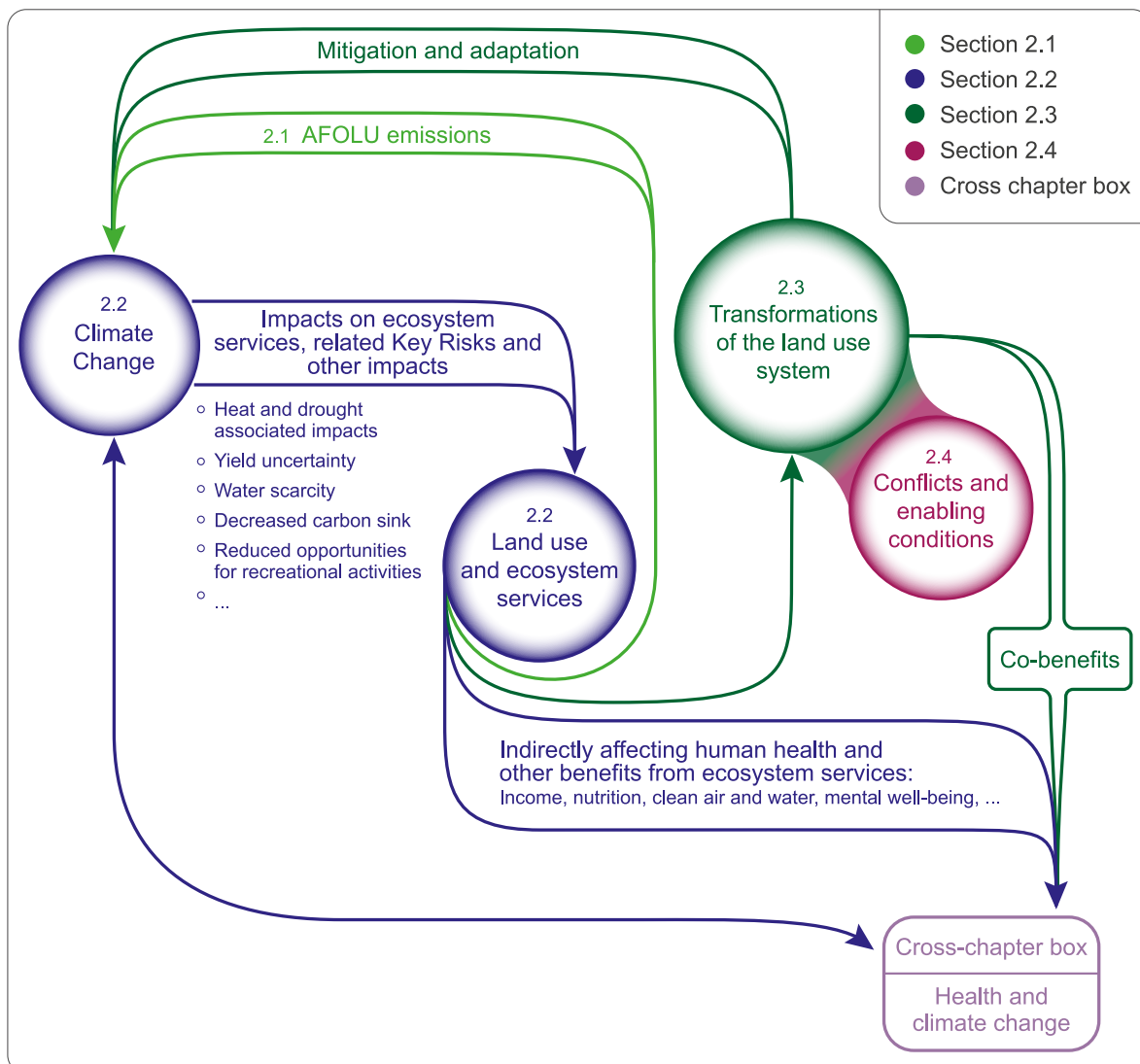


Figure 2.1 Chapter structure and overview of topics.

derive from ecosystem functioning (see 2.A.1). These services are closely linked to human land use. As land is a finite resource, land use in many cases involves land competition, i.e., the use of land for only one of several possible purposes (Haberl, 2015; Meyfroidt et al., 2022; Erb et al., 2024). Certain land uses may specifically affect the adaptation to and mitigation of climate change, in particular by inducing greenhouse gas emissions, depleting carbon stocks, or altering the resilience of ecosystems to climate change. However, ecosystem functions can also be employed to remove and sequester carbon from the atmosphere by increasing carbon pools in ecosystems (Griscom et al., 2017; Bossio et al., 2020), an essential but not sufficient strategy to combat global warming (Boysen et al., 2017; IPCC, 2019a). Moreover, ecosystems can also contribute to mitigating the impacts of climate change, especially through their regulating capacity.

In agreement with the concept of ecosystem services, the approach taken here is deliberately anthropocentric. This does not mean that we ignore or undervalue the ethical intrinsic values of all living beings and ecosystems (Vilkka, 2021), but it is consistent with the basic objectives of the assessment report. These are (i) to identify societal strategies to adapt to unavoidable climate change, (ii) to contribute to the design and implementation of such strategies, and (iii) to devise pathways for human activities (including production and consumption) and their land use impacts that are consistent with the goal of keeping global warming well below 2°C above pre-industrial levels. Thus, we describe activities and changes in human practices to adapt to or reduce the impacts of climate change. Since natural or near-natural ecosystems cover a relatively small part of the Austrian landscape and have already been covered in Section 1.6, this chapter will focus mainly on human land use.

Key input to this chapter was taken from science performed in Austria and about Austria. Relevant compilations are available as the recently completed Special Reports to the Austrian Assessment Report (in German language), specifically on Land Use and Climate Change (Jandl et al., 2024c), on Health, Demography and Climate Change (APCC, 2018), and on Structures for a Climate-Friendly Living (Aigner et al., 2022). The discussions that these reports were able to provide in much detail inform the views arrived at in this chapter.

The chapter covers the following elements (see Figure 2.1): Section 2.1 summarizes the state of current land use in Austria, associated resources, greenhouse gas emissions and ecological carbon stocks. Section 2.2 assesses the impacts of cli-

mate change on a range of ecosystems services are discussed and if possible quantified. Here, the Common International Classification of Ecosystem Services (CICES) is used to classify impacts – see 2.A.2 (Haines-Young and Potschin, 2018). Where traceable, indirect impacts of climate change (as on human health) are also assessed. Given the high dependence of the Austrian supply systems of land-based products from global value chains, special attention is paid to the assessment of the linkages between Austrian land use and global ecosystems (Chapter Box 2.1). Based on various national (Allianz Nachhaltige Universitäten in Österreich, 2021; Aigner et al., 2022) and international classifications (Roe et al., 2019), Section 2.3 discusses possible land-based activities and transformations to achieve climate change adaptation and mitigation and assesses their potentials (including health impacts). The resulting challenges related to potential land-use conflicts and opportunities to overcome them conclude the analysis (Section 2.4). Direct land-use considerations for human health are discussed throughout the chapter, while other health-related issues are addressed separately in Cross-Chapter Box 2, with interrelated concepts described in 2.A.3. The notion of considering ecosystems and their services as a foundation of human well-being (Reid et al., 2005) serves as the overarching concept.

2.1.1. Resource use and greenhouse gas emissions from Austria's land system

Biomass flows from ecosystems to consumption

Most land use and associated greenhouse gas emissions are related to the provision of biomass. Biomass can be used for the provision of food, feed, fibers and fuel. Figure 2.2 shows an approximation of biophysical biomass flows through the Austrian economic system (Kalt, 2015; Eisenmenger et al., 2016; Jacobi et al., 2018; Strimitzer et al., 2022), but following simple approaches (see 2.A.14). In total, the biomass input to the economy is about 24.5 MtC/yr (year 2020). The Austrian economy is deeply interconnected with global markets and heavily dependent on both imports and exports (*high confidence*). In terms of carbon units, biomass imports represent more than one third of the biomass input to Austria's economy. Exports are about half the size of imports (note that due to data limitations, exports of paper and highly processed wood products are not included). Agriculture production and wood harvest contribute about equally to domestic biomass extraction.

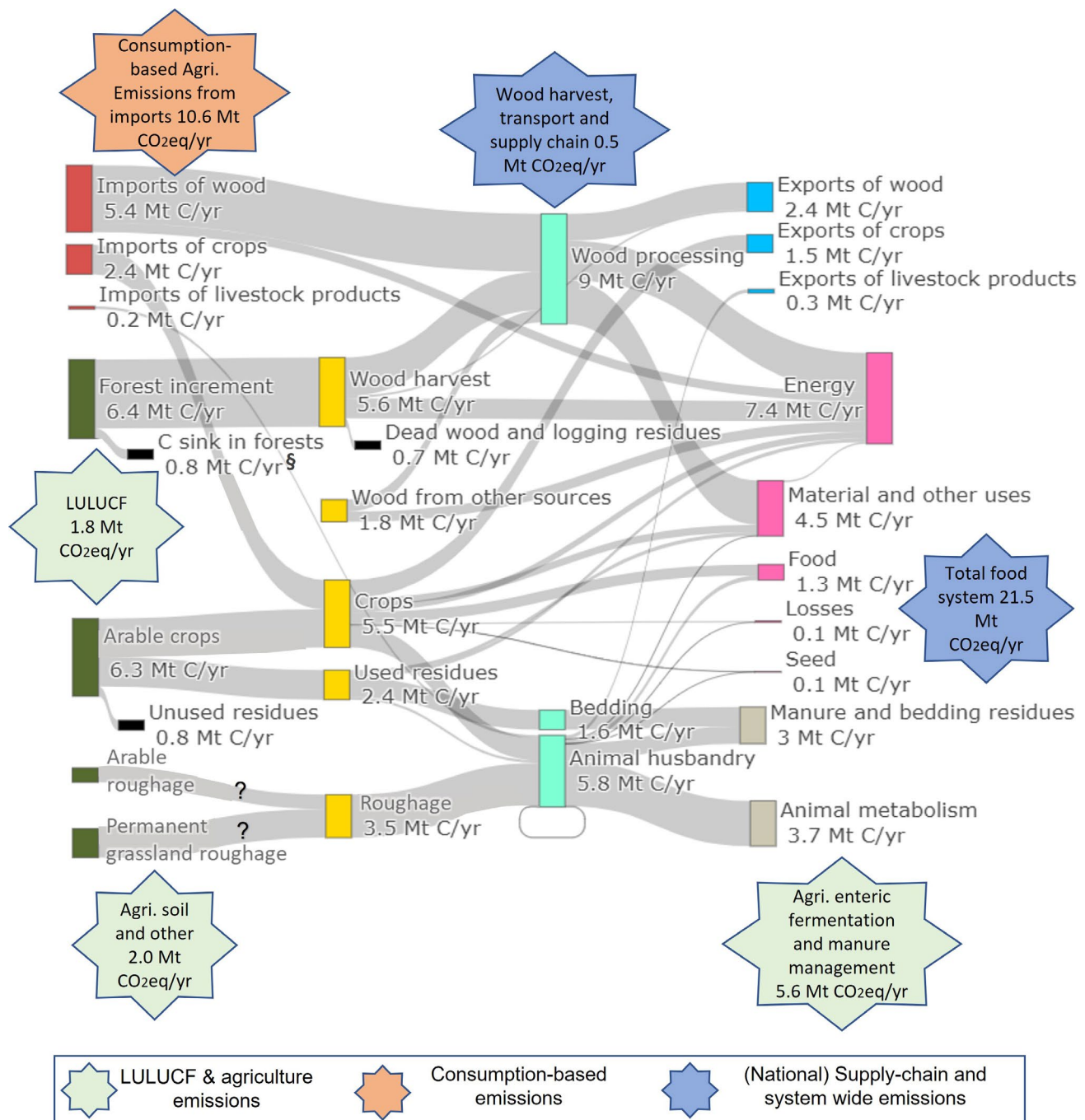


Figure 2.2 Approximation of biomass flows in Austria's socioeconomic system in MtC/yr and related GHG emissions. Biomass flows (year 2020) (Kalt, 2015; BMK, 2022; Erb et al., 2023a; Roux et al., 2023, updated as explained in 2.A.14). LULUCF and agriculture emissions are from Umweltbundesamt (2025a), on average for 2019–2023. These emissions are displayed in detail and for several years in Table 2.A.2 in 2.A.5. Consumption-based emissions are from Frey and Bruckner (2021) for the year 2013. Food system emissions are from Crippa et al. (2021) for the year 2015, and wood supply chain emissions are from Kühmaier et al. (2022) for the year 2018. Wood flows in [m³] have been converted to [tC] using a crude factor of carbon density [500 t dry matter/m³], dry matter biomass flows were converted to carbon fluxes applying a carbon content factor of 50 %. Note that foreign trade of manufactured wood products (millwork, furniture, paper, etc.) is missing in this scheme. [§] Forests acted as carbon sinks in 2020 (grey arrows), but are a source of CO₂ in the five-year average (colored stars). Color coding is used to indicate similarity of components (imports, domestic extraction, processing stages, exports, final consumption, etc.). The loop below animal husbandry represents animal products used as feed (especially milk and whey). Data are subject to various uncertainties, including statistical discrepancies (e.g., between forest increment, forest sink and wood harvest).

The largest processing nodes in Austria's economy are the wood processing industries and the energetic use of biomass (9 and 7.4 MtC/yr, respectively). The latter is associated with corresponding C-emissions to the atmosphere. At the production side, biomass provision is sustained by a flux of carbon from the atmosphere to the land ecosystems. For the quantification and balance of these flows (see Section 2.1.1). Also, an important node is the livestock sector, with feed input of about 5.8 MtC/yr and 1.6 MtC/yr of bedding, yielding 0.8 Mt of animal products and ca. 3 Mt of manure and bedding residues, while the rest is metabolized and exhaled by animals as CO₂ and CH₄.

The wood sector is particularly important in biophysical terms with a total domestic material input (DMI; domestic extraction plus imports) of 11.8 MtC/yr in 2020. Imports of wood and wood products exceeded the production of wood from domestic forests by 11 %. Exports reported in the Austrian wood flow diagram (roundwood, sawn wood and sawmill-byproducts) are about half of the import volume, however, foreign trade with millwork and paper is not included in the wood flow diagram and Figure 2.2, resulting in an underestimation of wood exports (see below). The domestic wood harvest averaged 89 % of annual stem wood increment in the last inventory period (2016–2021) and showed an increasing trend over the last decade, leaving only little room for enhancing domestic wood provision under sustainability criteria and with current management practices (European Environment Agency, 2017; Beck-O'Brien et al., 2022; Kirchmeir et al., 2022; Erb et al., 2023a). The amount of woody biomass used for energy purposes, at 6.4 MtC/yr, is almost equal to the total amount of wood harvested domestically from forest and non-forest ecosystems with woody vegetation in Austria. Overall, the energy use of wood biomass covers about 17 % of the gross domestic consumption of energy (BMK, 2023). 38 % of the energy use of wood derives directly from domestic harvest, which is directly used for energy, and 12 % comes from direct imports (firewood, sawmill by-products and pellets). The remainder (50 %) are residual materials from processing, including black liquor from paper production, which are of mixed domestic and imported origin. On average, the average share of imports in the energy use of wood biomass is 39 % (Erb et al., 2023a).

The agricultural sector shows a DMI of 12.4 MtC/yr with a dominance of domestic extraction. 1.3 MtC/yr are consumed as food (11 % of the DMI), while material and energy uses of agricultural biomass are significantly smaller. Animal husbandry, including bedding straws represent 64 % of the agriculture DMI and leads to an output of 0.8 MtC/yr

in the form of animal products (meat, milk, eggs, including hatching eggs and animal products fed to other animals). The remainder consists of manure, bedding residues, emissions and waste and represents a key component of AFOLU emissions (see below).

Current ecosystem carbon stocks and greenhouse gas emissions from agriculture, forestry and other land uses

Available data on C stocks are essential for estimating stock changes and hence greenhouse gas emissions or sinks in ecosystems. Land use related C stocks occur as soil organic carbon (SOC) and biomass carbon stock (often separated into above and below ground biomass). Land use is a key determinant of these carbon pools, interacting with other factors (e.g., organic soils show considerably higher SOC contents than mineral soils). The total C-stock in vegetation and soils is 1273 (±341) MtC (Table 2.1), of which about one third is in biomass and two thirds in the form of soil organic carbon (SOC). Conceding regional differences due to biophysical conditions, including soil types and local climatic conditions, changing land use will lead to a gradual adjustment of SOC in soil over decades (Baumgarten et al., 2021). Forests contribute more than 60 % to the total ecosystem carbon stock of Austria, followed by unmanaged/unsurveyed land, while all other categories play a smaller role.

On average over the last five years with data (2019–2023), the total sum of emissions from the UNFCCC-sectors 'Agriculture' and 'Land use, land-use change and forestry' (LULUCF) fluxes was a net source of greenhouse gases (flux from the biosphere to the atmosphere), of about 9.4 MtCO₂/yr (Figure 2.3 and Table 2.A.2), or about 12.3 % of the total GHG emissions in Austria (19.8 % in the year 2023). In the five-year average, the total carbon flux in agriculture and LULUCF reached a maximum sink strength of >13 MtCO₂eq/yr around 2000, which decreased continuously (by approximately 1 MtCO₂/yr) to turn from a sink to a source after 2014 (Figure 2.3A). Here and elsewhere in this chapter, total GHG emissions include also those of LULUCF.

Agricultural emissions are dominated by CH₄ emissions from enteric fermentation, i.e., ruminant livestock production, whereas soil N₂O emissions (direct and indirect) play a much smaller role, followed by manure management (see also Lauk et al., 2024). In total and on average between 2019 and 2023, emissions from agriculture, excluding direct and

Table 2.1 Area of land use and carbon stocks in Austria, 2020 (from Umweltbundesamt, 2023a; Baumgarten et al., 2021; ^a Seeber et al., 2022; ^b Tappeiner et al., 2008; ^c Tasser et al., 2020). Note that a fraction of grazing land is subsumed under unsurveyed land in this table.

	Area	Average carbon stock in biomass per area (above and below ground)	Average soil organic carbon per area in the layer 0–30 cm	Range of carbon stocks [§]
Land use	[1,000 ha]	[tC/ha]	[tC/ha]	[MtC]
Cropland	1,283	6.7±4.1b	62.5±19.9*	63–115
Mountain grassland	12	8.3±2.3a	108.73±41.9	1–2
Extensively used grassland	323	7.9±2.2a	122.2±58.1	23–61
Intensively used grasslands	459	6.1±1.9a	95.3±15.0	40–53
Vineyards / orchards	40	25.4±6.9c	49.1±15.6*	2–4
Forest ^Ω	4,015	106.5±10.0	115.3±46.0	702–1,080
Peatland**	21	41.3±14.5b	220.0±70.0*	4–7
Settlements	568	2±0.6b	39.6±12.6*	16–31
Unmanaged land/unsurveyed land	1,667	9.6±2.5a	146.8±25.5	218–303
Total	8,389	54.9±4.9	107.5±22.9	1,165–1,559

* Range estimate unavailable, the average of all ranges (±32 %) was taken.

** Natural peatland area only

^Ω Per-area C-stock data from the year 2020 FAO/FRA. Data do not contain deadwood.

[§] For ranges, error margins of individual components were combined assuming error propagation of a normal distribution for independent data.

Error margins of total were derived using the same logics. Hence also the range of the total is smaller than the difference between sums of low and high estimates.

indirect technical emissions (e.g., machinery, mineral fertilizer production) amounted to 9.9 % of total GHG emissions (10 % for the year 2023) (*medium evidence, high agreement*).

On average between 2019–2023, the sector LULUCF contributed +2.3 % to Austria's total GHG emissions (in the year 2023: 9.9 %). The LULUCF inventory shows strong annual fluctuations, particularly in the forest compartment (stock increases and decreases in existing forests, not so much in area expansion), which makes the interpretation of individual time cuts intricate. Figure 2.3A shows the total GHG fluxes between 1990 and 2023 according to the 2025 GHG inventory (Umweltbundesamt, 2025a). The data represent a major update of the calculation methodology, see 2.A.4 for a comparison with the previous inventory version. Changes in forest (forest remaining forest and new forest land) account for 0.3 % of total emissions in the five-year average (7.1 % in the year 2023). In 2018, and especially in 2019 and 2023, forests decreased in carbon stocks so that the aggregated agriculture and LULUCF sectors acted as strong net source of GHG emissions (*medium confidence*). In all years before 2018, forests had acted as carbon sinks and compensated for a considerable share of Austria's GHG emissions, especially around the year 2000. Changes in other land-use types (i.e., excluding forests), account for about 3.6 % of the total emissions on average (3.7 % in 2023) and harvested wood

products represent a sink of –1.6 % on the five-year average (–0.9 % in 2023).

While emissions from agriculture slightly decreased over the same period, mainly due to a decreasing livestock herd (FAOSTAT), the overall development is mainly driven by forest dynamics (Figure 2.3B). Increment increased from 2.8 m³/ha/yr in 1954 and 5.7 m³/ha/yr in 1961–70, to 9.4 m³/ha/yr for the 1981–1985 inventory, and decreased since then, reaching 9.3 m³/ha/yr in the period 1986–1990 and 8.2 m³/ha/yr in the period 2007–2009 to 2016 (Austrian National Forest Inventory, accessed in 2024). In the meantime, the inventory method has changed and might influence those findings. Schieler (1997) proved that the increments based on the 1961–1980 method are comparable with those since 1981. On the other hand, annual wood harvest increased from 3.4 m³/ha/yr in 1954 to 7.8 m³/ha/yr in the period 2000–2002 to 2007–2009 and was 7.4 m³/ha/yr in 2007–2009 to 2016–2021. Taking the total wood harvest from census statistics (BMLF, 2024b), the share of wood harvest triggered by wind, snow or bark beetle damage in Austria was on average 26 % between 1990 and 2021 (28 % in the last decade), and showed strong variations, with a minimum in 2001 (9 %) and a maximum in 2008 (55 %). Note that harvest estimates from the annual census statistics (HEM) are significantly lower than harvest estimates from

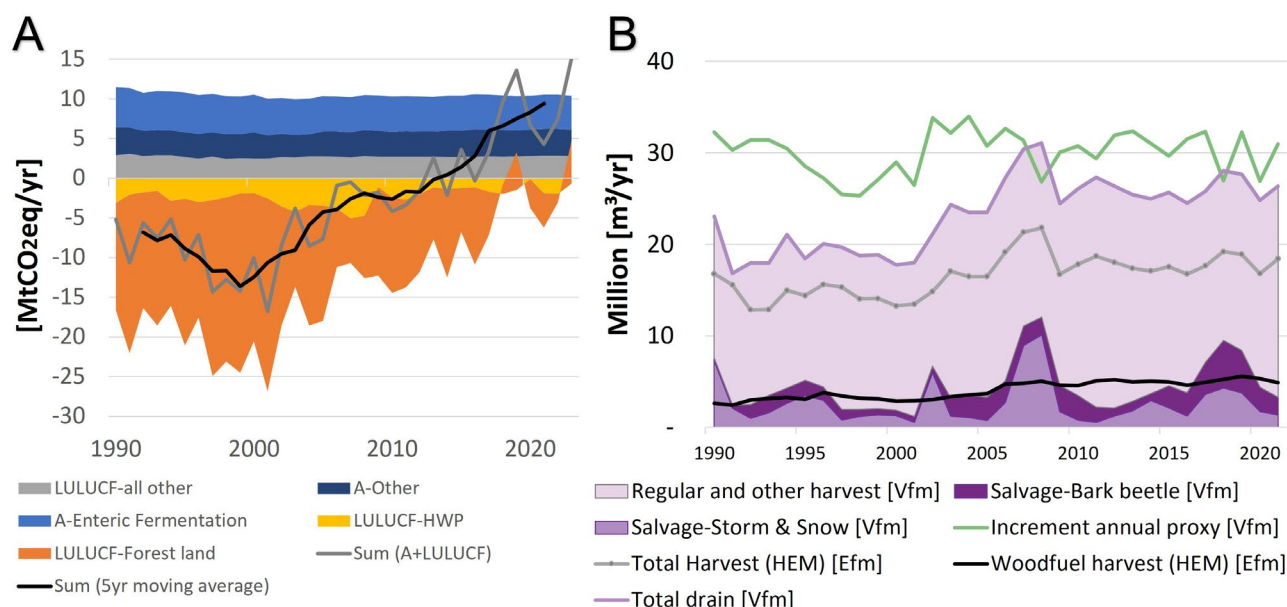


Figure 2.3 Austrian GHG inventory 1990–2023, version 2025 (Umweltbundesamt, 2025a). Panel (A) Total GHG-fluxes of the two compartments Agriculture (A), and Land use, Land-use change and Forestry (LULUCF). The agricultural flux is split into CH₄ from enteric fermentation (ruminant livestock; A-enteric fermentation) and other agricultural emissions (A-other), mainly N₂O from soils and manure management. The LULUCF flux is separated in three components, Forest land (LULUCF-Forest land), harvested wood products (LULUCF-HWP) and the sum of all other fluxes (LULUCF-all other). The gray line in panel (A) indicates the resulting annual net-flow, the black line the 5-year moving average. Not all years prior to 2005 were available in tabular format in the 2025 version; missing values were extracted from a figure published by Umweltbundesamt (2025b). Panel (B) Forest and forestry dynamics 1990–2021: Areas refer to harvest volumes, disaggregated into salvage logging for storm and snow and bark beetle as well as regular and other wood harvests according to BFW (Steyrer, 2020) and Umweltbundesamt (2023a). The gray and black lines indicate the total wood harvest and wood fuel harvest, respectively, according to the ‘Holzeinschlagsmeldung’ (HEM) that reports annual ‘harvestable volumes’ (not solid volumes) without bark and without natural losses (‘Erntefestmeter’ – Efm). HEM results are thus significantly smaller than the harvest volumes according to the Forest Inventories (FIs), which are, however, only appraised in inventory periods. The annual proxy for increment is based on Forest Inventory data disaggregated to annual fluxes using HEM information (Umweltbundesamt, 2023a). Note that the difference between increment and harvest in panel (B) basically determines the net C flux of forests in panel (A).

the forest inventory, even when differences in methodology and definitions are taken into account (Gschwantner, 2019). The harvest of wood fuel (including primary wood, thinning wood and harvest residues) increased exceptionally strongly, by a factor of 1.9 between 1990 and 2019, from 16 % to 28 % of the total harvest (excluding bark and natural losses; FAOSTAT).

National upstream or downstream emissions (land-related)

Land systems integrate various processes from production to consumption. In addition to the emissions subsumed in the emission accounts described above, these processes are associated with further emissions, that are accounted for in other sectors in the national GHG inventory (for details and further information, see 2.A.5). These emissions derive from on-farm energy use, from processing and retailing of agricultural products (downstream emissions), and the em-

bodied emissions of materials used in farming such as fertilizers and pesticides (upstream emissions), excluding the provision of infrastructure and machinery.

Globally, Crippa et al. (2021) estimate that food systems account for 34 % of total GHG emissions. About 71 % of these are related to agriculture and land use/land use change with the remainder resulting from processing, transport, storage, or disposal. For Austria, Crippa et al. (2021) estimate total food system emissions at 21.5 MtCO₂eq (based on GWP-100) in 2015, which is substantially higher than the agricultural emissions reported in the national GHG inventory (see above).

The current supply chain of wood biomass involves fossil energy inputs and thus generates emissions in addition to the land-use emissions that are included in the AFOLU sector. Life cycle assessments (LCA) have been conducted since the early 1990s to analyze the environmental impacts of various forest products and processes, but consistent results are lacking due to different boundary conditions (e.g., processes

included in the accounts, assumptions about productivity rates, or fuel consumption of machineries). A meta-study showed large differences in greenhouse gas emission estimates of wood products, ranging from 2.4–59.6 kgCO₂eq/m³ over bark calculated from site preparation to forest road, and from 6.3–67.1 kgCO₂eq/m³ over bark from site preparation to reaching a plant gate or consumer (Klein et al., 2015). In 2018, 492 ktCO₂eq were emitted for harvesting and transporting of 19.2 million m³ of timber, which corresponded to 25.63 kgCO₂eq/m³. Transport accounted for the largest share of emissions (77 %) within the supply chain, extraction accounted for 14 % of emissions, felling and processing 5 %, and chipping 4 %. Emissions from felling, delimbing, and crosscutting were much lower when using a chainsaw compared to a harvester (Kühmaier et al., 2022). However, chainsaw operations are associated with higher work-related accident rates (SVS, 2024).

Across-border impacts of Austrian consumption of agricultural and forestry products

There is *high confidence* that the consumption of forestry and agricultural products in Austria drives land use related pressures on ecosystems and greenhouse gas emissions in other countries (for an assessment, see Jandl et al., 2024c, pp. 147–152). Biomass use and processing in Austria is embedded in international trade networks, with imports exceeding exports. In terms of primary biomass equivalents, about half (45 % on average in 2010–2013) (Kalt et al., 2021) of the food, feed, fiber and biofuels consumed in Austria relies on imports (Schaffartzik et al., 2014; Kalt et al., 2021). Frey and Bruckner (2021) estimate that greenhouse gas emissions embodied in Austria's consumption of agricultural products reached 16.5 MtCO₂eq in 2013, with food products accounting for 12.7 MtCO₂eq. Almost two thirds of the greenhouse gas emissions embodied in the Austrian consumption of agricultural products occur outside of Austria, especially in other European countries (22 %), Asia (19 %) and Latin America (14 %) (Frey and Bruckner, 2021). This account includes emissions from agricultural activities and land use change, typically deforestation. Leather is the most important non-food agricultural product causing emissions (only beef, milk and dairy, and pork cause higher emissions), of which only 0.7 % occur domestically, while 25 % occur in India and 15 % in Australia.

Austria's dependence on bioenergy imports is higher than indicated by national energy statistics on direct wood energy imports, as part of the wood processing residues used

for energy come from imported sources (see [above](#)), questioning claims that bioenergy represents a self-sufficient energy source (Anca-Couce et al., 2021). This is because a large share of imports – Austria is the world's second largest importer of roundwood after China (FAOSTAT) – is processed in Austria, while final products are exported, and residues are used for paper production and energy purposes. Total roundwood imports amounted to 4.6 million m³ in 1990, 8.6 million m³ in 2000, 8.7 million m³ in 2010, 12.5 million m³ in 2020 and 8.7 million m³ in 2022 while the sawn wood exports show a similar pattern of 4.2 million m³ (1990), 6.4 million m³ (2000), 6.1 million m³ (2010), 6.1 million m³ (2020) and 5.9 million m³ (2022) (FAOSTAT). An older study calculated that taking embodied imports in the Austrian use of bioenergy from wood and agricultural products into account, reduced the domestic share from 84 to 67 % (Kalt and Kranzl, 2012). An analysis of wood flows in Austria reveals that in 2020, on average, 39 % of all wood and wood products used for energetic purposes in Austria originated from imports (BMK, 2023; Erb et al., 2023a). There is *high confidence* that biomass imports are associated with considerable direct and indirect embodied emissions (Marques et al., 2019; Pendrill et al., 2019; Peng et al., 2023), which have not yet been quantified for Austria's trade of wood.

Such impacts are operationalized with, e.g., concepts such as 'imported deforestation' risk, which in the Austrian case has declined from 3,000–5,000 ha/yr to 1,000–4,000 ha/yr, representing a 20–60 % reduction of deforestation related CO₂ emissions (Pendrill et al., 2022). However, in some countries, better governance of deforestation has shifted export driven agricultural expansion frontiers to non-forest ecosystems (Dou et al., 2018). Decreasing rates of deforestation embodied in Austrian consumption are laudable but need to be interpreted with caution as such spillover effects on non-forest ecosystems are often overlooked and may offset reductions in carbon emissions and biodiversity loss associated with decreasing rates of deforestation (Searchinger et al., 2015; Dou et al., 2018). The degradation of non-forest ecosystems embodied in Austrian imports remains largely unquantified. Agricultural imports have increased rapidly in recent decades. The share of imports in total agricultural area embodied in Austria's consumption increased by 130 % since the late 1980s (data from Roux et al., 2023). Depending on the specific indicator chosen, the methods used and system boundaries, studies find diverging trends associated to the environmental impacts of Austrian biomass imports (Gingrich et al., 2024). While pressures on ecosystems, mea-

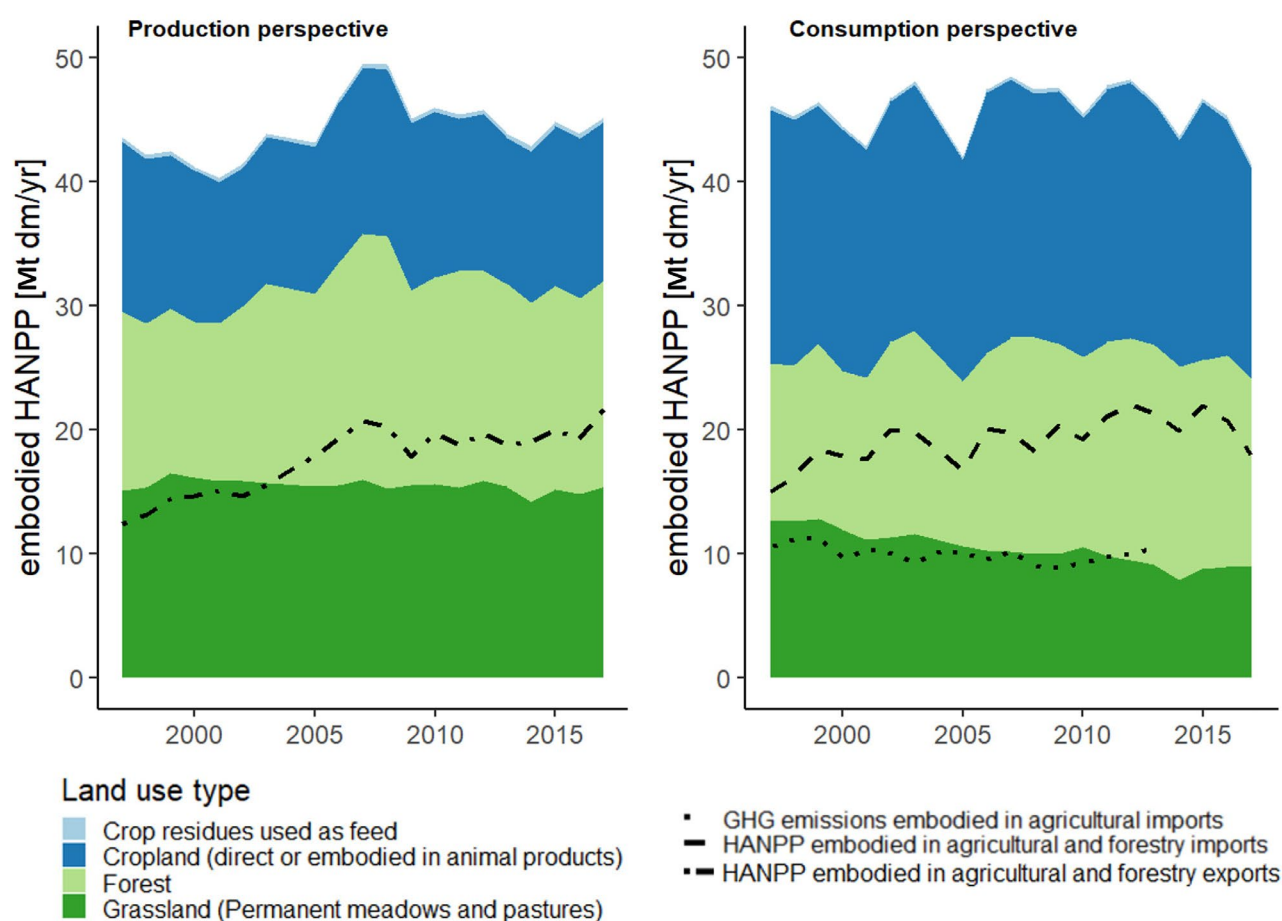


Figure 2.4 Human Appropriation of Net Primary Production (HANPP) embodied in Austria's production and consumption of agricultural and forestry products, by land use types (data from Roux et al., 2023, updated) (see 2.A.15). HANPP is an indicator for land use and pressures on ecosystems, accounting for the extent and intensity of land use (Haberl et al., 2014). Greenhouse gas emissions embodied in imports of agricultural products (dotted line) are from Frey and Bruckner (2021). Imports and exports are corrected for re-exports.

sured in Human Appropriation of Net Primary Production (HANPP) embodied in Austria's consumption of agriculture and forestry products decreased, the HANPP embodied in imports and exports increased since 1990 (Figure 2.4). HANPP embodied in biomass imports and exports are of similar magnitude.

2.2. Terrestrial ecosystem services under the influence of climate change

This section assesses the impacts of climate change on ecosystem services and their benefits, especially human health and economic income. Austria's ecosystems have been influenced by long-term management practices, affecting their resilience or vulnerability to climate change. Although it is difficult to disentangle the effect of management from those of climate effects, we attempt to do so in the following

subchapters. The section is structured following the Common International Classification of Ecosystem Services (CICES), to ensure the comprehensiveness of the assessment. Where possible, the assessment is made under different Global Warming Levels (GWL; see Chapter 1), and also considers changes in precipitation. The quantification of impacts is sometimes done based on ÖKS15 Scenarios. Note that, as explained in Section 1.2.2, these scenarios are subject to a time lag or 'cold bias': The impacts of climate change appear to occur earlier than modeled by ÖKS15. There is *high confidence* that climate change has an overall negative impact on ecosystem services in Austria, but that the impacts differ by region and ecosystem service considered. Table 2.2 provides an overview of the magnitude of the impacts of temperature and precipitation changes on the ecosystem services assessed in this chapter. See 2.A.6 for detailed quantifications and Figure TS.7 for a cartographic representation.

Table 2.2 Mean potential impacts of climate change on Ecosystem Services (E.S.) under GWL 3.0°C and GWL 5.0°C, differentiated by three major biogeographical regions and classified into qualitative impact levels (Schirpke and Tasser, 2024). Impacts were derived by identifying potential impacts on multiple indicators, used to quantify the potential ecosystem service supply, based on current literature. The indicators were multiplied by the potential impacts and spatially weighted with projections of temperature and precipitation under the two GWLs. For methodological details, see Schirpke and Tasser (2024). A strong negative impact is indicated by '-3'; a medium negative by '-2'; a low negative by '-1'; and a low positive by '1'. Values are averaged across regions. The regions encompass several ecosystems. E.S. not covered by Schirpke and Tasser were estimated by expert judgement (blue font). If supported by literature levels of confidence are given (*/**/*** = low/medium/high).

Values from publication (Schirpke and Tasser, 2024) attributed to ecosystem services from this chapter and reclassified into qualitative impact levels	Chapter section	GWL 3.0°C			Confidence	GWL 5.0°C			Confidence
		North-eastern plains, Alpine foothills and highlands	Northern and Central Alps	Southern lowlands and Alps		North-eastern plains, Alpine foothills and highlands	Northern and Central Alps	Southern lowlands and Alps	
Provisioning ecosystem services									
P1) Food and feed from arable crops	2.2.1	-1/+1	-1/+1	-1/+1	**	-1	-1	-1	*
P1) Food and feed from permanent crops	2.2.1	Research gap							
P2) Livestock products	2.2.1	1	1	1	**	1	1	-1/+1	**
P3) Products from hunting and wild animals	2.2.1	-1	-2	-1	**	-1*	-3*	-1*	*
P4) Products from aquaculture	2.2.1	1	1	1	**	1*	1*	1*	*
P5) Fiber, bio-based energy	2.2.1	-1	-1/+1	-1	**	-1	-2	-2	*
P6) Water	2.2.1	-1	-1	-1	**	-1/-2	-2	-2	**
Regulating ecosystem services									
R1) Climate regulation/ carbon sinks	2.2.2	-1	-1	-1	**	-1	-1	-2	*
R2) Biochemical cycles	2.2.2	-1	-1	-1	Research gap	-1	-1	-1	Research gap
R3) Mass movement and erosion control	2.2.2	-1	-1	-1	*	-1	-1	-1	**
Wind and fire protection	2.2.2	Research gap							
Water flow regulation and flood control	2.2.2	Research gap							
R6) Pollination	2.2.2	1	1	-1	**	-1	1	-1	**
R7) Pest control and invasive species	2.2.2	1	1	1	***	1	1	1	***
Cultural ecosystem services									
C1) Recreation	2.2.3	-1	-1	-1	***	-2	-2	-2	**
C2) Cultural heritage	2.2.3	-1	-1	-1	**	-1	-1	-1	*
C3) Aesthetic value	2.2.3	-1	-1	-1	***	-2	-2	-2	**
C4) Symbolic value	2.2.3	-1	-1	-1	**	-1	-1	-1	*

2.2.1. Impacts of climate change on provisioning ecosystem services and related benefits and limitations

Impacts of climate change on the provision of food and feed from arable crops

Austria's arable crop production for food and feedstock covers an area of about 1.3 million ha. The largest arable production areas are planted with wheat, maize/corn, barley and soybeans. Cereals, produced on about 58 % of arable land, are the most important crop group, followed by feedstocks (18 %) and oilseeds (12 %) (Statistik Austria, 2023a). On average, the production of arable crops incl. feedstocks generates 30–38 % of the production value of the entire agricultural sector (BMLF, 2023a).

There is *medium evidence* and *high agreement* that the effects of climate change described in Section 1.2.2, such as increased temperatures, altered vegetation periods and enhanced CO₂ fertilization will affect crop yields and product quality. Thereby, predicted yield deviations vary strongly. The variance depends on the GWL, the climatic region and the time period considered. In particular, the characterization of precipitation patterns as well as regional variables such as soil quality, soil water storage capacity, crop types and management practices (e.g., irrigation) play a role (Schönhart et al., 2014, 2016; Kirchner et al., 2015; Thaler, 2021). With *medium confidence*, for scenarios close to GWL 2.0°C, Austrian studies, all considering CO₂ fertilization effects and comparing to yields around the beginning of 2000, present yield changes spanning from -10 to +10 %, with regional disparities (Thaler et al., 2012; Eitzinger et al., 2013; Schönhart et al., 2014; Mitter et al., 2015a). Heterogeneity is observed between humid western and semi-arid eastern regions (Schönhart et al., 2014, 2018; Mitter et al., 2015a, 2015b; Kirchner et al., 2016; Thaler, 2021). With more pronounced climate change, one study predicts yield increases of 3–23 % for winter wheat and spring barley under close to GWL 4.0°C scenarios, but strong yield reductions of >-20 % for maize (Thaler, 2021). With *high confidence*, CO₂ effects on C₃ crops exceed those on C₄ crops (Ebrahimi et al., 2016; Ainsworth and Long, 2020; Thaler, 2021). However, the effects of CO₂ fertilization remain uncertain, and the effects of technical advancements (plant breeding, digitalization and other improvements in crop management) call for further research. In terms of product quality, wheat protein concentration could increase in scenarios with the largest yield reductions (Ebrahimi et al., 2016).

In addition to general yield trends, specific climate change phenomena as described in Section 1.2.2 – with *medium confidence* – will also increase the uncertainty of crop yields. Indirectly, trends such as elevated temperatures and altered precipitation patterns will affect the dynamics of weeds, pests and diseases (Eitzinger et al., 2013; Deutsch et al., 2018; Juroszek et al., 2020; Lehmann et al., 2020). Directly, the increasing occurrence of weather extremes such as thunderstorms, heavy rainfall (Mitter et al., 2015b; Naumann et al., 2015; Rajczak and Schär, 2017; Lehmann et al., 2018; Mäkinen et al., 2018), heat spells (Trnka et al., 2014; Mitter et al., 2015b; Mäkinen et al., 2018; Lorenz et al., 2019b; Bönecke et al., 2020), hail, and especially increased frequency and severity of droughts (Mitter et al., 2015a; Naumann et al., 2015; Hochrainer-Stigler et al., 2019) can lead to remarkable production losses. One study covering two Austrian drought scenarios up to the year 2040, models annual yield decreases of winter crops of up to 27 % on national average, causing annual production value losses of the most important crops of EUR₂₀₂₃ 78–191 million, depending on the scenario (Mitter et al., 2015a). The highest drought-related yield vulnerabilities of >20 % (maize) are modeled for the Pannonian zone in Burgenland and Lower Austria (Hochrainer-Stigler et al., 2019).

The impacts of climate change on arable crop production vary between the different production areas in Austria. While adaptation of management (irrigation, soil management, adaptation of crop rotations and choice of crop species) will be necessary to counteract negative impacts, productive cropping areas may also emerge in the western part of the country (Kirchner et al., 2016).

Impacts of climate change on the provision of food from permanent crops

In 2021, the two major branches of Austrian permanent crop production, namely wine and fruit production, covered an area of 46,634 ha (vineyards) and 15,760 ha (orchards). In 2022 wine and fruit production generated a value of EUR₂₀₂₃ 740 million and EUR₂₀₂₃ 447 million, respectively, representing 10 % of the agricultural sector (Statistik Austria, 2023b). The main fruits are apples and pears, apricots (and strawberries), and the major production areas are located in Styria (64 % of area), Lower Austria, Upper Austria, Burgenland (Statistik Austria, 2023b). Major wine production areas are located in Lower Austria, Vienna, Burgenland and Styria (BMLF, 2023a).

Literature quantifying yield reductions in permanent crops under different GWLs is not available for Austria and represents a major research and knowledge gap. However, there is *limited evidence* but *high agreement* that climate change will provoke changes in the risk of crop failure and product quality of permanent crops. The literature agrees that yields and product quality in Austrian wine and fruit production will be impacted mostly by elevated average temperatures and the related increase in the length of vegetation periods. In fruits, increasing spring temperatures lead to changes in phenology, and thereby especially to the earlier timing of bud break (Unterberger et al., 2018, for Styria; Haokip et al., 2020), potentially causing a phenological decoupling of plant-pollinator mutualism (Settele et al., 2016, for Europe) and strongly increasing the risk of severe damage up to total yield losses and quality losses due to the occurrence of late frosts (Unterberger et al., 2018; Dalhaus et al., 2020). For example, in 2023, late frost caused a total loss of apricot harvests in Wachau/Lower Austria (BMLF, 2024a), and in the years 2023, 2021 and 2020 production losses in all fruits of 10 to 14 % compared to the 10-year average (BMLF, 2023a, 2024a). In addition to late frosts, extreme weather events (heavy rain, thunderstorms, hail) directly endanger crops. Prolonged periods of heat and short-term extreme droughts can affect yields and product quality and require irrigation measures and investments in management systems such as cooling, shading, and smart irrigation (Hannah et al., 2013, international scale). In wine production, earlier ripening and higher temperatures during ripening alter quality parameters (Vršič and Vodovnik, 2012, for northeast Slovenia; Vršič et al., 2014). Production of high-quality wine grapes in regions at the margins of their climatic limits will become more difficult, while elevated temperatures could make some regions more favorable to produce current or new varieties (Moriondo et al., 2010, for Tuscany; Eitzinger et al., 2013; Santillán et al., 2020, for northern Italy). In Austria, the entire Waldviertel and Mühlviertel regions will potentially be suitable for viticulture by the end of the century (Formayer and Goler, 2013). Migration of production areas to higher altitudes is also possible (Eccel et al., 2016, for Trentino; Egarter Vigl et al., 2018, for South Tyrol; Alikadic et al., 2019, for Trento). Threats from climate change-induced changes in pest and disease dynamics are expected to increase (Salinari et al., 2006, for northwestern Italy; Caffarra et al., 2012, for northern Italy; Lehmann et al., 2020). For Austria, both fungal and insect dynamics are expected to be impacted by climatic parameters, with mixed results depending on climatic

variations (Legler et al., 2012; Zaller et al., 2013; Redl et al., 2021; Möth et al., 2023).

Impacts of climate change on the provision of livestock products

In 2021, livestock production in Austria produced a value of EUR₂₀₂₃ 4,417 million, representing 44 % of the agricultural sector, using large areas of cropland and grassland (Table 2.1). Animal production is, in economic terms, dominated by dairy products (40 % of the commercial value), beef production including veal (23 %), pork (20 %) and poultry and eggs.

Climate change will impact Austrian livestock production through the effect of heat stress on animals (Hempel et al., 2019; Mikovits et al., 2019) on the one hand, and through impacts on feed supply chains (see Section 2.2.1 for more detail) (Haslmayr et al., 2018) on the other hand (*medium evidence, high agreement*). However, estimates for Austria indicate rather low heat stress related losses in milk sales revenue of 0.6 % (0.1–2.5 %) even under a GWL 3.6°C (Schönhart and Nadeem, 2015). In addition to productivity losses, impaired welfare due to the increased frequency and intensity of heat stress occurrence may increase skepticism among societal groups towards animal farming. This emphasizes the urgency of mitigation strategies from an animal welfare perspective (Shields and Orme-Evans, 2015).

There is *medium evidence* and *high agreement* that, depending on the severity of climate change, grassland productivity can be expected to be maintained or even enhanced in large parts of western and central Austria, which are dominated by grassland (Haslmayr et al., 2018) (see Section 1.6.3). Water availability and rainfall distribution are the main factors for the expected development of grassland yields, with an increasing probability of yield depression of individual cuts (*high confidence*), thereby putting at risk a constant feed supply for ruminant livestock (Finger et al., 2010; Neuwirth and Hofer, 2013; Bahn et al., 2023). In alpine grasslands, severe climate change, represented by a reduced water supply of the order of 40–50 %, together with droughts of several weeks and partially an increased ambient temperature, induces shifts in vegetation and soil microbes, leading to enhanced water use efficiency (under GWL 1°C: 2018; no increased temperature: Tello-García et al., 2020, 2023) (*medium confidence*). Regions focused on the production of important feed crops (maize, cereal and legume grains, oilseeds) for all livestock species will be stronger affected by climate change (see above). The impact

on feed supply will be considerably variable across regions (see [above](#)).

In addition, securing the water supply for livestock has become an increasingly important issue for livestock farmers in certain parts of Austria in recent years (*limited evidence, medium agreement*). The livestock farming sector currently requires about 55 million m³ of water. An increase of 46 % is expected by 2050 (BMLRT, 2021b). Most likely, the situation will vary regionally, mainly depending on precipitation patterns and the type of water source (groundwater vs. spring discharge; for details see [below](#)). Given the high drinking water requirement of livestock, roughly three times the daily dry matter intake (Schlink et al., 2010), securing a continuous water supply is a critical issue for livestock farms, which will become even more challenging due to increasing conflicts of use (BAFU, 2014).

Animal health in a narrow sense (i.e., occurrence of health disorders as a consequence of climate change) is perceived as a potential challenge, but has not yet been researched in depth for the specific conditions in Austria. The infection pressure by certain vector-borne pathogens is expected to increase because of climate change (Gale et al., 2010). Bluetongue disease in ruminants, which has also appeared in Austria in the last one and a half decades (Pinior et al., 2018), is an example for vector-borne diseases, where in particular the interactions between vector and host are still poorly understood (Baylis, 2013). This poses a challenge for the development of specific preventive actions.

Impacts of climate change on the provision of products from hunting and wild animals

There is *high confidence* that climate change leads to elevational shifts in the distribution of habitats for many plants and animals of about 140–180 m per degree of temperature increase (Zu et al., 2021; Rubenstein et al., 2023). Since the 1970s, there has been an elevation migration of 36 m/decade (see [Section 1.6.4](#)). Especially in the peripheral Alps, but also in the lower elevations of the Central Alps, the subalpine and lower alpine, forest-free habitats are colonized by forests and shrubs and have thus largely disappeared (Chamberlain et al., 2013; Tasser et al., 2017). The distribution of most forest and shrub game species (especially ungulates) has remained stable or increased in response to the expansion of suitable habitats (Reimoser and Reimoser, 2016; Tasser et al., 2023). However, there is *high confidence* that the distribution of alpine habitat specialists could decline sharply as open grassland areas disappear (Chamberlain et al., 2013; Imperio et

al., 2013; Rehnus et al., 2018) (see also [Section 1.6.4](#)). These results confirm that the conservation of alpine game species such as the rock ptarmigan (Revermann et al., 2012) and the marmot (Tafari et al., 2013), but also chamois (Chirichella et al., 2021), will become problematic in the future, but this can be reduced by management strategies to preserve summer pasture areas (Chamberlain et al., 2013; Tasser et al., 2024).

Impacts of climate change on the provision of products from aquaculture

There is *high confidence* that climate change increases the temperature of freshwater bodies (Niedrist, 2023), causing a deterioration of water quality, e.g., due to a reduced dissolved oxygen and increased algal blooms and toxicity of pollutants (Ficke et al., 2007; Orság et al., 2023) (see also [Section 1.4.3](#) and below). For fisheries and aquaculture in Austria, this also means increased stress for fish and an increase in associated diseases and parasite infestations, as well as lower feeding and growth performance (Handisyde et al., 2006; Schindler, 2017; Casas-Mulet et al., 2021).

Austrian fish farming focuses mainly on salmonids, carp and African catfish (3,599 t salmonids, especially rainbow, brown and brook trout, 617 t carp and 494 t catfish) (Statistik Austria, 2022a). Furthermore, 32.9 million spawning fish and 25 million stocking fish are produced. Since salmonids are generally cold-water fish (average preferred temperature of 11–15°C in summer), while carp and catfish are cold- to warm-water fish (>21°C), climate warming will lead to a shift of breeding populations from salmonids to cyprinids, pike and catfish (Meisner et al., 1987; Reist et al., 2006) (*high confidence*). At the same time, salmonid species are expected to be displaced upstream in Alpine rivers, but warm-water species such as carp and some invasive species such as exotic rainbow trout, grass carp and sunfish will become established (Matulla et al., 2007; Rabitsch et al., 2013; Pletterbauer et al., 2015).

Impacts of climate change on health aspects related to food provision

Looking at food-related health issues, climate change certainly affects food safety (Duchenne-Moutien and Neetoo, 2021). Although food safety issues are not of major concern in Austria compared to lower- and middle-income countries (Cissé, 2019; Seitner et al., 2022), Austria is dependent on global supply chains (Leidwein et al., 2014) (see [Chapter](#)

Box 2.1) and also in Western European countries, an association between ambient temperature and number of salmonella infections has been demonstrated, even after controlling for seasonal effects (Kovats et al., 2004). Behavioral changes (e.g., more outdoor preparation of food) contribute to these increasing risks. However, it should be noted that climate effects on food safety and food-borne diseases in Austria are understudied. In addition to food quality and security, the effects of climate change on food quantity will also directly impact human health. Springmann et al. (2016) in their global modeling study also provide estimates for Austria under GWL 2.0°C–GWL 3.0°C (main scenarios) for 2050 accounting for (i) reduced calorie intake (mostly beneficial), (ii) reduced red meat intake (beneficial), and (iii) reduced fruit and vegetable intake (detrimental). All factors combined they estimate 220 (95 % confidence interval: 70–360) additional deaths annually due to these changes (compared to a ‘no climate change’ reference scenario).

Impacts of climate change on the provision of fiber

For Austria, fiber production from agriculture (fiber plants: Hemp, flax; animal fibers: Sheep wool) is minimal and hence not covered. In contrast, the use of wood fiber includes most wood products (timber, paper, cellulose) and therefore, the provision of fibers is mostly dependent on the forestry sector.

Forest ecosystems and forest management will be impacted not only by changes in climate trends, but also by increased variability and intensity of extreme weather events, such as drought, storms and floods (*high confidence*) (see also Chapter 1). In particular, mountain forests will experience higher temperatures (see also Chapter 7), which will lead to higher production rates and an expansion of the forest area at higher elevations in sites that are currently limited by temperature (Lindner et al., 2010). The disturbance regime will also be influenced by the changing climatic conditions, leading to more frequent and intense bark beetle infestations, wind throws and forest fires (Senf and Seidl, 2021). Climate change is and will continue to impact the tree species composition, productivity, and ultimately wood supply. At local warming levels above 2°C, especially conifer-dominated landscapes in mountain areas of Austria characterized by large trees, might shift to a landscape dominated by smaller, predominantly broadleaved trees (Albrich et al., 2020). Higher growth rates can be expected in higher elevation mountain areas due to longer vegetation periods and warmer temperatures, and generally, the provision of

timber might be influenced by increased disturbances and droughts (Obojes et al., 2018, 2020, 2022). Businesses will therefore face a potential scarcity of wood availability for certain assortments or species as forest management adapts to the changing climate. The results of the Austrian Forest Inventory 2016/21 of the Federal Research Centre for Forests (BFW) show a clear trend towards more broadleaved forests. Pure conifer stands have decreased by 6 % over the last decade, while mixed hardwood stands have increased by the same percentage. Due to climate change, spruce has already lost parts of its distribution between 600 and 800 m a.s.l (BMLF, 2023b).

Despite Austria's forests having lost their property of being a carbon sink (see Figure 2.3) large quantities of CO₂ are taken up in forest ecosystems. The current increment of Austria's forests (i.e., before harvest and mortality, as opposed to stock changes) is 24.7 MtCO₂/yr. However, scenarios show a decrease to 21.1 MtCO₂/yr if local temperatures increase by 3°C. In addition, if precipitation decreases by 30 %, capacity drops further to 19.0 MtCO₂/yr. The distribution of changes is heterogeneous (Figure 2.5), with higher altitudes experiencing increased productivity and lower altitudes experiencing decreased productivity, especially when accompanied by increased temperature. The probability of a single ‘bad year’ increases with increasing temperature and can lead to the destruction of large forest areas and the gradual release of previously stored CO₂. Furthermore, Kindermann (2021) points out that the CO₂ uptake becomes smaller than the CO₂ release, turning a forest from a sink to a source. Increased mortality results in an increased mass of deadwood in the forest, which may either remain in the forest or be harvested and used for fiber production. However, lower carbon uptake by forests means that, to keep the carbon stock constant, harvest of deadwood must also be proportionally reduced. On the other hand, forest biodiversity benefits greatly from structural diversity and the abundance of deadwood in forests (Oettel and Lapin, 2021; Rigo et al., 2024).

The distribution of forests showed an accumulation of ages with high rates of productivity rates in 1990. 30 years later, forests have matured and the age peak has flattened, leading to a decrease in productivity from 9.3 m³/ha/yr in 1990 to 8.2 m³/ha/yr in 2020. This trend of decreasing productivity is estimated to continue by the forest growth models EFDm, CALDIS (Kindermann and Ledermann, 2023), G4M and EFISCEN (Böttcher et al., 2011). In the coming decades, this trend can be reversed, by harvesting old and overmature forests with low increments and regenerating

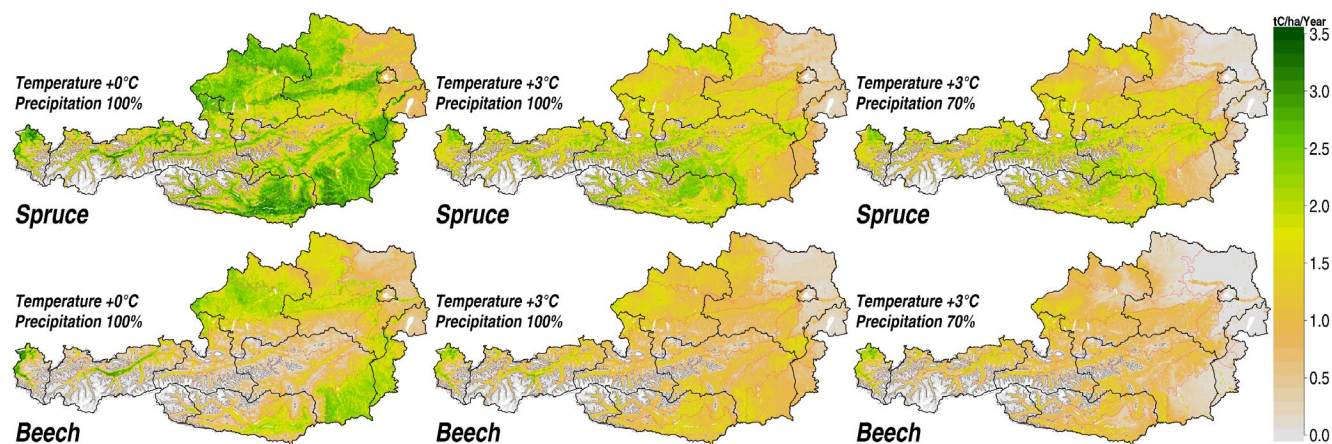


Figure 2.5 Estimated average productivity in tC/ha/yr of spruce (*Picea abies* L.) and beech (*Fagus sylvatica* L.) for (i) current climatic conditions; (ii) increased local temperature (+3°C); and (iii) increased local temperature (+3°C) and reduced precipitation (70 % of current climatic conditions) (Kindermann, 2021). Effects on other tree species can be found in Figure 2.A.2 for (i) current climatic conditions; (ii) increased local temperature (+3°C); and (iii) increased local temperature (+3°C) and reduced precipitation (70 % of current climatic conditions) (Kindermann, 2021).

them to younger forest stands with higher growth rates (see Section 2.3.1 for related effects on climate change mitigation). Overall, the growth of the same species in the same location was higher in the following stand generation (Rössler, 2014). In addition to climate, other factors such as nitrogen deposition can influence forest growth. Spiecker et al. (1996) have shown this trend of increasing growth for Europe. A recent study by Chakraborty et al. (2024) expects that growth will decline in the future.

In any case, the expected high amount of salvage wood will affect the market price of timber and can cause losses of income for forest owners due to limited opportunities to sell high quality sawn timber, rather than industrial round wood with lower quality. Based on the analysis of a past storm event in Italy, a 40 % drop in timber prices was observed (Udali et al., 2021).

Impacts of climate change on the provision of bio-based energy

Cropland-based biomass is insignificant for Austria's overall energy supply. Despite the negligible role of yield quality and therefore climate-induced changes in yield quality, the impacts of climate change on crops grown for energy uses are similar to the impacts on crops grown for food, feed, and other industrial purposes (see above). The two major cropland-based energy sources, bio-based liquid fuels and biogas, respectively account for only 4.4 % and 0.8 % of

total renewable energy demand in 2020 (Biermayr, 2022). About 11 % of cereal consumption in Austria was used for bio-ethanol production (AMA, 2022). Biogas feedstock was produced on 15,800 ha cropland, 7,000 ha grassland and cropland with second harvests or crop residues. Livestock manure and residues from the food industry and sewage systems are also included.

About 26.9 million m³ of the timber being harvested domestically, imported or coming from other sources (e.g., waste wood, groves) are used annually for energy supply in Austria, accounting for 55 % of the total energy supply from renewable resources (see Section 4.5). The material originates from harvested industrial roundwood or firewood, processes and by-products in the sawmill, pulp and paper industries (e.g., cross-cut ends, barks, products from further wood processing, wood chips, pellets), which has been argued to be CO₂ neutral by Jandl et al. (2024) but not in other sources (Norton et al., 2019; Erb et al., 2022; Peng et al., 2023) (for a discussion on carbon neutrality of biomass use, see 2.A.5 and Box 1.1 in Jandl et al, 2024c). The impacts of climate change on the provision of forest fuels are similar to those for fiber, although there is *limited evidence* and *medium agreement* that climate change will increase the amount of salvage wood harvested from the increasing number of disturbances (see above). This will probably increase the supply for renewable energy and other material uses in the future (Sohngen and Sedjo, 2005; Lantz et al., 2022).

Impacts of climate change on the provision of water

The provision of ecosystem services and related benefits of water bodies (surface- and groundwater) is manifold (Keeler et al., 2012; Hallouin et al., 2018; Lupi et al., 2023). In addition to supplying drinking water, healthy waters are rich in biodiversity, provide fishing grounds and recreational areas including bathing, and are essential landscape elements. They are also indispensable elements of water and food supply for neighboring ecosystems (e.g., wetlands). Reduced water availability and deteriorating water quality endanger these services.

There is *high confidence* that changes in rainfall patterns, drought duration and intensity can significantly impact pollutant transport, dilution and, together with increasing water temperature, related water quality. Therefore, climate change has the potential to counteract efforts to improve water quality and may lead to further deterioration. See 2.A.7 and Section 1.4 for a discussion of climate impacts on water fluxes and related substance transport, or indirect impacts due to climate change adaptation measures.

There is a *high confidence* that phosphorus pollution is responsible for 21.1 %, of Austrian surface water bodies failing good ecological status as defined in the EU Water Framework Directive (WFD). For conditions similar to GWL 2.0°C and increasing precipitation trends, Schönhart et al. (2018) estimate an increase in median total phosphorus river loads of about 20 % and, for decreasing precipitation trends, an increase in the of rivers orthophosphate environmental quality standards (EQS) by a factor of about 1.2 (*medium confidence*). Nitrate is responsible for 9 % of groundwater monitoring stations exceeding the WFD threshold (*high confidence*). Mehdi-Schulz et al. (2024) estimate a heterogeneous pattern across Austria with an increase of up to 10–15 % for N concentrations in some rivers in northeastern and southeastern Austria for a GWL 2.0°C and decreasing precipitation trends (*medium confidence*). Nitrate in groundwater can be assumed to follow a similar pattern. These impacts may affect current efforts to reduce nitrate levels below EQS by environmental programs in agriculture (e.g., Österreichisches Programm für umweltgerechte Landwirtschaft, ÖPUL) (*high confidence*).

In addition, pollution with priority substances deteriorates the chemical status of surface waters, with 100 % failing to achieve good status if either of the ubiquitous substances mercury and polybrominated diphenyl ethers (PBDE) are considered, while only 17 % are at risk of failing good sta-

tus if these substances are neglected (BMLRT, 2022). While the vulnerability of water bodies with decreasing flow under climatic stress continues to increase, this could become even more critical if the European Commission adjusts/lowers the thresholds for priority substances (European Commission, 2022; Brielmann et al., 2023; Clara and Müller-Rechberger, 2023) (*high confidence*).

There is *medium evidence* and *high agreement* that impacts of climate change on the provision of water will manifest locally and seasonally, with areas in northeastern and eastern Austria being most at risk of facing water scarcity (Mitter and Schmid, 2019; ZAMG, 2020; BMLRT, 2021a; Hanger-Kopp et al., 2024). Drinking water demand across Austria will rise until 2050 under GWL 2.0°C, particularly in western and Alpine regions with a high share of tourism, where water demand in some hotspots may increase by 50 % under GWL 2.0–3.0°C (BMLRT, 2021a). In a dry scenario, agricultural water demand may double by 2050 (GWL 2.0–3.0°C), whereas other material water uses, such as for industrial purposes, are not predicted to change significantly (BMLRT, 2021a). Usage intensity across Austria will largely remain within sustainable boundaries; however, in a very dry scenario, regions with intense usage in Eastern Austria exceed the available groundwater resources (GWL 2.0–3.0°C). Demand for drinking water will rise by approximately 15 % by 2050 under a very dry scenario – GWL 2.0–3.0°C, with about 10 % of these 15 % being due to population growth, and 5 % due to climate change (BMLRT, 2021a).

Water demand for agricultural irrigation will rise, particularly in northern, eastern, and southeastern Austria (*medium evidence, high agreement*). Across Austria, the total irrigable land area has increased by 30,349 ha (from 91,998 to 122,347 ha) between 2010 and 2020 (Statistik Austria, 2022b), representing 4.7 % of the total used agricultural area (Statistik Austria, 2024). About 85 % of the irrigated areas in Austria are concentrated in Lower Austria and Burgenland (Statistik Austria, 2022b). Very dry scenarios (GWL 2.0°C) show an increase in irrigable land in these federal provinces, as well as in Upper Austria and Styria, by 2050 (BMLRT, 2021a). In the same regions, scenarios considering severe multi-annual dry spells show increases in irrigated areas by a factor of 5.6 compared to a reference scenario (GWL 1.5°C), where increases further depend on the level of risk aversion of farmers (Mitter and Schmid, 2019). Currently, there is no monitoring of actual water use for irrigation. Such data would significantly improve the accuracy of predictions and thus adaptation decisions (BMLRT, 2021b; Hanger-Kopp et al., 2024).

Chapter Box 2.1. Impacts of climate change on Austria's global supply chains of food and other biomass products

There is *medium evidence* but *high agreement* that Austria's supply of food, feed, fiber, and bioenergy is increasingly dependent on global supply chains, and that imports from tropical and Mediterranean regions are more vulnerable to climate change than Austria's domestic supply. Due to the increasing reliance on imports, the supply of agricultural products to Austria is vulnerable to climate change not only in Austria, but also in countries exporting to Austria (Davis et al., 2021; Hedlund et al., 2022). Nonetheless, about two-thirds of Austria's imports of biomass originate from neighboring countries (Kalt, 2021), which, except for Mediterranean region, may largely face similar risks as Austrian production (ESPON, 2012; Knox et al., 2016; Hasegawa et al., 2022). On the other hand, the provision of tropical products (e.g., coffee, cocoa, palm oil, soybeans) is more vulnerable due to the concentration of production in a limited number of countries and their vulnerability to climate change (European Environment Agency, 2021). 16 % of Austria's imports of food and feed, in raw biomass equivalent, originate from regions that are moderately to highly vulnerable and do not yet appear to be ready to adapt to climate change (trade data from Roux et al. (2023), updated as explained in 2.A.15, vulnerability from Kan et al. (2023)). The supply of wood in Austria is slightly vulnerable to climate change, as about 5 % of Austria's imported raw material input (RMI) of wood originate from regions that are moderately to highly vulnerable and do not yet appear ready to adapt to climate change (Kan et al., 2023; Roux et al., 2023). However, for certain wood products, the share of imports from vulnerable regions can be substantially higher. Diversifying origins and reducing the overall demand for vulnerable products decreases the vulnerability of supply in Austria, while at the same time decreasing environmental pressures on global ecosystems.

Demand for European agricultural exports is also expected to increase in response to climate change, as a response to reduced yields in other regions of the world (Janssens et al., 2020). This increased demand could potentially increase land demand and pressure on ecosystems in Austria (*limited evidence, high agreement*).

2.2.2. Impacts of climate change on regulating ecosystem services and related benefits

Impacts of climate change on carbon sinks in ecosystems

The impacts of climate change on forests and other ecosystems are described in Chapter 1. Here, we build on Chapter 1, by describing the consequences for carbon sinks in forests and other ecosystems. The simulation under a strong warming scenario (GWL 2.0°C–GWL 3.0°C by 2050 and close to GWL 4.0°C by 2100) showed an increase in soil organic carbon (SOC) when conifers are replaced by deciduous tree species (Jandl et al., 2021). In the 150-year simulation, the majority of forest sites become suitable for deciduous forests. The build-up of a large soil organic carbon stock is driven by the harvesting pressure on the remaining coniferous forests. Deciduous forests were less in demand and developed under a regime of light forest intervention. However, towards the end of the century, when the temperature level is far above present levels, soil organic carbon stocks declined (Jandl et

al., 2021). Highly intensive production of wood biomass will decrease the carbon stock in forest soils by 3 % in 80 years (Repo et al., 2015).

Impacts of climate change on the carbon sink function of wetlands are outlined in Section 1.6.1. Peat accumulating wetlands are the ecosystems that store the most carbon per area. The effect of land use-related drivers of carbon loss on peat accumulating wetlands, namely drainage and agricultural and forestry management are estimated to be more severe than the effects of climate change. For German peatland sites, there is *high confidence* that drainage and drying out turns peatlands from a carbon sink to a large source of greenhouse gases with emissions averaging 25 tCO₂eq/ha/yr, with peaks up to >60 tCO₂eq/ha/yr (Tiemeyer et al., 2016; BMLRT, 2022). For Austria, the actual amount and location of agriculturally used drained peatland areas are understudied (Hogl et al., 2023). The Austrian NIR 2023 estimates 13,000 ha of grassland on organic soils, while arable land on organic soils is not listed. In contrast, a recent study estimates 31,000 ha of peatland area under mostly intensive agricultural grassland or cropland management (Hogl et al.,

2023). For Austria quantitative modeling studies on the impact of climate change on drained, agriculturally used peat soils and the carbon sinks remain a research gap.

Impacts of climate change on the regulation of urban micro-climate

Climate change affects regulating ecosystem services in urban areas. Rising temperatures, long lasting drought periods and altered precipitation patterns as observed in Austria (Chimani et al., 2016; Haslinger et al., 2022), can make trees more susceptible to diseases and can affect the ability of vegetation and green spaces in cities to filter pollutants, reduce the heat island effect, and regulate local temperatures, leading to increased energy demand for cooling, reduced air quality, and heat-related health issues. These impacts hamper the resilience of cities to environmental changes (Lafortezza and Sanesi, 2019). Urban forests, parks, or simply tree-lined streets – urban greens in general – are known to facilitate adaptation to climate change in terms of regulating temperature and water budget. This improves the public health and well-being of urban populations and contributes to sustainable living in terms of positive effects on humans, microclimate, soil and biodiversity (*high confidence*). More details on heat in urban areas can be found in below, in [Cross-Chapter Box 2](#) and in [Chapter 3](#).

Impacts of climate change on biochemical cycles

Ecosystem processes regulating the exchange of nutrients (including mineralization) and soil formation may be hampered by climate change, especially as altered soil humidity and temperatures will also affect soil biota. Results for Austria also take advantage of the specific sites established under the Long-Term Ecological Research network (Mirtl et al., 2015). Investigations for alpine grassland (Seeber et al., 2022) demonstrate that climate change influences the way carbon (C) and nitrogen (N) pools increase as a consequence of extensified grassland management. This effect is primarily driven by rising temperatures, as precipitation is not considered a limiting factor in this context. In forest soils, Kengdo et al. (2023) demonstrate increased carbon inputs due to increased fine root turnover. These cases provide proof that climate change would help to alleviate temperature limitations on many biological processes that support regulating services. However, warming of forest soils also decreases microbial carbon and nitrogen use efficiencies (Tian et al., 2023), thereby reducing regulation – an

observation that is in line with microbial biomass accumulation observed with soil cooling (Schnecker et al., 2023). More research is needed to establish the effect of additional stressors on biological systems, such as droughts (especially in areas already now experiencing water scarcity) or ozone damage to vegetation, given that the presence of ozone has been observed to reduce drought stress in oak trees (Peron et al., 2021). Similarly, the effects of drought on microbial communities that had been exposed to elevated temperatures and CO₂ concentrations in a treatment experiment were strongly alleviated (Metze et al., 2023). All these results come from experiments at Austrian sites or with Austrian substrates and demonstrate a high level of scientific activity, especially in recent years, but will only gradually allow conclusions to be drawn about climate change impacts on ecosystems and their ability to regulate nutrient flows, especially as the observations demonstrate that combinations of ecosystem stressors do in several instances not add up, but rather cancel each other out.

Impacts of climate change on mass movement and erosion control

Climate change will affect the frequency and intensity of gravitational processes through changes in precipitation amounts, duration and snow cover, or frost dynamics (*limited evidence, high agreement*). Permafrost dynamics in alpine environments influence rock-slope stability through shear stresses and reduced shear resistance of rock masses (Krautblatter et al., 2013; Mamot et al., 2021). Warmer temperatures and longer growing seasons lead to improved tree growth, but longer dry periods also mean additional stress (Schuldt et al., 2020). As tree species have different tolerances to stress situations, new competitive conditions will arise and the tree species composition will alter the protective effect of mountain forests. In addition, the protective effect of forests will be reduced by intensified disturbance regimes caused by temperature driven agents, such as increased bark beetle infestations in Norway spruce dominated forests at higher altitudes (Maroschek et al., 2015), and a higher chance for stand replacing forest fires due to longer drought periods (Müller et al., 2020) or more wind throws caused by extreme wind events (Costa et al., 2021). Protective functions against landslides and snow avalanches are negatively impacted by the stochastic creation of small gaps under warming scenarios with an increase in mean annual temperature up to 4°C across the Alps (Maroschek et al., 2015, 2024) (*limited evidence, high agreement*). The simulat-

ed shift of precipitation events from summer to winter and spring will promote wet snow avalanches in the mountains and the occurrence of flood-relevant snowmelt events, limiting the capacity of forests to control erosion control and reduce mass movements (Glade, 2020). Soil erosion could also increase in agricultural areas, which are usually not covered by vegetation in winter and spring (Glade, 2020). Forest vegetation can influence permanent or deep landslides through drainage in the catchment and directly on the landslide mass (Rickli et al., 2004), but the soil-stabilizing effect of tree roots is not strong in relation to the location of the sliding surfaces in the catchment area (Frehner et al., 2005; Bollinger et al., 2008; Losey and Wehrli, 2013). In general, forest vegetation will presumably exhibit a higher protection from precipitation events with longer duration but lower intensity than from short-term-high-intensity events (Kleemayr et al., 2020). Direct effects of climate change might have a stronger influence on the future supply of erosion control than management or natural disturbances (Seidl et al., 2019). The impacts of avalanches are difficult to predict with simulation models (in terms of time, space and size) as the influencing factors vary greatly over a very small geographical area and the effect of forests is hardly understood (Studeregger et al., 2020) (see also Sections 1.6.2, 1.7 and 7.4.2).

Impacts of climate change on wind and fire protection

Climate change affects the capacity of ecosystems to protect society from wind and fire as they act as natural barriers, reducing wind speed, regulate the local climate and prevent erosion. There is *high confidence* that climate change will increase the frequency and intensity of disturbances, which will affect the species composition, forest structure, forest cover and the amount of flammable material in the forest (Hlásny et al., 2021; Berčák et al., 2023). Windstorm damage in European forests has increased over the past century (Seidl et al., 2011; Schelhaas et al., 2015; Gregow et al., 2017; Patacca et al., 2023) and this trend is expected to continue (Ikonen et al., 2017; Seidl et al., 2017) especially due to the high vulnerability of flat-rooted Norway spruce dominated forests (Bourke et al., 2023). The combination of a high amount of salvage wood from wind disturbances and long drought periods (Senf et al., 2020) further increases the predisposition of these forests to bark beetle infestations (Hlásny et al., 2021) and wildfires (Müller et al., 2020). This will in particular reduce the capacity of the protection for-

ests in Austria to secure the living environment as well as critical infrastructure and settlements in the wildland urban interface (see also Sections 1.2.2, 1.6.2 and 7.4.2).

Impacts of climate change on the water flow regulation and flood control

Flood hazards are predicted to increase (Chapter 1, Table 1.A.3). Many ecosystems, particularly rivers and riparian forests, depend on floods to function. Ecosystems also regulate high and low flows in two major ways: They mitigate flood risk by providing retention space in the direct vicinity of rivers, and they prevent floods at the catchment scale through vegetation cover and soil type. In addition, drought in the catchment area may affect the water holding capacity of soils (Vári et al., 2022). Anthropogenic interventions such as land-use change, wetland drainage, and river regulation, have had major impacts on this regulating function in rivers and surrounding ecosystems (Jungwirth et al., 2002; Mergili and Duffy, 2022, for the river Lech). In comparison the direct impact of climate change on the capacity of ecosystems to regulate water flow and floods is probably small. Depending on the scenario and its assumptions about future precipitation, various effects can be expected, such as various types of ecosystem degradation due to increased heat and wildfires, or exceeding the ecosystem capacity to hold floods. However, there is little to no information for Austria.

Impacts of climate change on pollination

There is *high confidence* that climate change leads to a shift in the range of species, resulting in reconfiguration of species communities and decoupling of community interactions (Zulka and Götzl, 2015; Rollin et al., 2022). In general, an increase in mean annual temperature has a negative effect on the abundance of wild pollinators (Vasiliev and Greenwood, 2021). Bumblebees and hoverflies are particularly affected (Minachilis et al., 2021), but the degree of ecological specialization of species is also negatively correlated with the risk of extinction (Roberts et al., 2011). As a result of global warming, higher temperature improves foraging by reducing the energy cost of maintaining optimal body temperature, which has been shown for example, for honey bees (Abou-Shaara et al., 2017; Usha et al., 2020) (*high confidence*). On the other hand, there is *high confidence* that nectar abundance and total sugar content in nectar are negatively correlated with heat and drought exposure of plants (Borghi et al., 2019) as well as pollen quality and quantity (Zinn et al., 2010). The

associated effects are changes in the area and isolation of suitable habitat with appropriate forage plants and significant declines, especially in specialized pollinator species, but also in generalist species (Rollin et al., 2022).

Directly affected are related ecosystem services such as pollination services and pest control. The value of pollination alone is estimated near to EUR₂₀₂₃ 442.5 million in Austria, or 9.9 % of the total value of agricultural crop products (Zulka and Götzl, 2015). However, these consequences of climate change can be buffered by targeted management measures and nature-based solutions, such as the development of near-natural elements or habitats with appropriate forage plants in agricultural landscapes (Roberts et al., 2011; Zulka and Götzl, 2015). More near-natural areas increase the possibility of plant and animal migration and thus also of pollinators, while fewer natural areas make this process more difficult.

Low air quality and climate change also increase allergies (Bergmann, 2016). Climate change (mostly due to temperature and CO₂ increase) will affect plant growth and pollen production. Plants will react to heat stress and ozone by producing more pollen or producing pollen more frequently, and the single pollen particles will often have more allergenic proteins on their surface (*medium confidence*). Climate change will also affect the introduction and wider spread of new and sometimes also highly allergenic plants (like *Ambrosia artemisiifolia*) (Cheng et al., 2023).

Impacts of climate change on pest control, invasive species, vectors, and related health issues

There is *high confidence* that climate change increases risks to ecosystems, biodiversity, food security, and human and animal health (Cissé et al., 2022). Typical examples are neobiota species. Out of the 3,462 vascular plants occurring in Austria, 10.6 % are naturalized neophytes (Schratt-Ehrendorfer et al., 2022). If temporarily occurring species are included, a total of 1,463 non-native vascular plants have been recorded in Austria (Kalusová et al., 2024). Climate and global change are expected not only to open new pathways and territories for invasion, but also weaken the resilience of ecosystems and native species, thus facilitating the establishment of invasive species (IUCN, 2021). These species may

have the same impact as natural hazards and are very costly to eradicate or contain (Turbelin et al., 2023). One example in forests is ash dieback caused by an alien fungal pathogen (Marçais et al., 2022). In agriculture, the main route of introduction of invasive plants has been through deliberate imports as ornamental or crop plants (*medium evidence, high agreement*). A small percentage of these are considered invasive (AGES, 2023a) such as common ragweed (*Ambrosia artemisiifolia*) and jimsonweed (*Datura stramonium*), which are rapidly spreading over Austria (Follak et al., 2017, 2023). These plants not only cause yield and quality losses, but also health burdens, such as increased allergenic load and prolonged allergy seasons (Ambrosia) or poisoning along the food chain (Datura).

There is *high confidence* that climate change also affects blood-sucking arthropods (mosquitoes, biting midges, ticks, etc.), which are vectors for several pathogens (viruses, bacteria, protozoa) that cause mainly zoonoses (Rocklöv and Dubrow, 2020; Thomson and Stanberry, 2022). A disease vector is an organism, most often an arthropod, that transports a pathogen (viruses, bacteria, protozoa) from one host organism to another. Hotter summers and warmer winters (see Section 1.2.2) lead to increasing vector densities (Sonnberger et al., 2020; Duscher et al., 2022), due to higher overwintering success or multiple generations per year, expansion of endemic areas (e.g., tick-borne encephalitis, bluetongue disease), accelerated replication rate of pathogens in vectors, and more frequent years with favorable conditions for the transmission cycle (e.g., Rubel, 2021).

In Austria, native arthropods are potential vectors of emerging pathogens, that have caused several disease outbreaks, such as West Nile virus (Aberle et al., 2018), Usutu virus (Brugger and Rubel, 2009) or bluetongue virus (Purse et al., 2005; Lebl et al., 2013; Brugger et al., 2016). In addition, invasive vector species are increasingly establishing themselves in Austria. Examples include mosquitoes of the genus *Aedes* or *Anopheles* (Lebl et al., 2013; Bakran-Lebl et al., 2022), tick species such as *Hyalomma marginatum* (Duscher et al., 2022), and sandflies of the genus *Phlebotominae* (Poepl et al., 2013). These species are potential vectors for tropical and subtropical diseases caused by Chikungunya virus, Dengue virus, yellow fever virus, Crimean-Congo haemorrhagic fever virus or Leishmania parasites.

Cross-Chapter Box 2. Health and climate change

Hans-Peter Hutter; Hanns Moshammer

To gain a better understanding of how we might address the massive effects of climate change on human health in Austria, we look at the direct and indirect effects of climate change on human health, discuss beneficial and adverse health consequences of some mitigation (and adaptation) measures, and finally describe the carbon footprint of our health care system.

The health impact of climate change

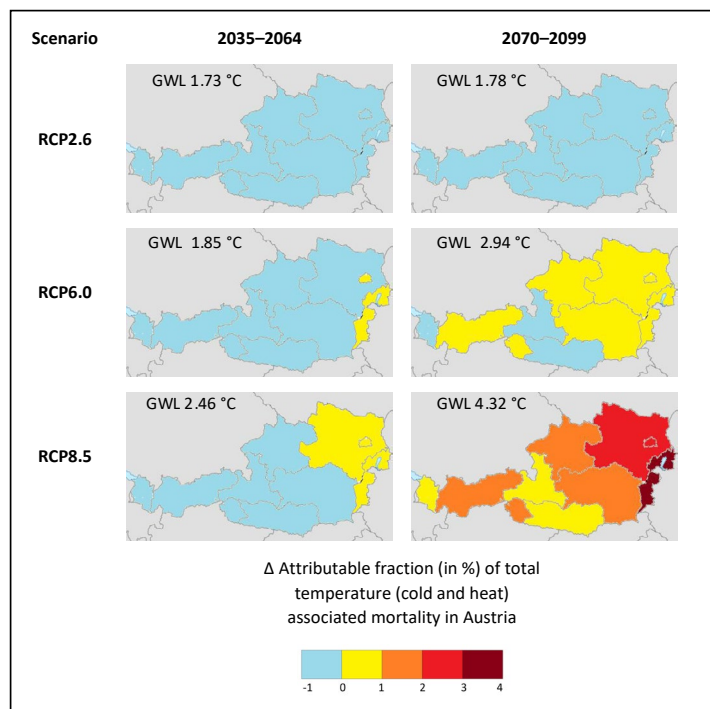
There are many ways in which climate change affects health (APCC, 2014, 2018; Weitensfelder et al., 2023). The media and the public are mostly aware of the direct health impact of heat waves. Indeed, extreme weather events such as heat waves, storms, heavy rains and droughts, are likely to increase due to climate change thus intensifying their direct impact on human health and well-being (see [Section 1.1.2](#)). From a medical point of view, the most important impact of climate change on health to date is through heat and heat waves (*high confidence*). In 2022, 419 (CI 109; 741) heat related deaths in Austria were estimated (Ballester et al., 2023). The most vulnerable to heat stress are the elderly, and even more so very old and chronically ill people. In addition, very young children and pregnant women are more vulnerable (Kuehn and McCormick, 2017; Chersich et al., 2020; Jiao et al., 2023). But outdoor workers, especially those with physically demanding jobs, also suffer from the heat (Cheung et al., 2016; Ferrari et al., 2023). Hot days and even more so, hot nights reduce regeneration and sleep quality. Therefore, general work performance suffers (*medium evidence, high agreement*). Other vulnerable groups are the socioeconomically disadvantaged with poor housing and lack of access to cool areas, health care, and urban green spaces. This also affects ethnic minorities (Gronlund, 2014; Ellena et al., 2020; De Schrijver et al., 2023).

Not only heat but also extreme cold is detrimental to health. Nowadays, more people die on cold days than on hot days (Gasparrini et al., 2017; Statistik Austria, 2022d; Masselot et al., 2023). As temperatures rise, heat-related deaths are predicted to increase and cold-related deaths to decrease (*high confidence*). According to Martínez-Solanas et al. (2021), heat-related deaths will exceed cold-related deaths in Austria by the end of the century and especially under high-emission scenarios ([CCBox 2 Figure 1](#)). However, estimates of cold-related deaths heavily depend on assumptions about effect-thresholds (Arbuthnott et al., 2018) and own data analyses demonstrate that increases in heat deaths already outweigh decreases in cold deaths in Austria (Moshammer, 2023).

The seasonal mortality pattern is first of all characterized by stronger prevalence of cardiovascular diseases, but also infectious diseases play a role (Madaniyazi et al., 2022; Statistik Austria, 2022d). Food-borne bacterial diseases peak in summer and viral respiratory infections in winter (*high confidence*). However, the relevance of temperature (high or low) is far from clear (Liu et al., 2020), making it difficult to assess the impact of a warming climate on these infectious diseases.

While the effects of temperature extremes on well-being, productivity, and physical health are already well understood, the long-term effects on mental health are still understudied in Austria (Weitensfelder et al., 2023). These mental health effects concern post-traumatic stress disorder (PTSD) after catastrophic weather events (Neria et al., 2008), increased suicide rates with increasing temperatures (Kim et al., 2019), but also climate anxiety (Clayton, 2020; Gago et al., 2024). Hickman et al. (2021) report surprisingly high numbers of climate anxiety among young adults, while no representative data are available for Austria. However, based on a convenience sample, Raile and Rieken (2021) report a high percentage of worries about climate change in Austria (81 %) with 41 % 'somewhat' and 16 % 'strongly' or 'very strongly' burdened by these worries. The societal polarization around climate change issues is also likely to reduce human well-being. There is evidence that climate change increases polarization (Wong-Parodi and Feygina, 2021), and that polarization in turn increases stress and anxiety (Fraser et al., 2022). In addition to the political polarization, many

young people suffer from the impression that the elder generations and the government do not take care of them and do not take their worries seriously (Hickman, 2020; Hickman et al., 2021).



CCBox 2 Figure 1 Difference in the attributable fraction (in % of total deaths) of total temperature (cold and heat) associated mortality in Austria, compared to the reference period (1976–2005) according to (Martínez-Solanas et al., 2021). The authors reported the values for 3 representative concentration pathways and for 2 time slots, translated into global warming levels. See 2.A.17 for a monochromatic version of this figure.

Regarding mortality during heat waves, there are indications of ongoing adaptation: As average temperatures rise, the threshold above which an increase in daily mortality is observed also rises (Weitensfelder and Moshhammer, 2020) (*limited evidence, high agreement*). Population-wide adaptation through a selection process may also contribute to the rising temperature threshold for daily mortality: Individuals most vulnerable to high temperatures have already died in previous heat waves, leaving the remaining population more resistant to upcoming heat waves (little evidence except for short-term mortality displacement up to several months, but high plausibility).

In addition to the short-term and long-term impacts of extreme weather events, there is a more complex relationship between human health and climate change associated with atmospheric transport and chemistry, soil and water ecosystems, forestry, agriculture, and human energy and transport infrastructure. Many of these changes will have repercussions on human health (APCC, 2018). A recent ARCP project examined the impacts of climate change on ozone concentration in Austria, including impacts on health (Rieder et al., 2023). With drier and hotter summers, average ozone concentrations will likely increase. However, regional ozone concentrations and especially the local peak of ozone concentrations are mainly affected by national emission scenarios: Lower local emissions of non-methane VOCs as well as nitrogen oxides will impact Austria's national ozone levels significantly more than global emission and climate trends. In the follow-up project Future_Capacity (Formayer et al., 2024a), interactions between ozone concentrations and high temperatures on mortality and morbidity were also examined in a systematic literature review (Wallner and Moshhammer, 2023). A total of 45 relevant studies were identified, most of which examined short-term effects on mortality (*high confidence*). They examined either the effect of high ozone levels on the strength of the heat-mortality association or the effect of hot days on the ozone-mortality association. Only few directly examined multiplicative interactions. Most studies demonstrated a clear (over-additive) effect of ozone and heat.

Climate and meteorology affect air quality by impacting the distribution of air masses and atmospheric chemistry. Temperature and pollutants jointly affect health. Meteorological conditions determine whether aerosols accumulate over time or if they are removed from the atmosphere by dry or wet deposition (Seinfeld and Pandis, 1998; van Zanten

et al., 2017). The occurrence of inversion days in southern and central Austria, as well as inversion intensities and magnitudes, decreased from 1961 to 2017 due to climate change (Hiebl and Schöner, 2018). This should imply reduced particulate matter (PM) pollution and better air quality. On the other hand, an increasing amount of secondary aerosols can be expected because NH_3 is an important precursor of fine particulate formation in the atmosphere (Spangl et al., 2006; Xu and Penner, 2012; Anderl et al., 2016; Backes et al., 2016a, 2016b), and increasing NH_3 emissions were found in Austria from 1990 to 2017 (Anderl et al., 2019). Since the fraction of secondary aerosols in total aerosol concentration can be high (Spangl et al., 2006), a better understanding of PM pollution is required to reduce this major environmental health threat (Hendriks et al., 2013). Overall, the effects of climate warming on the change in PM pollution will vary by region and season and there is still a lot of uncertainty in model estimates. However, a recent global study (Gomez et al., 2023) estimates that annual $\text{PM}_{2.5}$ levels will be about $10 \mu\text{g}/\text{m}^3$ higher in about 100 years due to GHG-induced warming for Europe and especially for the Alpine Region. While these increases are moderate compared to other parts of the world, notably Africa and South America, the agreement between the different models applied is comparatively good for the European region.

Due to hotter and drier weather events, forest fires are becoming more frequent, more intensive, and widespread. Wildfire smoke is characterized by high levels of PM with very small particle sizes and gases such as nitrogen oxides (Yousouf et al., 2014). Exposure to these pollutants in areas surrounding a wildfire can cause acute effects (e.g., irritation of the eyes, respiratory mucosa) or lead to the onset or exacerbation of acute and chronic respiratory diseases. Furthermore, exposure to forest-fire smoke is associated with cardiovascular diseases and mortality. Currently, wildfires are not yet perceived as a grave risk to health in Austria, but this could change in case of severe climate change (see [Cross-Chapter Box 1](#) and [Section 2.2.2](#)).

Low air quality and climate change also increase allergies (Bergmann, 2016) and exposure to pollutants (ozone) can enhance allergic reactions to pollen (Berger et al., 2020), while pollen is predicted to increase in number, exposure duration, and allergenic potential (see [Section 2.2.2](#)). Climate change (mostly due to temperature and CO_2 increases) will have an effect on plant growth and pollination. Plants will react to heat stress and ozone, by producing more pollen or producing pollen more often, and the single pollen particles will often also present more allergenic proteins on their surface. Climate change will also affect the introduction and spread of new and potentially highly allergenic plants, like ambrosia (see [Sections 1.6.4](#) and [2.2.2](#)). So-called thunderstorm asthma is increasingly observed: Pollen break up and allergens are released (Thien et al., 2018; Fuchsig and Scholl-Bürgi, 2022; Huang et al., 2022).

Following the 'One Health' approach, the effects of climate change on the health of plants, animals and humans can be assessed together. In that regard, we refer to the detailed discussions in [Section 2.2](#). Especially cultural ecosystem services have a direct bearing on human health and well-being.

In addition to immediate health risks from drowning, trauma, and infection, floods pose longer-term health risks from damaged homes, the need to relocate, or moldy homes. While data on immediate health effects are available in Austria, long-term effects including psychological and mental health impacts are still severely understudied. Therefore, only general conclusions can be drawn based on data from other countries, which indicate that severe effects might occur, especially on mental health (Fernandez et al., 2015; Matthews et al., 2019; Charlson et al., 2021; Schürr et al., 2023).

Hurricanes, tropical storms and tropical cyclones are not frequent in Europe. However, wind speeds of extra-tropical cyclones in Europe can reach 'hurricane force' according to the Beaufort wind scale (Goldman, 2014). Storms can affect human health either through direct effects, including injury or death during the storm from flying debris or falling trees, or indirect effects following the storm including reduced access to health care or medicines, exposure to carbon monoxide (from gasoline powered electrical generators), electrocution, and psychological impacts (Goldman, 2014).

Health related risks of droughts can be direct due to lack of (clean) water for drinking or hygiene measures. However, the danger of drinking water shortage due to droughts is currently not yet a major issue in Austria. Indirect effects are the adverse effects on agricultural outputs, which mainly lead to socio-economic consequences for producers.

While in Austria there is still room for adaptation to mitigate the above-mentioned consequences for health and livability, increasingly large parts of the world do not have this option. When an increasing number of people around the

world face impoverishment, loss of resources for livelihood, and a mounting vulnerability to – among others – infectious diseases, this might ultimately also have consequences for public health in Austria (APCC, 2018) (*limited evidence, high agreement*).

Health impacts of adaptation and mitigation measures

The number of climate change mitigation policies and adaptation measures increased in recent decades. Many adaptation measures will be effective immediately and contribute to reducing human vulnerability to climate variability. The benefits of other mitigations carried out today will not be evidenced until the coming decades because of the long residence time of GHG in the atmosphere.

CCBox 2 Table 1 Estimated health gains from selected mitigation measures (APCC, 2018; Weisz et al., 2020).

Measure	Description	Mitigation potential	Health benefits
Healthy diet	Reduced meat consumption in accordance with dietary recommendations	Up to 20 % reduction in individual footprint due to food intake (see also Table 2.3. and Section 2.3.2.)	20 % reduction of deaths caused by dietary factors
Physically active mobility for Vienna, Graz and Linz	Green Mobility: Targets for the modal share of trips for the years 2020/2025 are almost achieved. E.g., Vienna: Share of car trips reduced from 40 to 28 %	290,000 tCO ₂ eq reduction	27 deaths per year per 100,000 prevented
	Green Exercise: Targets exceeded; e.g., Vienna: Further reduction to 18 %	530,000 tCO ₂ eq reduction	58 deaths per year per 100,000 prevented
Insulation of houses	Better insulation of houses will reduce heat loss in winter and, if well done, can mitigate heating up in summer	Reduced energy needed both for heating and for cooling	Increased comfort and well-being. Especially relevant for low-income households in poor housing conditions
Health care sector	More targeted use of antibiotics (antibiotic stewardship)	Antibiotics use for human health needs accounts for 1 ktCO ₂ eq/yr	Indiscriminate use of antibiotics increases the risk of antibiotic resistance and has lots of adverse side effects
	Reduced use of metered dose inhalers (MDI)	Propellants from MDI account for 13 (2005) to 25.9 (2015) ktCO ₂ eq/yr	Dry powder inhalers can be used without propellants and their use is often easier

Mitigating climate change is often seen as an activity with local costs and global benefits. However, many mitigation measures also have a range of significant health benefits, both locally and in the near term, mainly because they also reduce other airborne emissions, for example, NO_x and particulate matter (APCC, 2018; Wolking et al., 2018; Rieder et al., 2023). Examples of these win-win situations include a shift from motorized to physically active traveling (walking, cycling, and partial use of public transport), healthy (less meat) diets, or better insulation of houses (CCBox 2 Table 1).

However, when considering climate change mitigation and adaptation measures as a whole, unintended consequences might arise, resulting in an actual drawback for human health. Therefore, it might be difficult to create a coherent framework for planning interventions. For example, burning wood instead of gas or oil for heating might in certain cases reduce the carbon footprint (see Section 2.3.2), but will often increase particulate matter air pollution (Haluza et al., 2012). The technology for low emission furnaces is available, but current limit values still allow much higher emissions (Umweltbundesamt, 2023b). Replacing fossil fuels with biofuels is likely to reduce particulate matter pollution but increase emissions of nitrogen dioxide (Hutter et al., 2015). The balance of these effects remains controversial. For Austria, especially the AQUELLA project (Bauer et al., 2007, 2009; Jankowski et al., 2009) has demonstrated the important

contribution of smoke from biomass burning to particulate air pollution confirming more global concerns (Sigsgaard et al., 2015).

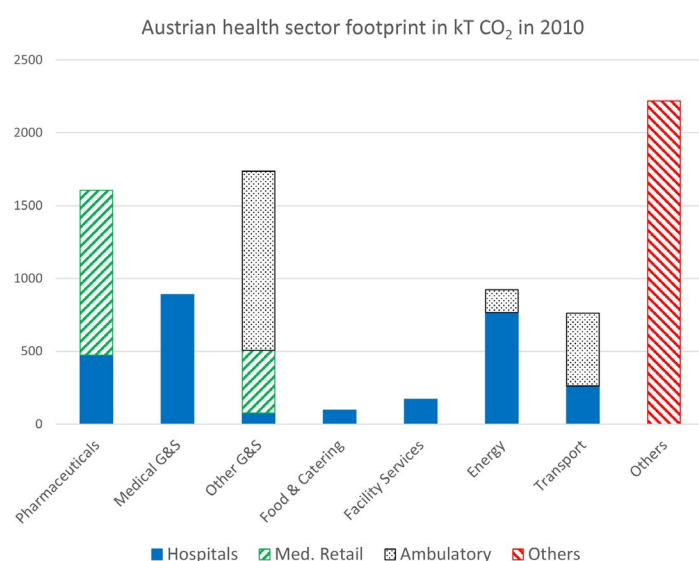
Air pollution contributes substantially to the burden of disease. Acute health effects of air pollution have also been demonstrated with Austrian data examining different endpoints and pollutants (Moshhammer et al., 2013, 2019, 2020; Neuberger et al., 2013). Chronic effects have been demonstrated in Europe by the large ESCAPE project (Beelen et al., 2015), which also included a large cohort from Vorarlberg. The ESCAPE data have been recently merged with those from other studies in the ELAPSE study to demonstrate health effects even at low levels of pollution (Brunekreef et al., 2021). Two recent overviews (in German) of long-term and short-term health effects of air pollutants have been provided by Weinmayr (2023) and Moshhammer (2023), respectively.

Another example is the impact of urban design strategies (see [Section 3.2.3](#)), while urban greening substantially influences the distribution of solar energy in urban areas, various health co-benefits are expected from these activities, such as reduced obesity and cardiovascular disease and improved mental health through increased physical activity, cooling spaces (e.g., shaded areas), and social connectivity (*limited evidence, high agreement*). On the other hand, other adverse health effects such as pollen allergies have to be taken into account, as allergies might increase with increased urban green space.

Adaptation strategies and measures can be planned directly to improve health. Climate change adaptation measures that are not primarily intended to improve health may have health-related side effects. Any adaptation measure (e.g., in forestry, agriculture, energy, industry, tourism) should therefore also be assessed regarding possible, unintended (negative) side effects on population health.

The carbon footprint of the Austrian health care system and mitigation options

The Austrian health care industry as a whole is responsible for 7 % of the carbon footprint of Austria¹ (Weisz et al., 2020). Their estimates for 2010 are presented in [CCBox 2 Figure 2](#). While medical goods and services account for about half of the total carbon footprint, direct energy use and transport account for roughly the other half, with direct energy use declining and transport emissions increasing. Reducing most of those emissions can be addressed with mitigation measures covered in [Section 2.3](#) (food production), [Chapter 3](#) (buildings, infrastructure, transport of goods and persons or information and communication technology) and [Chapter 4](#) (industry, energy).



CCBox 2 Figure 2 The carbon emissions of the Austrian health care system in 2010 according to Weisz et al. (2020): Pharmaceuticals, medical goods and services, other goods and services, food and catering, facility services, energy (for heating and cooling of buildings mostly), transport (of patients, staff and visitors), and others (including financing, administration, etc.) in hospitals, medical retail, ambulatory services and other parts of the health care system.

¹ This value encompasses the emissions of the goods and services consumed by the health system, and overlaps with various sectors.

However, there are at least some possible mitigation measures that are specific to the health care system. For example, some anesthetic gases (Koch and Pecher, 2020; Richter et al., 2020; Lehmann and Sander, 2021) and propellants of asthma inhalers (Rauchenwald et al., 2020; Wilkinson and Woodcock, 2022) have a large climate forcing potential. Weisz et al. (2020) estimate the greenhouse gas emissions of all anesthetic gases to be 21.4 ktCO₂eq in 2015. At the same time, metered dose inhalers account for 25.9 ktCO₂eq. While the former displayed a declining trend, emissions from inhalers increased (nearly doubled) since 2005. In addition to the emissions associated with the manufacturing of these medical devices (which are accounted for in the supply chain), the climate effects of the pharmaceuticals when released into the air must be considered.

Some health care providers are starting to implement reduction strategies. Some hospitals have declared a phase-out of the narcotic gases with the highest greenhouse potential, or are planning to install carbon filters to capture and reuse these gases. Dry-powder inhalers are often a viable alternative to the use of propellants in metered-dose inhalers. At present, it is difficult to establish industry-wide emission reduction targets, because data on current consumption and trends in Austria are not available.

A high-quality, sustainable health care system that focuses on prevention rather than disease would improve human health at scale, while further reducing the carbon footprint of health care. Sustainable health care would reduce unnecessary and emission-prone diagnostic and therapeutic interventions, with X-rays being a prime candidate for the former and antibiotics for the latter. Primary prevention and quality of life provisions are intrinsically more carbon neutral than the current emphasis on end-of-life, high-tech treatments and their associated supply chains.

Today, however, the evolution towards a sustainable health care system in Austria is in its infancy. Even with 'health check-ups' (now: preventive check-ups), the main aim is to discover illnesses in good time, not to maintain health. Our current health care system's orientation, facilities and financing are still primarily geared to the care of the sick and the treatment of illness (Green et al., 2002; Fiandaca, 2017). While treatment of illness is important, preventive care, avoidance of illness and maintenance of good health are not truly realized in the current system. While Austria proclaims goals such as 'Health in all Policies' as a strategy to introduce emphasis on prevention (Fonds Gesundes Österreich, 2015), the necessary budgetary commitments are still lacking (Rechnungshof Österreich, 2023).

2.2.3. Impacts of climate change on cultural ecosystem services and related benefits

Cultural ecosystem services are broadly defined as the non-material benefits that result from human interaction with the natural environment (Reid et al., 2005). Human well-being greatly depends on cultural ecosystem services, as they provide numerous non-material benefits that contribute to physical and mental health (Nowak-Olejnik et al., 2022; Schirpke et al., 2022). For example, landscapes, terrestrial and freshwater ecosystems, and natural features provide recreational activities, aesthetic experiences, inspiration and spiritual enrichment, and cultural identity (Table 2.A.1). While studies indicated the importance of maintaining cultural and (semi-)natural landscapes for the provision of cultural ecosystem services (Schirpke et al., 2018b; Lavorel et al., 2020; Schirpke et al., 2022), only few studies have explicitly addressed effects of climate change on cultural ecosystem services (Inglis and Vukomanovic, 2020;

Mucioki et al., 2021; Schirpke and Ebner, 2022). Most studies focused on recreational activities, while aesthetic, symbolic and inspirational values, education and identity have been less examined (Schirpke et al., 2022, 2024). In the following, only those cultural ecosystem services are presented, for which climate change impacts were reported in the literature relevant to Austria, while there are research needs for educational, inspirational, spiritual, and existence values (Schirpke and Tasser, 2024; Schirpke et al., 2024).

Impacts of climate change on recreational activities

Recreational activities comprise all kinds of outdoor activities practiced in natural and semi-natural ecosystems for recreational purposes. In Austria, particularly mountain areas and lakes offer manifold opportunities for outdoor recreational activities (Figure 2.6) (Schirpke et al., 2018a; Pröbstl-Haider et al., 2021), such as hiking, cycling, climbing, swimming, boating, skiing, and many others. Global

warming has predominantly negative impacts on recreational activities (the economic relevance for the Austrian tourism industry is described in Sections 4.3.3 and 4.3.2). There is *high confidence* that warmer temperatures reduce opportunities for winter sport activities such as alpine skiing and cross-country skiing due to a shorter winter season and insufficient snow cover (see Sections 1.3, 4.3.3 and 7.4), particularly at lower elevated sites (Tervo-Kankare et al., 2013; Steiger et al., 2021). Due to a projected decrease of snow days to 50 % under a GWL 2.0°C scenario, it is expected that winter sport activities will shift upwards to higher elevations (Endler and Matzarakis, 2011). Moreover, people indicated lower intention to engage in recreational winter sport activities under a scenario with low natural snow (GWL not specified) (Frühauf et al., 2020). In summer, the increased potential for mountain hazards due to melting permafrost, such as rock falls and debris flows, may restrict the use of alpine trails and climbing routes, and hence, recreational activities such as hiking, mountaineering, climbing, and mountain biking (Pröbstl-Haider et al., 2016) (*medium confidence*). Moreover, the increased number of disturbances in mountain forests limits the access to forests due to increased

salvage logging and increases the vulnerability of touristic infrastructure due to a reduced protective effect of forests (Lecina-Diaz et al., 2024; Müller, 2011). In contrast, warmer temperatures will extend the season for water-based activities (e.g., swimming, bathing, boating) at large lakes (see also Sections 1.4.2 and 4.3.3): Under GWL 2.0°C, a 40 % increase in warm days with temperatures above 25°C, and a doubling of hot days with temperatures above 30°C are expected by 2050 (Pröbstl-Haider et al., 2021). The increasing number of warm days will also increase recreational opportunities at mountain lakes (Schirpke and Ebner, 2022). However, climate change leads to more frequent low water levels (Soja et al., 2013), which reduces opportunities for water-based recreation (Wieland and Martinis, 2020). Warmer water temperatures also promote the occurrence of algae, cercariae, cyanobacteria (Gallina et al., 2011), which reduce the quality of water-based activities and increase health risks, especially in lowland lakes. Hot summers and increased evaporation will make lake water warmer and often more saline. This will increase the risk for swimmers to acquire wound infections from *Vibrio cholerae* (Le Roux et al., 2015; Hirk et al., 2016).

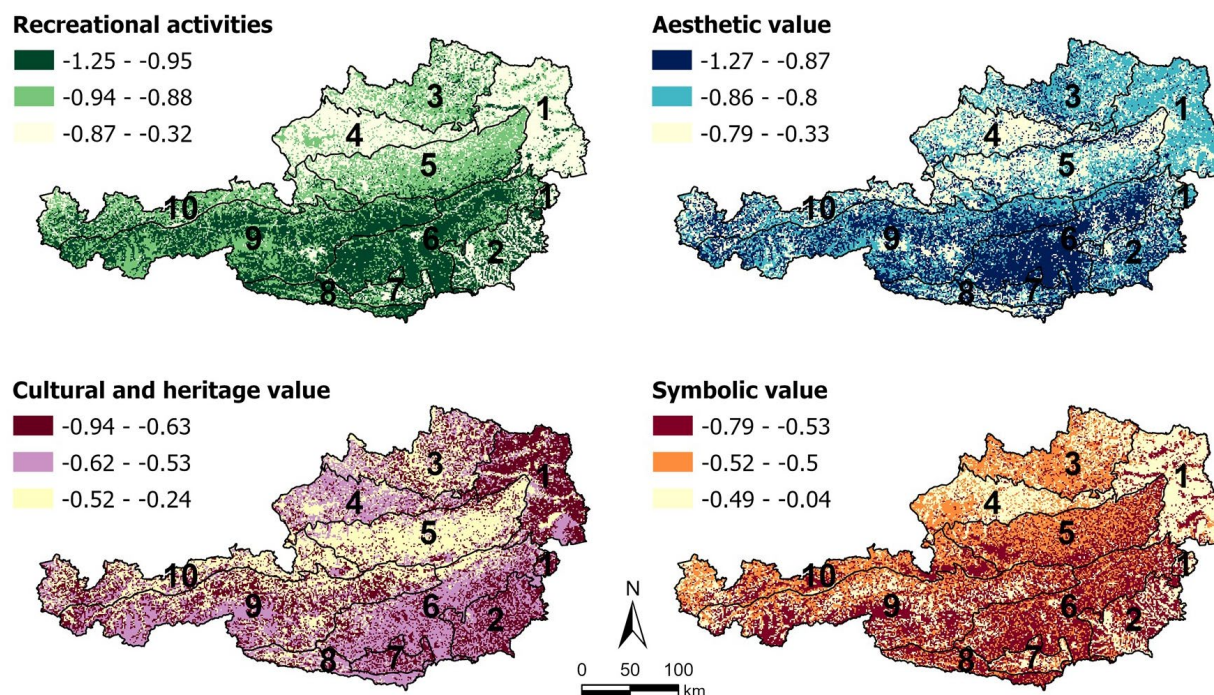


Figure 2.6 Potential climate change impacts on the provision of cultural ecosystem services (classification of impacts based on terciles). Impact values were derived by identifying potential impacts on multiple underlying indicators based on current literature, multiplied with ecosystem service supply and weighted with the spatial distribution of temperature and precipitation under GWL 5.0°C. Please note that the potential impacts on all cultural ecosystem services are negative. For methodology, see Schirpke and Tasser (2024). Numbers indicate major biogeographical regions (from data.gv.at/katalog/dataset/naturraumzonen): (1) Pannonian plains and hills, (2) Southern Alpine foothills, (3) Northern granite and gneiss highlands, (4) Northern Alpine foothills, (5) Northern Alps – east, (6) Central Alps – southeast, (7) Klagenfurt Basin, (8) Southern Alps, (9) Central Alps – central, (10) Northern Alps – west.

In general, there is *high confidence* that climate change induces a shift in the spatial and temporal demand for recreational ecosystem services (Vierikko and Yli-Pelkonen, 2019; Pröbstl-Haider et al., 2021; Wilkins et al., 2021). There will be an upshift in elevation where possible, i.e., high-mountain regions will become more attractive in summer due to cooler temperatures and in winter due to less uncertainty in snow cover compared to lower elevation mountain destinations (see Sections 1.3 and 4.3.4). Moreover, shoulder seasons, i.e., periods between peak and off-peak seasons, will become more attractive for recreational activities than hot summer periods.

Impacts of climate change on cultural and heritage value

Quantitative assessments of climate change impacts on heritage, aesthetic, and symbolic values under global warming levels are not specified, as the literature mostly consists of qualitative studies or studies using worst-case scenarios.

Landscapes and natural features provide various cultural and heritage values, that are closely connected to the management of landscapes, especially cultural landscapes. As a result of climate change, it can be expected that agricultural use will be intensified at lower elevations where the climate is favorable or where irrigation is possible, while the spatial extent of forests will increase at higher elevations due to an upshift of the tree line and accelerated natural reforestation processes on abandoned grasslands. Both developments lead to a decline of cultural landscapes and thus reduce related spiritual and cultural values (Figure 2.6) (Pröbstl-Haider et al., 2015; von Heßberg et al., 2021) (*limited evidence, high agreement*). Furthermore, there is *high confidence* that, under increasing drought conditions, it may not be possible to maintain traditional agroforestry systems that are of high cultural value, such as larch meadows or orchard meadows (Zoderer et al., 2016; Flinzberger et al., 2020), because larch trees will lose their habitat at lower altitudes (Obojes et al., 2018), while the productivity of orchard trees will be reduced (Hammel and Arnold, 2012).

Impacts of climate change on aesthetic value

The aesthetic value of a landscape depends on both biophysical characteristics of the environment and human perceptions (Daniel, 2001). Usually, this ecosystem service focuses on the visual characteristics of the landscape such as individual types of ecosystems, natural features, and spatial

landscape patterns (Schirpke et al., 2016). While some studies worldwide explicitly address climate change impacts on aesthetic values, and report negative impacts, for example, induced by species shifts (Inglis and Vukomanovic, 2020), or invasive species and the disappearance of snow patches (Mameno et al., 2022), there are only few studies in the Austrian or Alpine-wide context. In general, there is *high confidence* that climate change impacts are strongly linked to changes in land-cover composition arising from global warming or changes in precipitation patterns (Figure 2.6). For example, the expansion of forests at higher elevations leads to a decline in aesthetic value due to a reduction of the viewing depth and lower preferences associated with forest ecosystems (Schirpke et al., 2016, 2017). Moreover, a higher number of forest disturbances (e.g., wind throw areas, burnt areas) might reduce the aesthetic value of forests (Fleischer et al., 2017). The retreat of glaciers and snowfields reduces the aesthetic value of landscapes due to the loss of highly appreciated landscape elements (Schirpke et al., 2021). It also leads to an increase in debris, dry and desolate environments, which is perceived negatively by most visitors (Salim et al., 2021). In lakes, direct and indirect effects of climate change are expected to have negative impacts on visual water quality (*high confidence*), mainly due to higher levels of eutrophication and declining ecosystem quality, depending on the level of human use and the specific social-ecological conditions of the lake (Schirpke and Ebner, 2022). While remote lakes and high elevation lakes are more exposed to changing climatic conditions, human use is more likely to impact cultural ecosystem services at easily accessible and lower-elevation lakes (Ebner et al., 2022).

Impacts of climate change on symbolic value

Wild plant and animal species can provide a source of inspiration for people in different ways and may be used for symbolic representations (Schirpke et al., 2018b; Rüdisser et al., 2019). Climate change is expected to reduce suitable habitats for plants and animals that are symbolic for the European Alps, such as edelweiss, gentian, Alpine ibex, chamois, and marmot (Figure 2.6, see Section 1.6) (*medium evidence, high agreement*). For example, habitats of alpine plant species that occur in specific ecosystems and cold climates such as the edelweiss will be reduced or lost due to climate change (Grabherr, 2009; Maghiar et al., 2021). Symbolic animals such as chamois suffer from a decline in forage quality as a consequence of global warming (Reiner et al., 2022; Corlatti et al., 2023). In the case of marmots, the thinner snowpack,

which reduces the insulation effect of snow during the snow season, as well as changes in social and demographic structures due to a longer summer season, both have negative effects on the juvenile survival (Rézouki et al., 2016; Glad and Mallard, 2022).

Impacts of climate change on health related to cultural ecosystem services

Human well-being greatly depends on cultural ecosystem services, which provide important non-material benefits that contribute to mental and physical health (Nowak-Olejnik et al., 2022; Schirpke et al., 2022). A change of ecosystems also has a variety of effects on their health-supporting services. Most research on the recreational effects of ecosystems focuses on either greenery or biodiversity of natural surroundings, with some, but still insufficient supporting recreational influences of both. On the one hand, green landscapes have been shown to be associated with mental health and well-being, via various processes (Markevych et al., 2017): Greenery reduces harmful influences on (mental and physical) health, such as air pollution, noise, or heat, but it also provides a setting for building new capacities (via physical activity and social cohesion) and is also linked to the restoration of capacities. It has been shown that attention restoration (Kaplan, 1995) and a resulting slight enhancement of cognitive performance happens especially well in nature surroundings (Stevenson et al., 2018), although the results can sometimes be ambiguous (Ohly et al., 2016). Natural green surroundings also reduce stress (Ulrich et al., 1991) and even pain (Ulrich, 1984), thus contributing to well-being, mental health and recovery. Overall, and after controlling for socio-economic factors, living in green surroundings is associated with not only better physical health, but also better mental health (Maas et al., 2009; Triguero-Mas et al., 2015), although these studies are usually not able to identify causal mechanisms (Sandifer et al., 2015, for an overview). In addition, greenery leads to a cooler microclimate, which is important for reducing aggression and violence: Recent studies have shown increases in violent crime with rising temperatures (Hu et al., 2017; Miles-Novelo and Anderson, 2019). Whether nature and greenery indirectly promote social cohesion is a matter of discussion, but at least no direct connection between greenery and social cohesion could be found (Triguero-Mas et al., 2015). Similarly, no direct connection between greenery and physical activity could be confirmed (Triguero-Mas et al., 2015), but it has been shown that exercise, assessed by

walking, is more restorative in a natural environment than in an urban one (Hartig et al., 2003).

Whether biodiversity has benefits for mental health beyond those of greenery or nature is rather denied, with overall ambiguous results (Marselle et al., 2021). Overall, the association of biodiversity with (mental) health and recovery can be seen as equivalent to that of greenery (via reducing harm, restoring capacities and building capacities), but it can also show some harmful effects on human health, e.g., via allergens (Marselle et al., 2021). Regarding specifics of biodiversity, single studies suggest that species diversity is positively related to well-being, especially bird diversity (Cameron et al., 2020; Methorst et al., 2021), but partly also plant richness (Fuller et al., 2007).

2.3. Transformations and measures in the land use system to mitigate and adapt to climate change

The land use system not only contributes to GHG emissions, but also provides carbon sinks when carbon stocks in biomass, soils, and harvested wood products increase. Human activities may strive to mitigate emissions, increase sinks, and/or maintain system functions by adaptation strategies.

The following subchapters assess activities aimed at realizing such mitigation potentials, as well as activities aimed at adapting to climate change. The subchapters build upon the Avoid-Shift-Improve approach ([Cross-Chapter Box 4](#)), which gained particular attention in the IPCC AR6 (Creutzig et al., 2022b). For reasons of simplicity, we merge ‘shift’ and ‘avoid’ activities, as it is not always straightforward to unambiguously separate these two with regard to the land system. Thus, we discern two sections on the effects of Avoid-Shift-Improve measures namely:

Section 2.3.1, detailing on ‘improve’ activities, which aim at an increased efficiency (of material or energy use) of providing goods or services. These activities aim to reduce emissions without focusing on changing the quantity produced and consumed of a certain good or service. They may also aim at optimizing outputs under conditions of climate change, by adapting to climate change.

Section 2.3.2 detailing on ‘avoid and shift’ activities that either reduce resource extraction and consumption, or provide services with different, less emission-intensive resources. An example for the first would be the reduction of food losses, for the second the shift from animal proteins to plant-based proteins.

In addition, [Section 2.3.3](#) provides an assessment of nature-based climate solutions for adaptation and mitigation, including the technical mitigation potentials of existing land-system wide CDR approaches ([Cross-Chapter Box 6](#)).

Details on accompanying effects, such as the transformation from land to built-up area, are covered elsewhere in this report (e.g., [Section 3.2.2](#)).

[Table 2.3](#) consolidates the knowledge on mitigation potentials of land-based avoid-shift-improve activities in Austria. Mitigation potentials have a large uncertainty range, e.g., due to limited knowledge on implied transformation processes or feasibility parameters. Caveats, limitations, and research gaps, which are specific to a measure are listed below the corresponding row in the table. General limitations which hold across all measures are discussed below the table.

Table 2.3 Overview of mitigation potentials of transformations in the Austrian land use systems. Detailed mitigation potentials of each considered study are listed in [2.A.16](#).

Total potential* and sub-effects	Evidence on biogeophysical and technical feasibility and barriers	Evidence on economic potential, socio-cultural and institutional barriers and enabling conditions	Mitigation potential compared to nowadays (ca. 2020) [MtCO ₂ eq/yr]	Mitigation potential compared to reference scenario** [MtCO ₂ eq/yr]	Confidence	Number of independent studies (independent models) for Austria
*The total potential is the sum of the sub-effects ** Referring to the reference scenario in each respective study – see limitations below and Appendix A2.16 for the list of studies. Mitigation potentials represent estimated reductions in greenhouse gas emissions and increases in carbon sinks. Positive values represent reduced emissions or increased sinks. Negative values represent increased emissions or reduced sinks.						

Improve measures:

Change in tree species composition: Switching to native non-coniferous species in forests – See [Section 2.3.1](#)

<i>Long-term potential (Average ca. 2020–2150)</i>						
Total potential	low	low	-9.5 to -10.6	+1.1 to +1.9	low	2 (1)
Reduced processing emissions	n.a.	n.a.	n.a.	n.a.	n.a.	0
Effect on the sink in ecosystems (forest)	low	low	-0.1 to -1.2	+4.1 to +4.9	low	2 (1)
Effect on the sink in harvested wood products (HWP)	low	low	-2.8	-1.3	low	2 (1)
Effect on avoided emissions via substitution	low	low	-6.6	-1.7	low	2 (1)
<i>Short-term potential (Average 2020–2060)</i>						
Total potential	low	low	-3.7 to +0.3	-0.3 to +1.1	low	2 (1)
Effect on the sink in ecosystems (forest)	low	low	+0.2 to +4.2	-0.5 to +0.9	low	2 (1)
Effect on the sink in harvested wood products (HWP)	low	low	-0.7	+0.1	low	2 (1)
Effect on avoided emissions via substitution	low	low	-3.2	+0.1	low	2 (1)

Caveats: The effect on the forest sink materializes only under a high GWL (between GWL 4.0°C and GWL 5.0°C) and primarily beyond 2080. The interaction with increased disturbances from climate change is poorly known. Potentials of forestry measures are assessed as yearly averages over a long timeframe, up to 130 years, due to important non-linear dynamics (e.g., sink saturation and decarbonization of alternatives to wood). The comparison to 2020 (column 4) shows the difference in sinks/avoided emissions between the scenario with changed tree species composition, in a long-term average, and the value for 2020 in the reference scenario from the respective study. The increased emissions of the long-term average compared to 2020 are due to the decreasing trend in C sinks and avoided emissions, independently of the taken measures. The change in tree species composition moderately compensates for this overall trend (column 5). The potentials outlined here refer mostly to technical potentials from a current perspective. Time periods differ by studies.

Total potential* and sub-effects	Evidence on biogeophysical and technical feasibility and barriers	Evidence on economic potential, socio-cultural and institutional barriers and enabling conditions	Mitigation potential compared to nowadays (ca. 2020) [MtCO ₂ eq/yr]	Mitigation potential compared to reference scenario** [MtCO ₂ eq/yr]	Confidence	Number of independent studies (independent models) for Austria
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Shorter rotation cycles: Immediate rapid rejuvenation of old stands by shortening the end-use age, to limit the risk of storm damage – See Section 2.3.1

Long-term potential (Average ca. 2020–2150)

Total potential	low	low	-14.1 to -14.6	-2.6 to -3.4	low	2 (1)
Effect on emissions	n.a.	low	n.a.	n.a.	n.a.	0
Effect on the sink in ecosystems (forest)	low	low	-7.6 to -8.1	-2.4 to -3.2	low	2 (1)
Effect on the sink in harvested wood products (HWP)	low	low	-1.9	-0.4	low	2 (1)
Effect on avoided emissions via substitution	low	low	-4.6	+0.2	low	2 (1)

Short-term potential (Average 2020–2060)

Total potential	low	low	-1.5 to -10.1	-0.7 to -6.8	low	2 (1)
Effect on the sink in ecosystems (forest)	low	low	-1.1 to -9.7	-4.4 to -10.5	low	2 (1)
Effect on the sink in harvested wood products (HWP)	low	low	+0.9	+1.7	low	2 (1)
Effect on avoided emissions via substitution	low	low	-1.3	+2	low	2 (1)

Caveats: In total over all effects, this measure increases GHG emissions over the considered time period, mainly due to the reduced sink in forests. The interaction with increased disturbances from climate change is poorly known. Potentials of forestry measures are assessed as yearly averages over a long timeframe, up to 130 years, due to important non-linear dynamics (e.g., sink saturation and decarbonization of alternatives to wood). Time periods vary between studies. The potentials outlined here are mostly biogeophysical potentials, assessed from a current perspective.

Other Adaptive Forest Management – See Section 2.3.1

No data available, as no study exists for Austria.

Including: Fuel management strategies like selective thinning, prescribed burning, mechanical clearings, increasing structural diversity of stands, continuous forest cover, reduce game density, reduce stand density, etc.

Total technical mitigation measures in agriculture – See Section 2.3.1

Total potential	low	low	n.a.	+0.3 to +1.6	medium	2
Effect on agricultural emissions	low	low	n.a.	+0.2 to +1.2	low	1
Effect on agricultural soils and C sequestration	low	low	n.a.	+0.07 to +0.49	medium	1

Caveats: Aggregate of the technical measures in agriculture, including those quantified in more detail below (agricultural inputs, livestock farming, rewetting peatlands under agricultural use). (i) Effect on agricultural emissions: Aggregate of technical mitigation measures targeting CH₄ and N₂O emissions, including manure management, enteric fermentation, soil emissions, and fertilizer application, and assuming 80–100 % dissemination. (ii) Effect on agricultural soils and C sequestration: Including reduced tillage, non-inversion tillage on arable land (no data), broadening of crop rotations – increased soil biomass via field forage crops and legumes (no data), broadening of crop rotations – increased protein supply via forage legumes, implementation of catch/cover crops and greenings, use of manure instead of nitrogen fertilizer, amendment of organic substances such as biochar (no data), reducing soil compaction from wheel traffic, medium management intensity on permanent grassland, reducing conversion of permanent grassland, reducing cultivation on organic soils and reduced draining, organic farming with increased carbon sequestration measures, agroforestry (increasing tree cover in agricultural areas, silvopasture) (no data), and hedgerows. The effect on agricultural soils and C sequestration reflects mainly increased C sinks, but cannot be fully separated from decreased emissions and substitution effects of the above listed measures (about 0.1 to 0.2 MtCO₂eq/yr). Data comes from a meta-analysis, hence the *medium confidence*.

Total potential* and sub-effects	Evidence on biogeophysical and technical feasibility and barriers	Evidence on economic potential, socio-cultural and institutional barriers and enabling conditions	Mitigation potential compared to nowadays (ca. 2020) [MtCO ₂ eq/yr]	Mitigation potential compared to reference scenario** [MtCO ₂ eq/yr]	Confidence	Number of independent studies (independent models) for Austria
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Reducing GHG emissions by the rewetting of peatlands under agricultural use – See [Section 2.2.2](#)

Total effect on GHG emissions	low	low	+0.001 to +0.388*		low	2
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*Upper estimate for potential (expert judgement) assuming that rewetting of 50 % of 31,000 ha agriculturally used peatland area (Hogl et al., 2023) is possible, with a mean emission reduction of 25 tCO₂eq/ha/yr (BMLRT, 2022).

Caveats: Estimates assume optimal restoration, with zero emissions after rewetting. Estimates don't include additional carbon sequestration due to regained carbon sink function after rewetting. Estimation of average emission reduction is based on German data; Austrian emission data are lacking. Knowledge on the amount of peatland area and future conditions for rewetting is low.

Reducing GHG emissions from agricultural inputs (see sub-measures below the table) – See [Section 2.3.1](#)

Total effect on emissions, sinks and substitution	medium	medium	n.a.	+0.05 to +0.330	medium	1
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Caveats: The study is a meta-analysis, hence the *medium confidence*.

Including: Reducing mineral fertilizers – increasing legume forage, reducing emissions from machinery upstream, improving fuel efficiency, reducing emissions from pesticides, systemically applied precision agriculture techniques, reducing N-fertilizer application in lanes, reduction of N-losses by close-to-ground application of slurry, reduction of energy demand in agricultural buildings

Reducing GHG emissions from livestock farming; excluding the reduction of livestock (see sub-measures below the table) – See [Section 2.3.1](#)

Total effect on emissions, sinks and substitution	medium	medium	n.a.	+0.015 to +0.8	medium	1
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Caveats: The study is a meta-analysis, hence the *medium confidence*.

Including: Optimization of housing, increase of pasture feed intake, reduction of the protein content in feed rations of pigs and poultry, reduction of the protein content in feed rations of bulls, reduction of the protein content in feed rations of cows, refining herd management and feeding protocols, solid manure instead of liquid manure systems (no data), utilization of excrements via biogas plants, feed additives (no data), increase livestock yield and efficiency, extend the productive life, improve animal health.

Measures to reduce GHG emissions of processing, transport, and other processes in agricultural and wood supply-chains – See [Section 2.3.2](#)

No data available, as no study exists for Austria.

Increasing self-sufficiency for agriculture and forestry products and other trade related measures; effect on global GHG emissions embodied in consumption – See [Section 2.3.2](#) and [2.A.12](#).

No data available, as no study exists for Austria.

Shift and avoid measures:

Shift towards healthier and plant-based (EAT-Lancet) diets and according restructuring of agricultural production (incl. reduction of livestock products) – See [Section 2.3.2](#) (protein transition, calories), and in [Section 2.3.3](#) (*enabled afforestation/renaturation*)

Total potential	high	medium	+6.3 to +11.1	+5.0 to +15.4	high	6
Effect on agricultural emissions	high	low	+3.6 to +3.7	+2.5 to +5.6	high	6
Effect on the sink in ecosystems (afforestation / renaturation on freed area)	low	low	+2.7 to +7.4	+2.5 to +9.8	low	3
Effect on avoided emissions via substitution (additional production of bioenergy and bio-based materials on freed area)	n.a.	n.a.	n.a.	n.a.	n.a.	0

Total potential* and sub-effects	Evidence on biogeophysical and technical feasibility and barriers	Evidence on economic potential, socio-cultural and institutional barriers and enabling conditions	Mitigation potential compared to nowadays (ca. 2020) [MtCO ₂ eq/yr]	Mitigation potential compared to reference scenario** [MtCO ₂ eq/yr]	Confidence	Number of independent studies (independent models) for Austria
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Caveats: The sensitivity to the characterization metric needs to be evaluated. Socio-cultural transformation pathways are not described in the studies. Research gaps exist on transformation capacities, enabling conditions, and the contribution of institutions. Little is known about the regional-level and farm-level impacts and changes required for a shift from animal-based to plant-based food production. It is unclear to what degree this shift can be achieved through adjustments in farming practices and what fundamental changes to production systems would be needed in addition to that. Likewise, there is a clear research gap on the degree to which such a shift would induce farm closures and changes in rural structures. Impacts on ecosystem services, biodiversity, and landscapes are partly unclear. Available studies assume continuous population and emission growth. Hence, the mitigation potential comparing to the current situation (column 4) is smaller than when comparing to a reference scenario (column 5).

Halving food losses – See Sections 2.3.2 and 2.3.3

Total potential	medium	medium	+0.2 to +1.1	+2.1 to +4.7	medium	2
Effect on agricultural emissions	medium	medium	-0.4 to +0.5	+1.6	medium	1
Effect on the sink in ecosystems (afforestation / renaturation on freed area)	low	medium	+0.6	+0.5 to +3.1	low	2
Effect on avoided emissions via substitution (additional production of bioenergy and bio-based materials on freed area)	n.a.	n.a.	n.a.	n.a.	n.a.	0

Caveats: Data on food waste and losses are poor (research gap). Estimating quantities and avoidability is a major challenge. Halving food losses appears as a plausible assumption. Research gaps on transformational pathways exist. Data on avoidability at various processing stages in the value chain are lacking. The increased agricultural emissions compared to present day are due to the assumed population growth (column 4). Halving food waste compensates for this overall trend (column 5).

Reducing the overall use and harvest of wood to build up C stocks in forests – ‘Vorratsaufbau’ – See Sections 2.3.2 and 2.3.3

<i>Long-term potential (Average ca. 2020–2150)</i>						
Total potential	low	low	-2.6 to -4.2	+7.0 to +8.4	low	2 (1)
Effect on the sink in ecosystems (forest)	low	low	+1.4 to +4.4	+9.3 to +11.1	low	2 (1)
Effect on the sink in harvested wood products (HWP)	low	low	-2.2 to -3.4	-0.7	low	2 (1)
Effect on avoided emissions via substitution	low	low	-6.4 to -0.6	-1.6 to -2.0	low	2 (1)
<i>Short-term potential (Average 2020–2060)</i>						
Total potential	low	low	+1.4 to +5.4	+6.2 to +9.1	low	2 (1)
Effect on the sink in ecosystems (forest)	low	low	+4.7 to +12.0	+8.7 to +12.3	low	2 (1)
Effect on the sink in harvested wood products (HWP)	low	low	-1.9 to -2.8	-1.1 to -1.2	low	2 (1)
Effect on avoided emissions via substitution	low	low	-0.5 to -4.7	-1.4 to -2.0	low	2 (1)

Total potential* and sub-effects	Evidence on biogeophysical and technical feasibility and barriers	Evidence on economic potential, socio-cultural and institutional barriers and enabling conditions	Mitigation potential compared to nowadays (ca. 2020) [MtCO ₂ eq/yr]	Mitigation potential compared to reference scenario** [MtCO ₂ eq/yr]	Confidence	Number of independent studies (independent models) for Austria
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Caveats: The interaction with increased disturbances from climate change is poorly known. Scenarios have 2010 as base year and assume harvest of 20 million m³/yr in the reference scenario and of 15 million m³/yr on average between 2020 and 2150, excluding logging residues and natural losses ('Erntefestmeter'). Converted to 'Vorratsfestmeter' (i.e., including logging residues and natural losses), these volumes correspond to 30 million m³/yr in the reference scenario and 25 million m³ in the scenario with reduced harvest ('Vorratsaufbau'). Note that for 2020 the harvest volume assumed in the Care4Paris study (BFW, 2020) for the 'Vorratsaufbau' is close to the harvest level in 2016–2021 reported in the latest Austrian Forest Inventory (25 million m³ 'Vorratsfestmeter'). The comparison to 2020 (column 4) shows the difference between the sinks/avoided emissions between the scenario with reduced harvest, in a long-term average, and the value for 2020 in the reference scenario from the respective study (Braun et al., 2016; BFW, 2020). The increased emissions of the long-term average compared to 2020 are due to the decreasing trend in C sinks and avoided emissions, independently of the taken measures. The reduction in harvest strongly compensates for this overall trend (column 5). The potentials outlined here refer mostly to technical potentials from a current perspective. Time periods differ by studies.

Increase cascading uses of wood: Prioritizing long-life harvested wood products over energy – See Section 2.3.2

Total effect	Low	low		+0.1 to +0.5	low	2
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Caveats: The comparability of the two studies is low. One study compares a scenario where policies either favor material uses or energy. The other study shows two case studies, in which chips are used for boards and lignocellulosic ethanol for ethylene instead of energy.

Table 2.3 provides an overview of the mitigation potentials described in the scientific literature specifically applicable to Austria. The direct comparability of the studies is limited and any interpretation of the figures shown needs to consider the respective boundary conditions, baselines, methodological assumptions and resulting limitations, especially when attempting to provide information about combined potentials. It is strongly recommended to refer to the individual studies (listed in 2.A.16) and to examine their individual limitations, potential methodological differences, and research gaps more generally:

Limitations of individual approaches concern the quality including temporal, spatial, and categorical levels of aggregation and uncertainty ranges of the input data used. The boundary conditions and scope of the respective studies may differ from the purpose of describing mitigation potentials in this table, and therefore the adequacy may be limited. Potentials may differ whether measured against current conditions or future situations, in the latter case also strongly depending on projections and scenario assumptions. Some figures are based on rough, back-of-the-envelope calculations, which carry the risk of oversimplification. Moreover, much of the outlined potentials are theoretical, based on biogeophysical feasibility alone, without factoring in technical, socio-cultural, or political constraints that will affect real-world implementation, although some of the outlined strategies do take these aspects into account. In terms of economic feasibility, additional uncertainties arise from the use of price valuations in studies from different years. All studies assume the greenhouse gas characterization metric

GWP100, which is also the metric adopted in the UNFCCC. Choosing a different metric such as GWP20 or GWP* would affect the results (see 2.A.10).

Methodological differences may also be the result of different original objectives of the studies used. This may lead to differences in the underlying assumptions (e.g., different market prices of end products, energy prices, political willingness for implementation) and to discrepancies between the baseline parameters against which mitigation potentials may be measured. Mitigation potentials derived from different studies may be mutually exclusive and thus not additive, adding complexity to the combination of individual mitigation potentials. Especially for measures requiring land area, careful consideration of land use priorities and constraints in terms of availability and additionality is needed. Sub-measures are often aggregated into larger measures, and sometimes grouped into bundles, but this is often done without a consistent or systematic approach. Furthermore, interaction effects between mitigation measures can result in unwanted impacts on other economic sectors. Some of the emissions reduction strategies might be effective immediately, while others have a delayed effect. The most prominent example is carbon sinks, which can play a crucial role in both short and long-term mitigation, but are effective over decades (e.g., 30–150 years) and have considerable uncertainties in their magnitude and stability. Such factors are treated inconsistently in different studies. Carbon stocks are reversible and depend on future activities. As carbon sinks can be affected not only by human intervention but also by natural biophysical processes, the impacts of climate change

itself need to be considered, again leaving margins for different and contradicting approaches.

Research gaps exist in our understanding of the processes leading to the emission and sequestration of GHGs on land. Obviously, the table above only accounts for mitigation potentials that are known and have been addressed in research studies. Due to the complexity of biological processes and the small flux densities over large areas, many factors determining these fluxes remain poorly quantified and may not have been adequately studied. This is even more the case for factors that modify the fluxes (mitigation measures). Known examples are the emission behavior of organic soils or the feedback of climate change on many of the processes. Other research gaps relate to the synergies and trade-offs of mitigation measures with other sustainability objectives or their effectiveness under climate change.

2.3.1. 'Improve' measures

Adaptive forest management – 'Improved' forest management to mitigate and adapt to climate change

Austrian forests, which had been carbon sinks varying around $-15 \text{ MtCO}_2/\text{yr}$ for several decades, lately have been turning into a carbon source ($+5.4 \text{ MtCO}_2/\text{yr}$ for 2023, which meant a source also on a five-year average: $+0.2 \text{ MtCO}_2/\text{yr}$, see Figure 2.2 and Table 2.A.2). This is the result of the net effects of removals of atmospheric CO_2 through biomass increment and carbon losses caused by natural disturbances, forest management (timber harvest, thinning) and changes in carbon stocks in soils, influenced by inflows and decomposition of organic matter. To maintain or enhance this sink, particularly in the light of expected future climate impacts, adaptive forest management (AFM) approaches to climate change propose three main principles (Bolte et al., 2009; Brang et al., 2014; Spathelf et al., 2018): (i) Increasing resistance to disturbances by improving the stability of forest stands, (ii) promoting resilience of forests for a rapid restoration of forest functions to desired conditions after disturbances, and (iii) promoting the adaptability of forest stands by selecting appropriate species during regeneration, changing species shares during mixture regulation, increasing the diversity and diversification of forests to facilitate the transition to new forest states (Spathelf et al., 2018). Optimizing the rotation length is also discussed for AFM, depending on site characteristics and market demands, to reduce the windthrow risk due to a limitation of the top height reached

(Schelhaas et al., 2015) or reduce the risk of a higher mortality of not adapted tree species and to keep the increment rate on a high level (adaptation and focus on substitution). However, on average between 2020 and 2150, shortening rotation cycles would decrease the carbon sink in forests by 2.4 to $3.2 \text{ MtCO}_2/\text{yr}$ compared to a reference scenario. In addition the sink in harvested wood products will be decreased by $0.4 \text{ MtCO}_2/\text{yr}$ and the avoided emissions from substituting fossil fuels and abiotic materials will increase by $0.2 \text{ MtCO}_2/\text{yr}$ (see Table 2.3 and 2.A.16 for individual studies) (BFW, 2020; Ledermann et al., 2022). Changing tree species composition to species that are expected to perform better under a changed climate (Schelhaas et al., 2015) can avoid risks associated with specific pests, diseases or disturbances (Seidl et al., 2009) or drought-intolerant species at the stand or landscape level. According to the results of the Care4Paris project, changing the composition of species to native non-coniferous species would increase the carbon sink in forests by 4.1 to $4.9 \text{ MtCO}_2/\text{yr}$ on average between 2020 and 2150 compared to a reference scenario. On the other hand, the sink in harvested wood products would be reduced by $1.3 \text{ MtCO}_2/\text{yr}$ and the avoided emissions from the substitution of fossil fuels and abiotic materials by $1.7 \text{ MtCO}_2/\text{yr}$ (see Table 2.3 and 2.A.16 for individual studies) (BFW, 2020; Ledermann et al., 2022). Advanced planting with shade-tolerant tree species in mature stands can support tree species change, as harvesting mature stands and regeneration them with new species might result in lower forest carbon stocks in the short term (Kindermann, 2021). In this context, assisted migration strategies transfer more adapted or adaptive tree species (including non-natives) to regions outside their current natural range that are characterized by a suitable climate, thus artificially extending the range distribution of more resilient tree species (Gömöry et al., 2020; Mauri et al., 2023). Assisted migration of tree species has the potential to increase carbon sinks and might allow larger harvest volumes that remain below increment, but uncertainties are large and risks are manifold (Pötzelsberger et al., 2020; Chakraborty et al., 2024). Fuel management strategies like selective thinning, prescribed burning (along railroad embankments, on grasslands or meadows), mechanical clearing or grazing with goat, sheep, or donkey can reduce the fuel loads and thus the probability of large and stand-replacing forest fires (Ascoli et al., 2023; Müller et al., 2020).

There is strong evidence that tree species richness and high genetic diversity positively influence the adaptive capacity of forests to climate change (Brang et al., 2014;

Spathelf et al., 2018). Increasing the structural diversity of stands by retaining ecosystem legacies (e.g., seed trees, deadwood, stand remnants) after disturbances will enhance the restoration capacity (Spathelf et al., 2018). In addition, the heterogeneous ownership structure and different management strategies help to promote diversely structured forest ecosystems in Austria. There is *high confidence* that management for continuous forest cover can help maintain a favorable microclimate in forest stands and provide continuous natural regeneration (Spathelf et al., 2015; Vacek et al., 2019; Zellweger et al., 2020). However, the density and distribution of game populations is a key factor that in many cases jeopardizes a successful natural regeneration without protective measures (Schodterer, 2022). Moderate reductions in stand density have been shown to effectively mitigate drought stress (Elkin et al., 2015), but the effects vary across forest sites, species, and context (Castagneri et al., 2022). As forest management adjusts the tree species composition to increase the resistance and resilience of ecosystems while maintaining high levels of productivity, the supply to the timber, pulp and paper market will change in the long run (increasing the share of deciduous tree species). This development will entail transformation of the timber industry (Klein et al., 2016; Lantz et al., 2022). For more details about climate change adaptation, see Chapters 4 and 5 in the APCC Special Report on land use and climate change (Baumgarten et al., 2024; Kraxner et al., 2024).

Emissions linked to energy use along the supply chain of wood (see Section 2.1.1) are mostly influenced by road maintenance, biomass harvesting techniques, forwarding and biomass transport and depend on the considered tree species, age classes, rotation length, wood assortments, and site quality parameters (Klein et al., 2016). Mitigation measures that focus on these parameters are: Efficient transport, reduced fuel consumption or shifting to alternative energy sources, improved road and skidding line network.

Agricultural management to mitigate and adapt to climate change

Emission reductions are linked to the activities responsible for the relevant emissions (see Section 2.1.1). In agriculture, an important mitigation option is to increase SOC (Table 2.1). The literature, as summarized by Kraxner et al. (2024), shows a wide range of measures, such as non-inversion tillage on arable land, changes in crop rotations including increased biomass supply from forage grasses and legumes, the integration of catch/cover crops and intercropping and

greenings, the use of manure instead of mineral nitrogen fertilizers, or the addition of organic substances such as biochar. Systemic crop management approaches have been suggested to combine benefits of individual measures (Kraxner et al., 2024).

Adding N fertilizer to soils drives N₂O emissions from soils, so reducing fertilizer application also reduces emissions. Minimizing N inputs may take advantage of more efficient fertilizers such as nitrification inhibitors or precision agriculture to reduce N₂O emissions by up to 38 % (Winiwarter et al., 2018), possibly with minor yield losses (Foldal et al., 2024). The application of biochar has also been described to efficiently reduce N₂O emissions (Liu et al., 2018; Borchard et al., 2019). The potential mitigation effects of systemically applied precision agriculture techniques (PAT) have a wide range (*limited evidence, medium agreement*). High investment costs, high demand for expertise, and a lack of training materials are barriers to the use of PAT (Kraxner et al., 2024).

The whole production chain is also relevant (Osterburg et al., 2013; Grassauer et al., 2021). For Germany, there are reports on the trickle-down effects of reducing N inputs from mineral fertilizer, e.g., through taxation (Isermeyer et al., 2021). Optimizing feed rations and livestock protein intake can reduce emissions associated with feed production and N fertilization (Pierer et al., 2016). A mitigation potential of >30,000 tCO₂eq/yr is estimated at costs below EUR 100/t for pig farming and between EUR 100–200/t for ruminant farming (Fritz et al., 2022; Sinabell et al., 2023) (*medium confidence*). Increasing legume forage reduces the need for protein feed imports and synthetic fertilizers (Stagnari et al., 2017), potentially abating emissions by >15,000 tCO₂eq/yr at costs between EUR 100–200/t (Fritz et al., 2022; Sinabell et al., 2023). Also, managing grasslands at medium intensity and increasing pasture feed intake can be cost-effective options, mitigating >45,000 tCO₂eq/yr at costs below EUR 100/t (Lorenz et al., 2019a; Fritz et al., 2022) (*medium confidence*). In addition, more efficient use of machinery offers an economically viable potential of mitigating >7,500 tCO₂eq/yr at costs below EUR 100/t (Fritz et al., 2022; Sinabell et al., 2023). For fossil fuel use, efficiency improvements and biofuels or electrified machinery can play a minor role, but no technique is available for substantial mitigation.

There are several mitigation options to tackle emissions from livestock farming (see also compilation by Kraxner et al., 2024). Feed additives can reduce enteric CH₄ formation in cattle by up to 30 % (no cost assessment available) (Lewis

et al., 2013; Abecia et al., 2018; Van Wesemael et al., 2019). Indirect mitigation measures, such as refining herd management and feeding protocols, improving livestock management practices and animal health exhibit a mitigation potential of >20,000 tCO₂eq/yr and costs below EUR 100/t. Extending the productive life of cows may further mitigate >20,000 tCO₂eq/yr at costs below EUR 100/t (Dallago et al., 2021; Fritz et al., 2022; Sinabell et al., 2023). An option with high mitigation potential, but far-reaching socio-economic consequences for livestock producers and the entire value chain, is the (further) reduction of livestock numbers based on assumptions of reduced food losses, reduced protein intake or a shift towards plant-based diets and agriculture (see Section 2.3.2). Nevertheless, Austrian livestock production systems appear rather efficient in terms of GHG emissions in the international context due to higher N efficiency and lower N₂O emissions, the dominance of dual-purpose breeds in cattle production and hence the allocation of GHGs to milk and beef, lower use of imported feedstuffs which are loaded with large amounts of GHGs from land use change. Weiss and Leip (2012) calculate average Austrian GHG emissions from meat and dairy production per unit of output to be among the lowest in the European Union. For example, average emissions are about 1 kgCO₂eq/kg for Austrian cows' milk compared to an EU average of about 1.3–1.7 kgCO₂eq/kg cows' milk and more than 2.5 kgCO₂eq/kg for cows' milk from Cyprus. Mitigation measures applicable to all livestock species are the optimization of housing and farm manure systems (e.g., Hörtenhuber et al., 2010; Sajeev et al., 2018).

Austria is still a long way from the number of animals per farm or per area found in other industrialized countries. However, even in Austria, there is a trend towards concentration and intensification with increasing problems of odor nuisance (Weitensfelder et al., 2019; Oetl et al., 2022) and bio-aerosols, while ammonia is also a precursor of fine particulate matter in the atmosphere (Liu et al., 2023).

The adaptation of agriculture to climate change requires first and foremost adapting current land use. For arable land, important adaptation measures are, similar to mitigation measures, the broadening of crop rotations, the diversification of crops and the integration of catch crops (protecting soils from drying out) and undersowings, which contribute to humus build-up (measures are described in Jandl et al., 2024c). Quddoos et al. (2023) show that adaptation options help to considerably reduce the adverse effects of climate change for Austrian farms. Similar to cropland, grassland productivity might also profit from moderately warmer temperatures as long as sufficient water is available

(Haslmayr et al., 2018; Schaumberger et al., 2019; Volk et al., 2021). However, this requires the adaptation of cutting frequencies and fertilization to changing climatic conditions. Changing climatic conditions might allow an increased use of alpine pastures, but negative effects on biodiversity must be considered.

Climate change may affect the spread of harmful organisms. Universal predictions of pest and disease dynamics and universal control strategies are not possible, but have to be developed specifically. One basic option is to diversify crop rotations (which, e.g., can stop the spread of the maize rootworm: Feusthuber et al., 2017; Falkner et al., 2019). Adequate crop rotation with early, effective weed control and a monitoring system throughout the growing season can prevent the establishment and spread of invasive plants (AGES, 2023b, 2023a). New technologies, such as drone technology, are being used to control *Datura spec.* in crops (Riegler-Nurscher et al., 2023). Useful organisms such as pollinators may be lost, but improved agricultural management, such as near-natural elements or habitats with appropriate forage plants in agricultural landscapes, can counteract such losses (Roberts et al., 2011; Zulka and Götzl, 2015).

To adapt to climate change-induced water shortage, numerous adaptation measures are discussed (Jandl et al., 2024c): Active and efficient irrigation (where water sources are available), soil-related measures such as reduced tillage, permanent ground cover, and windbreaks are well-established means. Furthermore, fertilization should be adapted to changing nutrient dynamics, water balance and seasonal fertilization requirements. In practice, barriers to widespread implementation lie in farmers' risk attitudes and management practices, market mechanisms and institutional design (Mitter et al., 2019; Hanger-Kopp and Palka, 2022).

Climate change-induced summer heat waves and droughts affect growing conditions for crops. This requires the breeding and establishment of new crop species or varieties. In particular, plant breeding research particularly has to focus on heat and cold tolerance, efficient use of nutrients and water, and resistance to pests (VLK, 2019). In grasslands, the use of drought-resistant varieties is becoming increasingly important, which will also be reflected in breeding programs (Krautzer and Graiss, 2015). New crop species like chickpea (Neugschwandtner et al., 2013) or amaranth (Gimplinger et al., 2007) may become competitive. Rising temperatures, including milder winter conditions, allow the planting of winter forms of traditionally spring-sown crops like pea (Neugschwandtner et al., 2020), faba bean (Neugschwandtner et al., 2015, 2023a), and poppy (Neugschwandtner et al.,

2023b). For winter wheat, facultative cultivars are a promising solution to avoid insufficient vernalization during very mild winter seasons (Koppensteiner et al., 2022).

Heat stress also poses a significant threat to livestock in terms of health, animal performance (e.g., feed conversion, daily weight gain, and milk production), well-being, and economic implications for farmers (Hörtenhuber et al., 2020; Herzog et al., 2021; Schauburger et al., 2021). The implementation of adaptation measures is crucial to reduce the adverse effects of heat stress in confined livestock facilities. Such techniques include cooling the inlet air, refining management protocols, and optimizing feeding strategies (Vitt et al., 2017; Mikovits et al., 2019; Schauburger et al., 2020; Herzog et al., 2021). For more details on climate change adaptation, see Chapter 4 of the APCC Special Report on land use and climate change (Baumgarten et al., 2024) and Smit and Wandel, 2006).

The implementation of mitigation and adaptation measures at the local (farm) level requires adequate financial and technological resources, as well as the information and organization skills to manage these resources accordingly (Smit and Wandel, 2006); without these, adaptation success may be limited. Zeilinger et al. (2023) confirm such under-adaptation to climate change for Austrian farms in arable regions. Recent literature suggests that developing the adaptive capacity of farms is a promising policy tool to enhance adaptation (Vanschoenwinkel et al., 2020). Mitter et al. (2019) identify prerequisites for adaptation intentions of Austrian farmers, including awareness of effective adaptation measures, acceptance of personal responsibility for their farms, and positive adaptation costs.

2.3.2. 'Shift and avoid' measures

Protein transition – shift towards healthy, plant-based diets

There is *high confidence* that the composition of food produced and consumed has a highly significant impact on per capita carbon emissions, driven in particular by the number of farmed livestock and the amount of related products (Jandl et al., 2024c). Past and recent trends in diets in Austria are presented in 2.A.8. Dietary choices impact decisions on agricultural land use, livestock management, processing, transport, and ultimately disposal, and are therefore important for climate protection. Consequently, major potentials from a transformation of diets result from reducing the total amount of products produced and consumed (including to-

tal food intake and food waste), as well as shifting the type of products (degree of processing, transport requirements, seasonality) and the kind of products consumed (i.e., dietary choices such as vegan vs. livestock-based products).

This section tackles the role of choices in agricultural food products (protein transition, i.e., a shift to diets with decreased shares of animal products), with other options being discussed in Section 2.3.2. There is *high confidence* that dietary change cannot be understood as the sole responsibility of end consumers, and that achieving dietary change through a bundle of measures involving all actors across the food system could facilitate an effective and just protein transition (Harwatt, 2019; Willett et al., 2019; Vermeulen et al., 2020; Roux et al., 2022; Mempel et al., 2023; Penker et al., 2023; Voigt et al., 2024) (see 2.A.9 and Table 6.1 for policy instruments related to diets across the food system). Life cycle assessments typically show large differences in the GHG emissions of agricultural products, with livestock-based products having substantially higher emissions than plant-based products when related to the energy or protein content of the food as a functional unit (Table 2.4). This is true for both estimates per unit of kcal and per unit of protein (Tilman and Clark, 2014). The main reasons include the low feed-to-product conversion rates with correspondingly large land requirements and, especially in the case of ruminant livestock, CH₄ emissions from enteric fermentation. Consequently, ruminant products typically embed the most emissions among all animal products for typical GWP100 estimates. A discussion about GWP100 vs. GWP* can be found in 2.A.10.

Austria is among the world leaders in per capita meat consumption (including bones, tendons parts, and trim fat), with an annual per capita intake of 34.2 kg of pork, 12.8 kg of poultry, and 10.4 kg of beef in 2021 (Statistik Austria, 2022e). The study by Frey and Bruckner (2021) highlights that beef consumption accounts for 38 % of the greenhouse gas emissions from Austria's agricultural product consumption. These data, combined with the high emissions per unit of livestock products, indicate significant per-capita greenhouse gas emissions from the typical Austrian diet (*high confidence*).

Shifting towards the so-called Planetary Health Diet developed by the EAT-Lancet Commission (Willett et al., 2019), i.e., a dietary standard with high shares of vegetarian food that takes into account planetary boundaries and human health, would reduce the demand for animal products and correspondingly restructure agricultural production. It would yield a mitigation potential of 5.0 to

15.4 MtCO₂eq/yr (compared to individual reference scenarios), including reduced agricultural emissions and enabled afforestation (Schlatzer and Lindenthal, 2020; Lauk et al., 2022; Sun et al., 2022; Le Noë et al., 2023a; Preinfalk et al., 2024) (see Table 2.3 and 2.A.16 for the individual studies). From a consumption-based perspective, shifting to the Planetary Health Diet (EAT-Lancet) would reduce GHG emissions embodied in Austria's consumption of food by ca. 9.3 MtCO₂eq/yr, or 1.02 tCO₂eq/cap/yr (Semba et al., 2020). A shift to vegan diets increases the mitigation potential by ca. 2 MtCO₂eq/yr compared to a planetary health diet (Le Noë et al., 2023a). At the European level, Westhoek et al. (2014) estimate that a 50 % reduction in meat, dairy and eggs from a 2004 reference diet would reduce GHG emissions by 25–40 %.

Note that the diet proposed by the EAT-Lancet Commission (Willett et al., 2019) is beneficial in terms of a reduced carbon footprint and for the health of consumers (Ekmekcioglu et al., 2018). There is *high confidence* that shifting towards plant-based diets, especially reducing red and processed meat, reduces the risk of various diseases such as colorectal cancer and cardiovascular diseases (Chan et al., 2011; Yip et al., 2013; Bouvard et al., 2015; WHO, 2015; Farachi et al., 2017). The risk of colorectal cancer increases by 17 % for every 100 g of red meat consumed per day and by 18 % for every 50 g of processed meat consumed per day (Bouvard et al., 2015).

Furthermore, the production and consumption of agricultural commodities, such as livestock products, feed, or oil crops for food and bioenergy, is the world's leading driver of deforestation, prompting both climate change and the transmission of zoonotic diseases from wildlife to humans (Faust et al., 2018; Pendrill et al., 2022). Averting epidemics of wildlife-borne infectious diseases requires a socio-ecological transformation, a redesign of the global food system and a transition to diets that are plant-based or low in animal products (Wegner et al., 2022).

Meat substitutes. Livestock-based meat as protein source can be replaced by several substitutes, such as legumes and processed plant-based meat (PBM) (He et al., 2020), insect-based meat (IBM), and (in vitro) cultivated meat (CM) (Sinke et al., 2023). These innovations are poised to capture a significant share of the global meat market, estimated at 60 % by 2040 (Gerhard et al., 2019; He et al., 2020). Despite optimistic market and investment scenarios, regulatory, social, economic, ecological, and agronomic challenges (e.g., Codex Alimentarius Austriacus) have to be solved for these products (Eker et al., 2019; Kim et al., 2020; Moran and Blair,

2021; Noguerol et al., 2021; Siddiqui et al., 2022). Table 2.4 compares the environmental impacts of conventional meat (beef, pork, and chicken) and various meat substitutes, based on Life Cycle Assessments. Note that these assessments are based on current data and refer to relatively new processes, so there are large uncertainties and significant room for improvement. Meat substitutes exhibit notable ecological advantages, offering a viable strategy for transitioning away from high-impact beef production towards more environmentally sustainable meat options. Notably, the elevated energy requirements associated with CM and PBM production underscore the imperative for utilizing green energy sources to mitigate CO₂ emissions (Sinke et al., 2023).

Table 2.4 Comparison of the environmental impact of conventional meat (beef, pork, and chicken) (Nijdam et al., 2012; Willett et al., 2019; Sinke et al., 2023), cultured meat (Sinke et al., 2023) plant-based meat (Nijdam et al., 2012; Saget et al., 2021), and insect-based meat (Smetana et al., 2016), related to 1 kg meat. The protein content of meat was assumed at 22 %. Values for plant proteins are adapted from Poore and Nemecek (2018). Negative values show a carbon sink.

Specific environmental impact related to meat production	Energy [MJ/kg]	GHG Emissions [kgCO ₂ eq/kg]	Land use [m ² /kg]
<i>Animal meat</i>			
Beef	60–105	9.9–141	7–462
Pork	28–40	4.4–12.3	8.8–16.5
Chicken	24–26	2.2–9.9	5.1–8.8
<i>Processed meat alternatives</i>			
Cultured Meat	25–481	1.9–24.8	0.19–6.9
Plant-based meat	143	1.0–12.3	2–3
Insect-based meat	2–64	0.17–3.2	0.07–1.03
<i>Plant proteins</i>			
Tofu		1.6–5.6	1.8–4.9
Peas		0.6–1.7	2.8–14.2
Other pulses		1.0–3.8	9.9–41.3
Nuts		-3.7–3.8	4.5–26.6

There are a number of trade-offs that need to be considered to enable a just transition to fewer livestock and animal products. While there are multiple alternative uses for arable land used for feed (e.g., food, fuel or fiber production), there are fewer alternative uses of permanent grasslands. Options include feedstock used in biogas plants or green biorefineries (Höltinger et al., 2014). A plausible option for marginal permanent grasslands is reforestation. Reforestation of grasslands is likely to increase total carbon sequestration in soils and biomass (Schirpke et al., 2017) but can create pressures on landscape quality or biodiversity, especially for extensive-

ly managed grasslands such as alpine meadows (Hussain et al., 2019). Dietary changes are also likely to have substantial impacts on farm incomes. Introducing the EAT-Lancet diet in the EU-27 has been estimated to increase agricultural income by 71 % in the long run (2050) due to shifts to high value-added crops such as fruits, vegetables and nuts (Rieger et al., 2023). In the short-run, however, there may be income losses (-12 % in Germany for partial EAT-Lancet implementations due to its specialization on livestock production) (Rieger et al., 2023). Similar impacts can be expected for Austria, although for permanent grassland regions, the shift to vegetables and fruits production is more costly and the income losses may be more pronounced. For further discussion on co-benefits and trade-offs related to dietary change and livestock reductions, see 2.A.10.

Pets. In Austria, there are approximately 2 million domestic cats and 766,000 dogs (FEDIAF EuropeanPetFood, 2023). These pets primarily subsist on meat-based diets (Swanson et al., 2013; Okin, 2017; Martens et al., 2019; Pedrinelli et al., 2022; Scherer et al., 2022). The IPCC report recognizes carnivorous pets as a significant factor in potential GHG mitigation, estimating their contribution at approximately 0.8 MgCO₂eq/cap (Creutzig et al., 2022b). It is important to acknowledge that a substantial portion of pet food in the industrial sector is derived from animal by-products, which are inedible residuals obtained through animal rendering processes (Alexander et al., 2020; Acuff et al., 2021; Pedrinelli et al., 2022). Nevertheless, it should be

noted that not all pet foods exclusively rely on by-products, and that some of them may contribute to GHG emissions (*robust evidence, low agreement*).

Non-protein related food measures – ‘avoid’ measures

Non-protein-related food measures refer to all changes beyond changing protein sources in human diets (see above) and switching to products produced under climate-friendly management and technologies (see above). These measures include reducing the total amount of products consumed, i.e., avoiding excess calorie consumption, reducing food losses, and changing the origin and processing degrees of food products. Figure 2.7 shows the food system emissions from the two groups, pre- and post-agricultural production and agricultural sector emissions, according to the national GHG inventory for the years 1990 and 2020 (Umweltbundesamt, 2022). Both groups of emission sources are in the same order of magnitude with diverging development patterns.

In 2019, 34.5 % of adults in Austria were overweight and 16.5 % were obese. The number of obese people has increased since 2006 (Statistik Austria, 2022c). Reducing overall food intake, especially the production and consumption of high-calorie products, would hence not only spare agricultural land and GHG emissions, but also help to reduce obesity and its associated diseases, such as ischemic heart disease, stroke, hypertension, type 2 diabetes

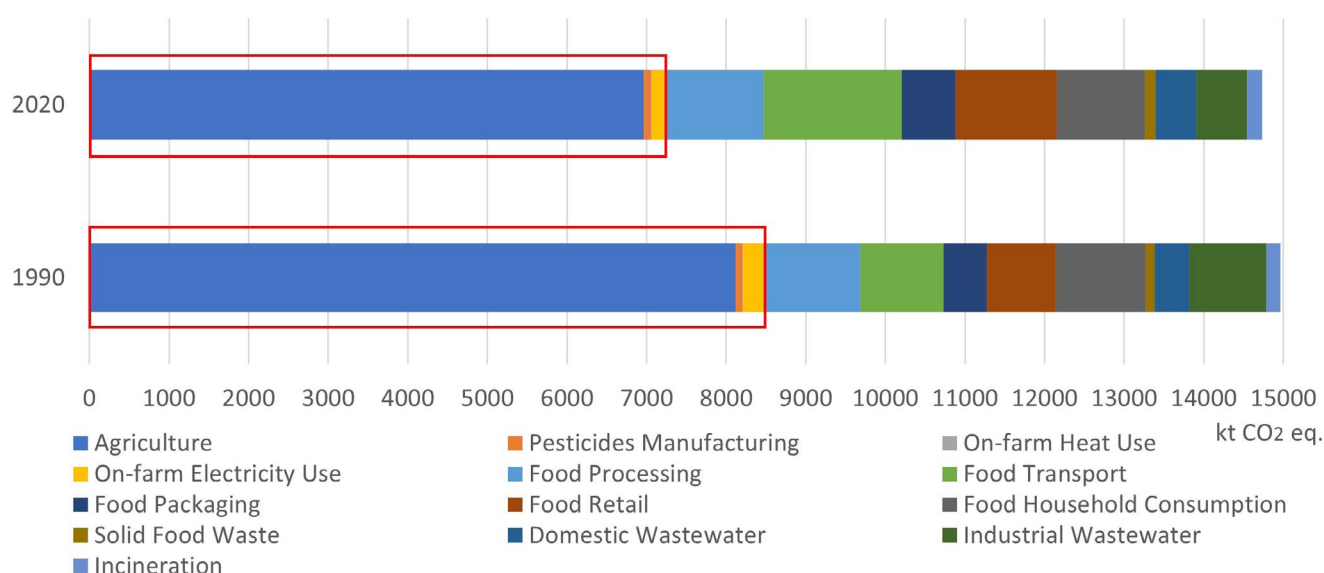


Figure 2.7 Agricultural, pre-production (red box) and post-production emissions (ktCO₂eq) of the Austrian food system by component in 1990 and 2020 (data: [fao.org/faostat/en/#data/GPP](https://faostat.fao.org/en/#data/GPP); and Umweltbundesamt (2022)). A monochromatic version of the figure can be found in 2.A.11.

mellitus, colorectal cancer, postmenopausal breast cancer, endometrial cancer, kidney cancer and osteoarthritis (Lette et al., 2016). Estimates of the calorie intake in Austria range from 2,673 kcal/cap/day (3,100 kcal/cap/day including food waste) for the year 2022 (Pecher et al., 2024), to 3,117 kcal/cap/day (3,610 kcal/cap/day including food waste) for the year 2015 (Lauk et al., 2022), and 3,429 kcal/cap/day (excluding food losses) for the year 2010 (Sun et al., 2022). A large-scale survey of Austrians in the year 2014–2016 estimated the total calorie intake at 1,815 kcal/cap/day (women) and 2,453 kcal/cap/day (men; both excluding food waste), which is lower than other estimates but still above dietary recommendations for about 50 % of the Austrian population (Rust et al., 2017). Most estimates are substantially above FAO recommendations for a balanced average Austrian diet of 2,533 kcal for the year 2020 (FAOSTAT, 2023).

Thus, **adapting current diets** has a strong mitigation potential (*robust evidence, medium agreement*) and leads to synergies with human health. However, it is not straightforward to disentangle reductions in calorie uptake ('avoid') from changes in diet composition ('shift', see [above](#)), because even calorie reduction scenarios require assumptions on individual diet components, i.e., whether they reduce diet components proportionally or disproportionately (e.g., stronger reductions of products with large GHG emissions).

Linearly translating the current to the recommended levels (i.e., -25 % in calories uptake) according to FAO for Austria would reduce agricultural emissions by ca. 2 MtCO₂eq/yr, or ca 0.2 tCO₂eq/cap/yr. Hiç et al. (2016) estimate the average emissions related to food surplus are at 0.12 tCO₂eq/cap/yr. Kim et al. (2020) estimate country-level GHG emissions for different diets and show ranges for Germany from <0.5 to >1.5 tCO₂eq/cap/yr. These ranges are comparable to the mitigation potentials estimated for the Planetary Health Diet suggested by the EAT-Lancet commission (see [above](#) and [Table 2.3](#)), which also includes a calorie reduction, e.g., to a maximum of about 2,600 kcal/cap/day in Semba et al. (2020). Other authors concur with these estimates, reporting substantial sustainability impacts from over-consumption similar to consumers' food waste (Alexander et al., 2017). Creutzig et al. (2022a), however, assume small mitigation effects from calorie reductions due low GHG emissions from high-calorie products such as sugar.

The potential for carbon sequestration on land no longer needed for agricultural production – or needed for nourishment of a growing future world population to prevent forest loss and other land use changes – need to be added to these emission savings and are shown in [Table 2.3](#).

Food losses occur throughout the value chain, while food waste refers to the consumption stage (Parfitt et al., 2010). Neither can be fully avoided, but substantially reduced. Estimates of mitigation potentials are smaller than for changes in overall diets (*robust evidence, medium agreement*), but reducing food losses and waste is considered an important and 'no-regret' climate mitigation measure (Springmann et al., 2018). Halving food losses in Austria would result in a mitigation potential of 2.1 to 4.7 MtCO₂eq/yr (compared to a reference scenario), including reduced agricultural emissions as well as a carbon sink due to enabled afforestation, assuming that these products would not have been produced (see [Table 2.3](#) and [2.A.16](#) for the individual studies) (Le Noë et al., 2023a; Preinfalk et al., 2024). For comparison, Parfitt et al. (2010) estimate unavoidable household food waste in the UK to be around 20 %. Therefore, if similar reductions were to be applied to Austria, the mitigation potential would be 0.14 tCO₂eq/cap/yr. In Austria food waste amounts to 1.1 Mt/yr, of which 49 % comes from private households, 16 % from farms, 11 % from food production, 16 % from gastronomy and 8 % from trade (Luck and Obersteiner, 2021). Springmann et al. (2018) estimate the effect of waste and loss reduction on emissions to be about one-fifth that of dietary changes (the latter including a change in diet mix). Similar results are reported by global food system studies for Europe (Kalt, 2015; Mayer et al., 2022; Rööß et al., 2022). However, specific data on food losses and food waste in Austria are scattered. Scherhaufer et al. (2016) summarize studies showing total losses of about 1.1 million tons of biomass per year, which would be about 0.12 t/cap/yr, with about half of the losses occurring in households, and the rest distributed among agricultural production, processing and retail, and outside-home catering. Crippa et al. (2021) estimate end-of-life emissions in the food system to be about 1.39 MtCO₂eq/yr, or about 6 % of Austrian food system emissions in 2015.

Transport between different locations of production, processing, consumption, and disposal along the food value chain offers further mitigation potentials. Crippa et al. (2021) estimate transport emissions in the Austrian food system at about 2.49 MtCO₂eq/yr, or 12 % of total food system emissions. Only part of these emissions are avoidable, with typical examples of high GHG emissions and thus mitigation potentials for air-transport of fresh products. Local food systems are defined by small geographical distances between the steps of the food value chain. Despite potential emission savings from transport, they can cause additional emissions at other stages along the value chain (Schönhart et

al., 2009). Therefore, their overall potential must be regarded as being small (*high confidence*).

A sufficiency-oriented bioeconomy – ‘shift and avoid’

Like bioeconomy strategies in general, the Austrian Bioeconomy Strategy implemented in 2019 aims to reduce climate impacts by shifting resource use away from abiotic (especially fossil fuel-based) towards a higher share of biomass use. In Austria, biomass currently accounts for only 23 % of direct material consumption (38 Mt/yr), the rest being mineral, fossil and metallic resources (BMK, 2020). There is *high confidence* that a shift towards a bioeconomy needs to be complemented by additional measures to avoid the degradation of domestic and international resources and ecosystems. A key reason is that Austria, typical of European countries, already appropriates a high fraction (56 %) of its domestic potential net primary productivity through biomass use and land conversion (Gingrich et al., 2015), and net imports of agricultural products contribute to additional pressures on ecosystems abroad (Haberl et al., 2012). Such additional measures need to ensure (a) sustainable production processes, (b) efficiency improvements in the provision of energy and material services and well-being, and (c) reductions in production and consumption of material and energy sources, i.e., sufficiency (Rockström et al., 2021; Creutzig et al., 2022a). The prioritization of individual elements in bioeconomy strategies varies across stakeholders (Hausknost et al., 2017; Stern et al., 2018). Scientific debates have focused on substitution and efficiency gains, while sufficiency options in a bioeconomy have received much less attention, especially with regard to their social feasibility (Schipfer et al., 2024).

Many factors influence the climate impacts and sustainability of wood harvest and use, illustrated by red triangles in Figure 2.8. The mitigation effect of wood use ultimately results from the interplay of three major elements: (i) Changes in C-stocks in forests due to wood harvest, (ii) changes in socioeconomic wood pools (harvested wood products), and (iii) the substitution of emission-intensive products and services with wood products (see also 2.A.13). There is a large body of literature assessing the interplay of these elements (Bhan et al., 2021; Cowie et al., 2021), which in principle suggests two different approaches (see Box 1.1 in Formayer et al., 2024b, for a detailed comparison). One quantifies actual (observed) GHG emissions over time (e.g., the UNFCCC emissions account scheme; see 2.A.5) (Jandl

et al., 2024c), while the other compares different counterfactual scenarios and calculates substitution effects as well as ‘carbon opportunity costs’ (Norton et al., 2019; Erb et al., 2022; Fehrenbach et al., 2022; Soimakallio et al., 2022; Peng et al., 2023).

The climate effect of substitution is particularly complex to assess (Formayer et al., 2024b, Box 1.1). In direct comparisons, the substitution of biomass for fossil fuels appears to be disadvantageous for biomass in terms of emission reduction, due to its high carbon emission factor. The combustion of solid biomass releases about 29.9 tC/TJ of carbon stored in the biomass, compared to 17.2 tC/TJ for natural gas liquids, 20.2 tC/TJ for diesel oil, and 27.6 tC/TJ for lignite. These ‘smoke-stack’ comparisons do not take into account the renewable nature of biomass and therefore provide only partial insights (Cowie et al., 2021). More comprehensive accounts therefore consider all greenhouse gas fluxes in ecosystems and society. The comparative climate impact of biomass use then depends on the actually achieved reduction of the product or process under consideration (substitution), which often is jeopardized by overcompensation and rebound effects (York, 2012; Harmon, 2019; Leturcq, 2020), as well as on the comparative emissions impact of the respective material or energy use. The latter is shaped by both the emissions intensity of the substituted product or process and the emissions impact of additionally harvested biomass, both of which are variable over time (Buschbeck and Pauliuk, 2022). Global results show that in many cases, natural succession of ecosystems has a more beneficial climate impact than growing crops for bioenergy – second-generation bioenergy production compete over natural succession only when the displacement factor is very high, i.e., when very emission-intensive processes are substituted (Kalt et al., 2019). Once wood is harvested, extending the lifetime of wood products (e.g., using wood in buildings rather than burning it as bioenergy) reduces their climate impact, because carbon is stored in socio-economic structures for some time before it is released to the atmosphere (Allianz Nachhaltige Universitäten in Österreich, 2021). However, comparing the relative climate impacts of using versus not using wood is particularly complex, because long-term stock-flow dynamics in both ecosystems and socio-economic structures affect the net emissions impact (Seppälä et al., 2019). Results for Germany point to the high temporal variability of displacement factors for wood use (Buschbeck and Pauliuk, 2022). Thus, the relative performance of different wood use strategies depends on the temporal scope of analysis and planning (*medium evidence, high agreement*).

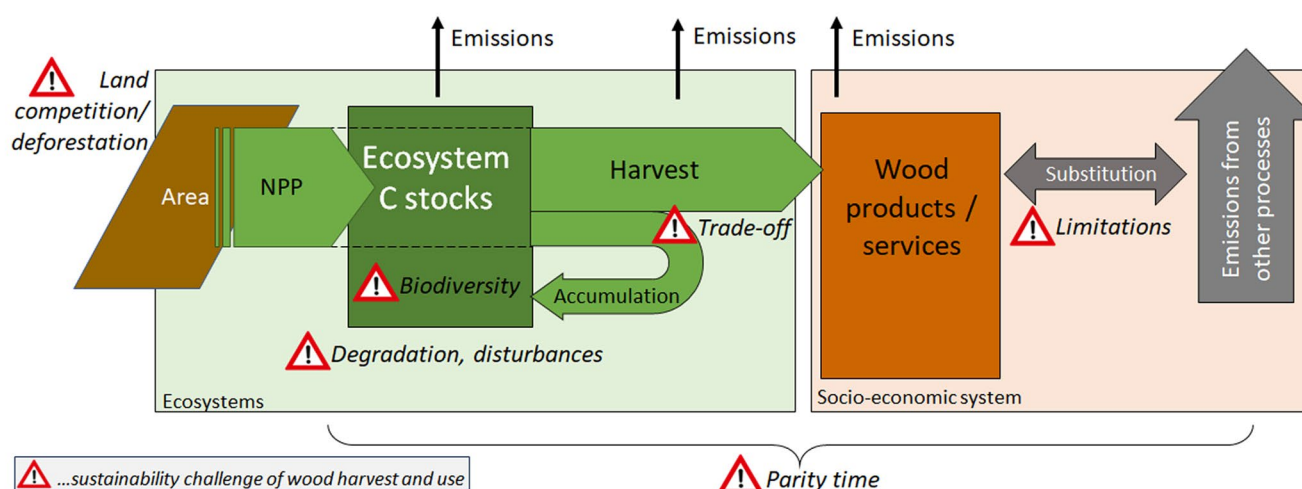


Figure 2.8 Carbon stocks and flows related to wood use and associated sustainability challenges. NPP refers to Net Primary Productivity.

There is no comprehensive assessment of displacement factors for Austria. Some researchers focus on the beneficial potential of providing biomass to substitute fossil fuels and abiotic materials and creating socio-economic carbon pools in harvested wood products (Braun et al., 2016; Jandl et al., 2018), while others argue that, particularly in the short term, wood harvest should be constrained to maintain net forest carbon sequestration due to the lack of readily available alternatives for carbon removal and to enhance biodiversity in forests (Bellassen and Luyssaert, 2014; Searchinger et al., 2018; Luick et al., 2021; Erb et al., 2022; Norton et al., 2022). For a description of contrasting positions and their main arguments, see Box on climate neutrality of wood use in Chapter 1 of the APCC Special Report on land use and climate change (Formayer et al., 2024b).

The overall global climate impact of wood use in construction and buildings is currently debated in the literature, with very optimistic (Mishra et al., 2022) and more cautious estimates coexisting (Johnston and Radeloff, 2019). However, there is consensus that from a climate change mitigation perspective, material uses of wood are favorable over energy uses (up to a factor 2 in a centennial perspective), as this result appears in practically all modeled conditions (Braun et al., 2016; Kalt et al., 2016; Fehrenbach et al., 2022). Furthermore, the ‘cascading’ use of wood is a powerful strategy, emphasizing that wood should first be used for material purposes – ideally over long periods – and only burned or pyrolyzed at the end of the product’s lifecycle (*high confidence*) – although interpretations of what ‘cascading’ means in practice vary across stakeholders (Ludvig et al., 2021). Estimates of the mitigation potential of using wood for materials

rather than energy range from 0.1 to 0.5 MtCO₂eq/yr (Braun et al., 2016; Kalt et al., 2016) (see Table 2.3 and 2.A.16 for individual studies). The lifetime of wood use varies across product categories (Braun et al., 2016), and increasing lifetimes can result in higher wood shares in a given product category, thus leading to C accumulation in socio-economic stocks. Longer lifetimes of wood products may also allow for lower annual wood demand and thus lower harvest volumes. Increased material wood use and increasing shares of long-lived products (as opposed to, e.g., wood bioenergy use) contributed to a long-term increase in the pool of harvested wood products of 115 MtC between 1830–2010 in Austria, while forest C pools increased by 240 MtC over the same period (Gingrich et al., 2016). For future trends, Braun et al. (2016) project a continuation of C accumulation in harvested wood product pools until 2100, corresponding to 180–350 MtCO₂eq across scenarios. In their assessment, forest C stocks will increase in the scenario with less wood extraction, and decline in the scenario with higher wood extraction, while conversely, the effects of product substitution will be higher when more wood is used. Substitution effects are subject to time dynamics, and their mitigation effects decrease with the decarbonization of the economy (Buschbeck and Pauliuk, 2022; Jandl et al., 2024b).

In particular, the increased use of timber in construction, a sector which is currently responsible for 8 % and 14 % of Austria’s CO₂ and material footprint, respectively (BMK, 2020), can both substitute highly emission-intensive products (e.g., steel) and remain in use for particularly long lifetimes, i.e., decades or more. However, if increased construction timber cannot be derived from current domestic wood

processing chains, it would require more imports. In global assessments, there is *high confidence* that a shift towards more construction timber would require large-scale land use changes and intensive tree plantations (e.g., Hertwich et al., 2019; Mishra et al., 2022). For Austria, Kalt (2018) estimates that by ramping up the share of wood in residential building construction to 50 % (from currently 22 %), the C-stock expansion in timber buildings could amount to 9.2 MtC by 2050, and further savings of 2–4.2 MtC would be realized by substituting emissions for the provision of mineral construction materials. Kalt (2018) considers such a scenario theoretically feasible and without impact on international forest C pools (due to increased harvest volumes), as the additional wood demand would remain far below Austrian sawn wood and panelboard exports. However, the absolute emissions impact of using wood in construction depends on the carbon impact of wood harvesting on forests and the emissions intensity of the construction sector (Buschbeck and Pauliuk, 2022); a recent study for Austria finds that the climate change mitigation effect of increased wood use in buildings is in most cases overshadowed by the forgone carbon sink (carbon opportunity costs) in forests (Maierhofer et al., 2024) (see Section 3.2.2). Currently, stakeholders from the wood sector do not consider an increase in the share of timber in residential construction to be likely, because of institutional constraints (Vihemäki et al., 2019). In addition to wood, other bio-based materials have been proposed for sustainable construction, such as mycelium, hempcrete, flax boards, straw, and reed (Yadav and Agarwal, 2021), but no assessment is available for Austria.

In addition to increasing the share of wood in construction, further emissions could be avoided in the residential sector through demand-side (or sufficiency) strategies (see Sections 3.3.1 and 3.2.2): In a global meta-study, Creutzig et al. (2022a) quantify the potential reduction of emissions through building design, size and use at 25 % (10–40 %) of global residential emissions. Kalt (2018) includes a scenario of moderately declining per-capita floor space, but the additional emissions savings potentials that might be realized through demand-side strategies, such as ending the decline in household size (Ivanova and Büchs, 2022) or fostering co-housing (Ivanova et al., 2020), have not been systematically quantified for Austria.

After its lifetime, timber from demolished buildings can again serve as raw material for material or energy use.

Kalcher et al. (2017) quantify scenarios for Austria and find that, in their ‘standard’ scenario, the amount of wood available annually from the demolition of residential buildings alone will double by 2100. However, they also stress the poor data availability on residential buildings in Austria.

Bioenergy use has increased in recent years and is currently the largest renewable energy use in Austria, accounting for 247 PJ, or 17.3 % of total primary energy supply, while the fraction in domestic primary energy production is 47.5 % (BMK, 2023). Increased use of bioenergy, as the last step in the wood use cascade, and derived from agricultural residues, can play a certain role in achieving renewable energy targets (*robust evidence, medium agreement*). The APCC Special Report on land use and climate change (Jandl et al., 2024c) concludes that no reliable estimate on sustainable bioenergy potentials can be made at present due to the many trade-offs that are difficult to account for. In the existing literature, bioenergy potentials for Austria are estimated to reach 310–420 PJ by 2030–2050 (Krutzler et al., 2016; Anca-Couce et al., 2021), but these estimates do not explicitly consider system-level interactions between wood harvest and forest biomass stocks (Erb et al., 2016; Olsson et al., 2019; Pingoud et al., 2018). For instance, Kalt et al. (2019) show that at the global level, in terms of climate change mitigation, bioenergy from short rotation coppice is only competitive with natural succession on abandoned agricultural land over longer time frames (>30 yr) and with high displacement factors.

Measures to save energy, such as insulation in residential buildings, have been described as being favorable over increased bioenergy use (Peng et al., 2023; Jandl et al., 2024c). Through efficiency gains and insulation, the demand for wood energy can be reduced in absolute terms: Kranzl et al. (2018) estimate that by 2050, wood in residential final energy use will decrease by 25 % compared to 2020, as building renovation reduces overall energy demand for residential heating. There are knowledge gaps regarding the future supply of timber in Austria, integrating the complex interplay between, on the one hand, climate change and forest management choices that impact the composition of tree species, and on the other hand, technological change or adaptation in the milling industry that might change the use or processing potentials of different wood qualities. Furthermore, inter- and transdisciplinary collaboration will be required to robustly assess the potentials and impacts of sufficiency measures in the context of bioeconomy strategies (Schipfer et al., 2024).

2.3.3. Nature-based (climate) solutions

Nature-based solutions to increase the carbon sink of managed ecosystems

Nature-based Solutions (NbS) are actions that protect, sustainably manage and restore natural and modified ecosystems to provide multiple benefits for human well-being and biodiversity (Cohen-Shacham et al., 2016; Keesstra et al., 2018; Oral et al., 2020). NbS have large potential benefits for the mitigation of and adaptation to climate change (*high confidence*).

Under certain conditions, land ecosystems can take up carbon and thus counterbalance the accumulation of CO₂ in the atmosphere. Besides soils, woody biomass is the largest carbon pool in terrestrial ecosystems both in Austria and on a global scale (Jandl et al., 2024c). Woody vegetation, particularly in forests, has acted as a net carbon sink in Austria since the 19th century (Gingrich et al., 2016, 2022), due to both the expansion of area under woody vegetation and the increase of timber stocks in existing forest areas. Timber stocks in existing forests increase due to an increase in average age. This occurs in protected forests, but also in managed forests if management intensity is low (e.g., as observed in small-scale forest ownerships). There is *high confidence* that both the expansion of woody area and the increase in timber stocks continue to have potentials for future carbon sequestration, but are constrained by ecological limitations and land-use competition (Jandl et al., 2024c). At the same time, they may have co-benefits with biodiversity (Oettel and Lapin, 2021).

Adapting forest management can contribute to reducing the gap between actual and potential biomass stocks (*high confidence*) (see [Chapter Box 2.2](#)). The effect has been quantified globally (Houghton and Nassikas, 2018; Cook-Patton et al., 2020; Walker et al., 2022; Mo et al., 2023; Roebroek et al., 2023), but not for Austria. For Austria, Braun et al. (2016) find that in a scenario of reduced timber extraction from all forests, the overall cumulative mitigation potential in the forest sector would range between 600 and 800 MtCO₂ until 2100, compared to any scenario of increased wood use. This difference comprises an increase in the forest sink of 1100 to 1300 MtCO₂, a decrease in the HWP sink of 100 to 200 MtCO₂, and a decrease in avoided emissions from fossil fuels of 300 to 400 MtCO₂. A similar finding is presented in Weiss et al. (2020) (see also Kirchmeir et al., 2022). In order to achieve a net mitigation effect, the reduction in wood harvest in Austria needs to coincide with strategies to

reduce the overall material and energy use and to limit imports (at the EU level), to avoid leakage of wood harvest to other countries and an increased use of other materials and fuels (Meyfroidt and Lambin, 2009; Meyfroidt et al., 2022). According to the Weiss et al. (2020) study, between 2020 and 2150, the contribution of the forest-based sector to national GDP under a reduced harvest scenario would be about 80 % of the contribution under a reference scenario. This corresponds to ca. EUR 1.77 billion less per year, for an average mitigation effect of 7 MtCO₂/yr over the same period, i.e., ca. EUR 250/tCO₂ (Weiss et al., 2020).

Expanding the forest area in Austria is theoretically possible. Forests currently cover 48 % (2016/2021) of the domestic land, compared to 38 % in 1935 according to the Forest inventory (Waldinventur). Since 1981/1985, forest area has increased mainly due to the expansion of non-managed forests, by 0.135 Mha as opposed to 0.023 Mha for managed forests (Haszprunar et al., 1989). In addition, there are areas covered by trees that are not counted as forest. Due to competition with other land uses such as agriculture, the realistic potential of forest expansion appears to be limited, if demand for agricultural area is not reduced (Kraxner et al., 2024). See [Table 2.3](#) for mitigation potentials of afforestation enabled by a protein transition and reduced food losses. The extent to which forest expansion is considered in climate-change mitigation scenarios is sometimes not explicitly quantified (e.g., Kirchner et al., 2016). But it can be assumed that the C sequestration effect of afforestation is small for time frames up to 2040. Increasing the area under trees in agricultural and urban settings, e.g., through agroforestry and urban trees, could contribute to sequestering additional C in managed ecosystems, with reported values for aboveground carbon storage ranging from 11–27.4 tC/ha in cities and up to 67.5 tC/ha in agroforestry systems (Nowak and Crane, 2002; Strohbach and Haase, 2012; Dorendorf et al., 2015; Bertsch-Hoermann et al., 2021; Golicz et al., 2021). If adequately implemented, such measures can achieve co-benefits for health, biodiversity and climate change adaptation (APCC, 2018; Jandl et al., 2024c) (*medium evidence, high agreement*). Biodiversity impacts can be positive when natural ecosystems such as mires and forests are restored, and negative when extensively-used agroecosystems are intensified or replaced by plantations (see [Cross-Chapter Box 6](#)). Expanding fast-growing tree plantations on previous cropland is one way to increase carbon pools, as they accumulate biomass very rapidly (Gonçalves et al., 2021) and increase the average carbon density per unit area compared to cropland. This can be done for example with en-

ergy plantations such as coppice forests of pure even-aged stands of fast-growing species, managed with a high density in very short rotations, sometimes fertilized and/or irrigated (Stojanović et al., 2017). Trade-offs with food production are possible. Highly pure or mixed even-aged forests managed only for carbon sequestration without considering the quality of timber and associated higher market prices (e.g., applying thinning from below, not removing forked or damaged trees of poor quality, maintaining wood of trees species with low market price) often do not meet the management objectives of forest owners. Compensation payments to forest owners have been shown to increase interest in biomass production for carbon sequestration (Ovando et al., 2019; Winkel et al., 2022).

Agroforestry has a medium potential to mitigate climate change (*medium evidence, high agreement*). Agroforestry systems currently cover 1.9 % of used agricultural land in Austria, dominated by sylvopastoral systems (Den Herder et al., 2017). Converting subalpine grasslands to sylvoarable systems can result in carbon sequestration, but reduces harvest due to reduced biomass growth under tree cover: In the Austrian Eisenwurzen, a scenario analysis found sequestration rates of 3.4 tC/ha/yr by 2050 while yields were more than halved (Bertsch-Hoermann et al., 2021). There is no assessment of biomass carbon pools in agricultural hedgerows for Austria, but a study for the Netherlands (Van Den Berge et al., 2021) concludes that trees in hedgerows show high and persistent increments of 0.7–4.3 tC/km/yr in stems alone, with basal areas of 22.1–44.9 m²/km. Their exclusion hence represents a major gap in national greenhouse gas inventories. However, no time-frame is given for this estimate. Wenzel et al. (2023) quantify the effect of hedgerows on SOC in top soils in Upper Austria, and show that SOC increases under hedgerows for decades, albeit at declining rates, resulting in higher SOC of 16–106 MgC/ha and 35–119 MgC/ha under hedgerows aged 1–30 and 31–70 years, respectively.

There is an ongoing debate, *with medium evidence and low agreement*, whether it is more advantageous to combine forest production and pasture (by cattle) on the same area (forest pasture) or separate the two land uses by creating open pure pasture areas and allowing the surrounding forests to become increasingly dense and enhance the carbon sink (Stöckli, 2013). On the one hand, the heterogeneous forest structure typical of forest pastures has positive effects on species and landscape diversity, as well as on tourism (Schirpke et al., 2019; Anderle et al., 2022). On the other hand, the forest pasture reduces the growth and yield of the

forests, hampers the successful natural regeneration of tree species, and can cause damage to the residual trees, making them vulnerable to pests and diseases (Noack et al., 2010) and reducing the potential carbon sink. Conflicts of interest emerge between agriculture, forestry and tourism when cooperation between actors and interest groups is limited (Johann, 2013).

The potential for carbon sequestration through rewetting of agricultural peat soils and uncertainties about the actual amount and use of agriculturally used peatland represent research gaps. The national greenhouse gas inventory reports 13,000 ha of organic soils in the category 'grassland remaining grassland' (Umweltbundesamt, 2024).

Nature-based solutions to adapt to climate change and disaster risk reduction

Nature-based solutions are not only linked to climate change mitigation, but also entail multiple synergies and co-benefits for ecosystem services, contributing to multiple global agendas, including disaster risk reduction, climate change adaptation, and sustainable development (Martin et al., 2021). There is *high confidence* that taking advantage of nature-based solutions (NbS) helps to mitigate the negative impacts of climate change in urban settings and make cities more resilient to environmental changes (Faivre et al., 2017; Laforteza and Sanesi, 2019). Urban forests, parks or simply tree-lined streets – urban greens in general – are known to facilitate adaptation to climate change in terms of temperature and water budget regulation (see urban heat islands in [Section 3.2.3](#)). Urban greening must consider climate-resilient tree species that can cope with future conditions to secure its benefits (Foldal et al., 2022). For example, non-native tree species already present in the urban Alpine area of Austria and neighboring countries were recorded and assessed for their drought tolerance (Herbsthofer et al., 2020). However, in terms of climate change mitigation, the contribution of urban green strategies remains small to moderate (Strohbach and Haase, 2012; Ariluoma et al., 2021) unless further indirect effects on avoided energy demand for cooling buildings are considered (Quaranta et al., 2021). See [Section 3.2.2](#) for such indirect effects related to the built environment and urban planning.

Nature-based solutions entail strong health co-benefits (*high confidence*). In particular, increasing the number, distribution and density of green trees in urban areas improves urban public health and well-being of urban populations and contributes to sustainable living in terms of positive effects

on humans, microclimate, soil and biodiversity (Haluza, 2024; Spörl et al., 2024). Nature-based solutions also support several ecosystem services and their health co-benefits described in Section 2.2 (food security, air pollution, psychological health, etc.).

Beyond urban areas, the development of near-natural areas increases the possibility of migration of plants and animals and thus also of pollinators, counteracting the negative impacts on pollination. There is *limited evidence*, but *high agreement* that nature-based adaptation measures such as the restoration of wetlands, revitalization of rivers, no-tillage and cover-cropping in agriculture, and urban green gardens

may restore natural flood control capacity – by providing retention space and improving soil water holding capacity (Seddon, 2022). Despite several decades of experience with river restoration, evidence on its effectiveness is limited, as evaluation is difficult due to the context specificity of projects and realizations at diverse scales with differing objectives (e.g., Kurth and Schirmer, 2014 for Switzerland; Nilsson et al., 2016 for other European instances). Moreover, implementation is still often obstructed by the path dependencies of gray measures, such as straightened riverbeds, which have long lifetimes and are costly to reverse (Hanger-Kopp et al., 2022; Seebauer et al., 2023).

Chapter Box 2.2. Carbon sequestration potentials of forests

Forests cover 48 % of the Austrian territory, of which 83.7 % are commercial forests. As forests are able to accumulate and store substantial amounts of carbon (Erb et al., 2018; Arneth et al., 2019), their potential to sequester atmospheric carbon dioxide and provide carbon sinks is relevant for the national GHG budget (Umweltbundesamt, 2023a; Jandl et al., 2024c). This box discusses the conditions for long-term carbon storage and the underlying assumptions needed for estimation. It (i) quantifies current stocks and their historical development, (ii) introduces management strategies to maintain and increase stocks, (iii) discusses theoretical and observed carbon densities, and (iv) examines the pathways to arrive at such quantities. For simplicity, land conversions (land use change to forests or from forests to other uses) are not considered here.

The C budget of forests is characterized by stocks and by stock changes. We only consider above- and below-ground woody biomass, including deadwood, since additional carbon pools such as soil organic carbon are still poorly understood (Le Noë et al., 2023b). Stock estimates (Table 2.1) are derived from the volumetric data of the Austrian Forest Inventory using an average conversion factor of 0.345 tC/m³ (2.9 m³=1 tC), a factor taken from 1990 forest inventory data as converted to total carbon (including branches, leaves, roots) by Umweltbundesamt (for 1990, 973 million m³ and 339 MtC) and which we maintain here for all comparisons. Stock changes reflect C uptake from the atmosphere (e.g., increment) and biomass C removal (harvest, decomposition and depletion). In Austrian commercial forests, the forest C stock increased from 80.7 tC/ha in the period 1961–70 to 121.0 tC/ha in 2016–18 (Gschwantner, 2019) (*high confidence*). This increase is the result of removals being lower than increment in most years (Figure 2.3).

Forest management options aimed at maintaining forest functions include selective cutting (both thinning and harvesting) as well as tree planting. Management may be directed to favor growth (to extract forest products, but also to remove atmospheric CO₂ efficiently), which requires relatively young forests (60–140 years) and management interventions such as 2–3 thinnings before the final harvest. By contrast, management can also aim to maximize carbon stocks in forests, by selecting tree species that can accumulate high stocks and have low damage risks, by making thinnings to allow long rotation times, making the final harvest before reaching the degradation phase and keeping regeneration times short.

In order to estimate C sequestration potentials, it is important to understand (although challenging to assess) what carbon densities can eventually be achieved in forests. Ecological considerations originate from biophysical principles using parameters such as the net primary production (Saugier et al., 2001) and applying the ‘potential vegetation concept’, i.e., the vegetation that can be expected under current or pre-industrial climatic and soil conditions, as a benchmark (Erb et al., 2018; Bastos et al., 2021). Actual biomass stocks are understood to be depleted due to the removal of organic material, such as wood or deadwood, and this depletion establishes a stock gap. Global studies of existing forest biomass stocks at the landscape level report that their carbon storage is 24–39 % below the natural potential in the temperate zone (Erb et al., 2018; Walker et al., 2022; Mo et al., 2023).

Data from existing primeval forests in Europe help to quantify this natural potential. Such forests are sparse and small, so results are uncertain and only partially representative. In a meta-study, Keith et al. (2024) present data from 18 sites in Central Europe characterized as primary forests (none in Austria). Several of these sites had carbon stocks exceeding 200 tC/ha, and only 3 sites had less than 150 tC/ha. For the Białowieża forest in Poland, potential vegetation has been estimated at 189 tC/ha, while current C stocks are considered to be 123 tC/ha, even though the forest has been left unmanaged for centuries (Matuszkiewicz et al., 2021). In Austria, the small area of Rothwald showed an average stock of 175 tC/ha (timber stock decreases of more than 44 tC/ha were observed during a wind throw in 1966) while surrounding managed stands had 266 tC/ha (Schrempf, 1986). Similarly, the Bavarian Forest National Park (Nationalpark Bayerischer Wald) exhibits lower timber stocks (without deadwood) of 96 tC/ha in the unmanaged core zone, compared to 138 tC/ha in the managed zone next to the core zone (Heurich and Sinner, 2005).

Optimum management options from a forestry perspective have been outlined by Zeide (2004), differentiating between optimizing for harvest or for carbon stocks. A steady-state of forest development needs to cover the carbon pool in all stages of the forest cycle at the landscape scale, as well as site- and tree-specific growth and mortality rates caused by disturbances or due to physical age limits of trees (Wirth et al., 2009; Oettel et al., 2020; Ehbrecht et al., 2021; Kobler et al., 2024). Management decisions allow a managed forest to exceed the C storage of potential vegetation. Specifically, the planting of selective tree species (Douglas-fir, *Pseudotsuga menziesii*) (Spannlang, 2022) or the possibility to minimize calamities (Vanomsen, 2006; Kautz and Delb, 2023; Hurteau et al., 2024) are essential factors to increase carbon stocks beyond primeval forests.

C sequestration potentials have been quantified either as a carbon gap to an ecological potential or as an impact of forestry management. There is *robust evidence*, but *low agreement* on which approach is appropriate. When quantifying a C sink, it is not important whether that sink is man-made or natural. The difference becomes relevant for specific management decisions, and for the longer-term robustness of such a sink. The temporal aspect is also decisive for sink dynamics. Luyssaert et al. (2008) show that also old-growth forests further accumulate carbon over centennial time spans (which could explain differences to the potential C stocks observed by Matuszkiewicz et al. (2021)), despite disturbances and calamities (wind, insects, fire). Thus, C sequestration will also occur at the same time scale of centuries.

Specific modeling of such developments over time for Austria in the CareforParis study (BFW, 2020; Ledermann et al., 2022) estimated a peak stock of 193 tC/ha by 2130 for an RCP8.5 scenario (GWL 4.34°C for 2081–2100) assuming average extreme events combined with a management target to increase stocks. In contrast, in a scenario based on current management but with massive calamities, stocks were estimated at 55 tC/ha in 2150 (data presented includes standing deadwood). Here, calamities provide a decisive management risk, with potential impacts also for strategies aimed at maximizing C stocks. The lack of understanding of this risk is a research gap, which will remain challenging to close given the time scales of forest growth.

The above modeling approaches consider calamities as well as C-stocks in the form of standing deadwood. To put into perspective, in 2023, 1.03 MtC forest were destroyed by bark beetles and 0.74 MtC by windthrow (BFW, 2023), together about 0.4 tC/ha if evenly distributed over Austria's forested area. That is 2 ‰ of the biomass C stock, but around 20 % of the annual increment (see Figure 2.3b). The Austrian Forest Inventory measures 7.1 tC/ha deadwood for Austrian forests (Oettel et al., 2020), with values in the small areas of unmanaged natural forest reserves reaching 7.9–37.6 tC/ha, at half lives of several decades (Hararuk et al., 2020; Seibold et al., 2021), with large observed variation (Harmon et al., 2020).

Further challenges in estimating the future development of Austrian forests are related to the legacy of multiple uses in the past (Gingrich et al., 2007, 2021, 2022), which led to a dominance of spruce as a single tree species. Adapting forests to climate change requires, i.e., altering the tree composition (Wessely et al., 2024), which means replacing part of the existing forest stock. Using forests as carbon sinks adds to the complexity, especially if biodiversity is also taken into account (for diverging views on management impacts, see Luick et al., 2021; Jandl et al., 2024a). Assumptions about the use of harvested wood products to substitute more carbon-intensive materials or practices (Weiss et al., 2020) are excluded here and may conflict with the forests' C sequestration potential, see Table 2.3. For a systematic comparison of two differing perspectives on net C effects of forest management and wood use, see Box 1.1 in Jandl et al. (2024c).

2.4. Conflicts, lock-ins and enabling conditions – focusing on the example of agricultural land use

The land use system includes a network of actors, activities and institutions along the value chain, from production to food waste, embedded in ecological, social, political, cultural and economic contexts (Penker et al., 2023). Climate change and sustainable development are challenges to society that require action at local, national, transboundary and global scales. Forestry and agricultural legislation, urban and spatial planning, and nature conservation provide the (legal) framework for action and guidance. Climate change and environmental crises, partly driven by dynamics outside the land use sectors, can exacerbate existing conflicts or create new ones (Formayer et al., 2024b). Ongoing soil sealing and urban sprawl has been exacerbating the competition for and conflicts around biologically productive land (see [Section 3.2.2](#)).

Focusing mainly on the example of agricultural land use, this section looks into barriers, conflicts, and lock-ins as well as enabling conditions for a transformation. For illustrative purposes, forest-related literature is added in some parts.

2.4.1. Barriers, conflicts, and lock-ins

Land is a limited and scarce resource (Haberl and Erb, 2017). The land system, globally as well as in Austria (Formayer et al., 2024b), is coined by strong (intrinsic) trade-offs, target- and interest conflicts (*high confidence*). Land use, e.g., in forests and agroecosystems, has different societal functions, such as production, recreation, or nature conservation, entailing substantial goal conflicts (Bontempi et al., 2023). Moreover, people project different values onto land, from direct or instrumental use values to indirect or intrinsic values (Meyfroidt et al., 2022) and relational values (Leopold, 1949; Himes and Muraca, 2018).

The current specific allocation of the scarce resource land to different uses (Gerber et al., 2018) results from the interaction of a wide variety of stakeholders (land owners, land users, consumers, processors, retailers, public sector), natural site conditions, historical development, market conditions, and technological possibilities. Changes in the allocation of land use and the associated rights and duties to land have environmental, economic and societal effects bearing high conflict potentials. For example, maximizing the carbon sink through large scale reforestation might result in a fundamentally changed landscape and might negatively

affect other ecosystem services such as food production or water provision (Jackson et al., 2005; Ferreira et al., 2018), and impact current land users such as farmers by decreasing or completely suppressing their current livelihoods. Such trade-offs are frequent in the land system (Meyfroidt et al., 2022). Negotiating the values and interests among stakeholders (Ellis et al., 2019), and measures to reduce the overall demand for certain ecosystem services (Haberl and Erb, 2017) can help to mitigate trade-offs. In contrast to the strong influence of sector-specific goals and interests, spatial planning struggles to fully assert its organizing and coordinating functions, significantly limiting its capacity to mitigate trade-offs across sectors and ensure climate-friendly decision-making (Svanda and Zech, 2023). There is *medium evidence* and *high agreement* that such trade-offs mostly affect less powerful, often also less wealthy, stakeholders (Howe et al., 2014; Pichler et al., 2022).

The outcomes of such land use conflicts are often reinforced by path dependencies and ‘environmental amnesia’ making them difficult to be reverted (Meyfroidt et al., 2022; Aigner et al., 2023). As noted in the APCC Special Report on land use and climate change (Jandl et al., 2024c), there is *high confidence* that a fundamental conflict unfolds between economic growth and environmental conservation. Under the current conditions of production and consumption, growing economic performance in Austria and worldwide is closely linked to increasing resource and energy consumption (BMK, 2020) and is associated with negative environmental impacts such as pressure on water resources, rising greenhouse gas emissions (at least in a multiannual average), biodiversity loss (Otero et al., 2020; Moranta et al., 2022; Santika et al., 2024) and soil sealing. This leads to an implicit preference for substitution-pathways and efficiency-pathways over conservation (restoration) or sufficiency pathways (Birch et al., 2010; Allain et al., 2022; Boyer et al., 2023; Eversberg et al., 2023; Fleischmann et al., 2024). However, there is *high confidence* that the effects of efficiency gains, including, e.g., yield increases, are often partly compensated or even overcompensated due to rebound effects, i.e., increases in consumption (Paul et al., 2019; García et al., 2020; Erb et al., 2023b; Haberl and Erb, 2023; Preinfalk et al., 2024).

In Austria, both, economic performance and resource and energy consumption are growing, albeit resource and energy consumption increase at a lower rate than GDP (relative decoupling) (BMK, 2020). There is *limited evidence*, but *high agreement*, that a climate-friendly land system cannot be achieved without fundamental, comprehensive

structural changes, which involve industry and trade, technological innovations and individual approaches (IPCC, 2019a; Penker et al., 2023). The fundamental problem with regard to environmental problems is that landowners (e.g., farmers, forest owners) are not paid for delivering environmental services (as they are mostly public goods) and focus their production activities on private goods such as food, timber products, and recreation services (Cooper et al., 2009; Winkel et al., 2022). Long-term investment decisions by private actors (e.g., livestock housing) or cultural values and norms (e.g., on ‘good farming’ standards) can reduce the acceptance for alternative production systems. Consequently, the acceptance for environmentally oriented production is comparatively low, if not made mandatory or subsidized by the government. Fostering payments for ecosystem services, better monitoring of ecosystem supply and demand, enhanced policy integration, and improved bottom-up participation and learning among ecosystem service innovators are therefore important strategies (Winkel et al., 2022). Non-acceptance is often reinforced through lobbying by interest groups or even protests (Nature Food, 2024) of the respective sectors, which render it difficult to integrate climate and environmental policies with sectoral policies (Plank et al., 2021).

Difficulties might also arise to change the diverse drivers of current land use. One example is the apparent difficulty in reducing the share of animal products in diets, in Austria and in the EU as a whole, despite the apparent benefits and synergies between climate and biodiversity protection and human health (see Section 2.3.2). To avoid facing the conflicts related to a transformation towards less animal protein production and consumption, dietary change is often hidden behind consumer-narratives (Vermeulen et al., 2020; Duluins and Baret, 2024), preventing structural discussions on solutions to incentivize and support producers in the protein transition. A media analysis of three Austrian newspapers published between 2000 and 2019 shows evolving informal institutions, such as behavioral norms embracing meat-free or reduced-meat diets and no debates about changes in formal institutions, such as regulations and other policy interventions (Hundscheid et al., 2022). Hundscheid et al. (2022) attribute this lack of debates about changes in formal institutions to the deeply entrenched cultural significance of meat, which is actively defended by actors safeguarding the status quo. Kortleve et al. (2024) conclude that in the EU agricultural subsidy system, animal husbandry receives far more support (>80 % of all subsidies) than plant production. On the other hand, animal production, which

is to a large degree export oriented, is of key economic importance and a significant reduction in animal husbandry would impact companies as well as numerous family farms. Farms are mostly faced with a small number of comparatively large retail chains and processors and consequently have little bargaining power in the value chain (Jäger et al., 2024), and consumers are mostly not prepared to pay the corresponding higher prices. Thus, while farmers often have to implement environmental and climate mitigation measures, they cannot simply pass on the resulting costs to retail chains or consumers.

The mechanisms of international markets are also relevant in this context. National regulations need to respect the European frame and international trade agreements (e.g., WTO), and the development of international competitiveness of the strongly export-oriented Austrian agricultural, forestry and timber sectors (see Section 2.1.1) is a key factor for the development of (environmental) regulations. A sole focus on consumer responsibility and market-based mechanisms would affect the social justice dimensions, i.e., the distribution of costs and benefits of the transformation towards climate-friendly structures. From a consumer perspective, there is *high confidence* that unhealthy foods or ‘empty calories’ (Tilman and Clark, 2014) are cheaper, more readily available, and also constantly featured in advertising compared to healthier alternatives, which contradicts a socially just transformation towards climate-friendly living and is associated with higher C-emissions on-average (Rao et al., 2013; Ravensbergen et al., 2015; Penne and Goedemé, 2021). A ‘climate-social policy’ aimed at exploiting synergies between reduction of social inequalities and climate change mitigation has not yet been formulated for Austria (Armutskonferenz et al., 2021). Structures of social inequality are key, for example for dietary practices (Penker et al., 2023), and can result in food poverty or obesity due to the unaffordability of healthy food in terms of quantity and quality (Bonaccio et al., 2012).

A further key sustainability conflict in the current land production system relates to working conditions (*medium evidence, high agreement*). Many economic activities related to the land system (production, processing, retail) rely on low or comparatively low wages and/or profits, and precarious working conditions are widespread (Penker et al., 2023). Additionally, the number of serious accidents at work is still very high in the Austrian agriculture and forestry, despite improved technology and prevention measures (Kogler et al., 2015). Barriers to the implementation of resource-conserving or emission-reducing measures often lie in higher

labor or capital inputs, which increase production costs, and in reduced land productivity (Jäger et al., 2024), although this is not always the case (Fontana et al., 2013). In this context, it should be noted that farms in Austria are comparatively small and mostly run as family farms, where labor is usually a scarce resource.

Further barriers and lock-ins can be found in existing and contradictory policy frameworks and funding systems, within the CAP direct payments and even within agri-environmental-climate schemes (Kletzan-Slamanig et al., 2022; Jäger et al., 2024).

2.4.2. Enabling the transformation

A successful transformation strategy must consider all these barriers, conflicts and lock-ins, including the international nature of markets and policies. ‘Climate-friendly’ land use changes, e.g., in agriculture or forestry, affect not only land use and the land users themselves, but also society via several socially relevant public goods and bads (Sauvage, 2014). Many of these goods (e.g., agrobiodiversity, cultivated landscapes, recreation and experience in nature) and bads (e.g., nitrogen and phosphorus inputs resulting in greenhouse gas emissions or water pollution) have no market (as opposed to food, animal feed, timber, etc.) and are therefore not coordinated through market mechanisms (Cooper et al., 2009). (Agri-environment-climate) policy interventions represent a means to compensate for management and opportunity costs, as is already implemented in Austria, e.g., under the agri-environmental program ÖPUL. This program offers a broad range of measures aimed at mitigating greenhouse gas emissions and supporting agriculture in adapting to new conditions, such as greening, manure storage, or manure spreading. In the forestry sector, several CDR measures are also proposed to improve the overall mitigation, but there are no policy instruments in place to compensate forest landowners for potential financial losses and foster strategies to increase sufficiency, recycling and product-lifetime of timber products (Jandl et al., 2024b). Financial compensation for the provision of public goods or the avoidance of public bads provides income opportunities for land users, resulting in negative net taxes on farm production in Austria and other OECD countries – in contrast to positive net taxes in most countries of the Global South (Eastwood et al., 2010). For a successful transformation, social questions of poverty and inequality have to be effectively addressed at the national and international levels (Club of Rome, 2022; Hoffmann et al., 2024).

The Austrian Court of Auditors recommended the definition of quantifiable objectives, assessment indicators and the collection and use of data on the state and change of the environment for effective agri-environmental schemes – ÖPUL (Österreichischer Rechnungshof, 2013). According to the follow-up report, these recommendations were not or only partially implemented (Österreichischer Rechnungshof, 2016). In 2024, at the European level, the European Court of Auditors (ECA) identified a gap between farming incentives and the EU’s green targets (European Court of Auditors, 2024). A key finding of the ECA is that, with the exception of organic farming, the European Commission will not be able to measure the contribution of the Common Agricultural Policy, which accounts for just under a third of the EU’s total budget for 2021–2027, to its climate goals (European Court of Auditors, 2024). Therefore, a comprehensive provision of knowledge and information is a prerequisite for a successful transformation. Nevertheless, research efforts and innovations (such as agrivoltaics) are currently not well transferred to land use stakeholders. Education systems play a key role in ensuring that knowledge is passed on effectively, e.g., to farmers but also to consumers (Jäger et al., 2024). The development of suitable information and indicator systems is a key aspect and can be enhanced (Wolfslehner and Vacik, 2011; Grima et al., 2023). Austria-supported developments such as the further elaboration of the Agricultural Knowledge and Innovation Systems (AKIS) or the transformation of the European Farm Accountancy Data Network (FADN) into a Farm Sustainability Data Network (FSDN) are positive examples. However, providing information is hardly sufficient to steer transformations such as reducing the consumption and production of meat and avoiding food waste (Jäger et al., 2024). Further progress needs to identify and develop synergies between technological innovations (digitalization, precision farming or robotics), regional development and the mitigation of greenhouse gas emissions (Kraxner et al., 2024; Schipfer et al., 2024).

Austria lacks a systemic approach to sufficiency strategies, reducing consumption and production levels through avoid-shift-improve approaches (Plank et al., 2021) (see [Sections 6.5.1, 6.5.4](#) and [Table 6.2](#)). Such an approach would take as its starting point the highly integrated, complex-dynamic nature of socio-ecological dynamics, acknowledging that land systems are cross-cutting and involve various policy areas (including environment and climate, health, agriculture, consumer protection). There is a need for a climate protection law that contains strategic targets in line with the Paris climate goals as well as effective sanction mechanisms and

requirements for improvement in order to protect Austria's climate goals against regression (Hollaus et al., 2023) (*medium evidence, high agreement*) (see [Section 6.2](#)).

It becomes clear that only an integrative policy development allows for an orchestrated embedment of climate protection into various policy areas. International assessment reports conclude that food, energy and water security as well as biodiversity conservation rank high on the Agenda 2030 for Sustainable Development, rendering the promotion of synergies between and across sectoral policies a key strategy (IPBES, 2018). However, the current policy design and formulation in Austria is often sectoral. Moreover, the long-standing concentration of environmental and agricultural agendas in one ministry (2000–2020) has contributed to the concealment of potential conflicts of interest (Penker et al., 2023). Promising developments include a new organization on sustainable food (AGES, 2024) that bridges the three Ministries of Health, Agriculture and Climate, as well as the Sustainable Food Initiative by the Austrian Promotional Bank (AWS, 2024).

Abandoning the current attribution of responsibility for climate protection, which is largely placed on consumers by policymakers and businesses, has the potential to create enabling conditions for a sustainability transformation (Penker et al., 2023). Public food procurement (meals in schools, hospitals, canteens) or reducing taxes on plant-based foods are examples of transformative policies that can support the co-benefits for climate friendly and healthy food supply (see [Table 2.A.4](#) for further measures along the entire food system). Ensuring the resilience and resistance of forests through diverse forest management practices, implementing integrative measures to maintain biodiversity and promoting payments for non-marketable goods and services are key elements for a sustainable transformation. The measures described in the report of the UniNetz initiative provide a wide array of measures in this direction (Vacik et al., 2022). Identifying and engaging with potential repercussions of climate policies on land users can enhance the legitimacy of such effective regime destabilizing measures and can thus contribute to resolving lock-ins (Hundscheid et al., 2024). An integrative food policy relies on combining different policy areas and has been shown to foster decentralized self-organization, entrepreneurship and social learning (Penker et al., 2023), which could open windows for transformative innovations.

Polycentric governance is proposed as an appropriate way to deal with resource management problems, in which decision-making centers take each other into account in com-

petitive and cooperative relationships and have recourse to conflict resolution mechanisms (Arneth et al., 2019). Polycentric governance aims to open the scope of action for context-specific solutions and coordinated interaction between actors at different levels (local, regional, national, and global) and to foster decentralized self-organization, entrepreneurship and social learning. Such approaches have been shown to allow for flexibility and context-specificity in the light of the uncertainties inherent in, for example, the food system and for successful adaptation (*medium evidence, high agreement*) and require horizontal as well as vertical integration of policy areas or levels (Plank et al., 2021). The need for a common nutrition policy is discussed at both European and national level (IPBES, 2019; SAPEA, 2020; Penker et al., 2023), as is the need to use all governance instruments in the field of nutrition (SAPEA, 2020; WBAE, 2020). See [Section 6.4](#) for more details on governance mechanisms.

A climate-friendly coordination between the production of food, feed, fiber and fuel, and between production, conservation and restoration can be supported by scaling up local land use planning to the regional or even to the national level (Svanda and Zech, 2023). Further suggestions from the spatial planning literature for achieving climate goals involve legal requirements for sectoral plans to contribute to climate-friendly structures, avoiding financial incentives for climate-harmful land use structures (e.g., commuter bonus 'Pendlerpauschale'), or new incentives for unsealing former industrial areas or parking lots (Svanda and Zech, 2023) (*medium evidence, high agreement*) (see [Sections 3.2, 3.4, 6.5.1](#) and [Table 6.2](#)).

Environmental programs can reduce conflicts by financially supporting the provision of public goods such as climate-resilient soils, mitigation, biodiversity, and other land-based ecosystem services. However, utilitarian and transactional approaches to trade-offs are likely to depreciate the conservation of biodiversity and ecosystems, for example when forests are mostly used for timber production or carbon sequestration, neglecting a wide array of human-nature relations and associated values. New approaches are emerging to address trade-offs considering both social and ecological aspects and the values of different people, while counteracting uneven power relations among actors (Ellis et al., 2019). Other recent examples involve nature-positive scenarios based on the Future Nature Framework (Pereira et al., 2020).

Here, a research gap emerges as well: Chapter 6 of the APCC Special Report on land use and climate change (Jäger et al., 2024) concludes that in the field of emission develop-

ments of the LULUCF sector, there are hardly any cross-sectoral scenario analyses that quantify and map the different land use types and their feedbacks on other sectors for Austria (Jäger et al., 2024). This gap has not yet been filled, but such scenario analyses would be of great importance for the development of a climate protection strategy in the area of land use in Austria and for the analysis of possible land use conflicts between sectors.

Transforming or building new structures is seen as essential to achieving climate goals (Aigner et al., 2023). A holistic view of the agri-food sector, for example one that looks at farmers' land use decisions, the structure of the food industry, the retail sector and consumer demand in an integrated way (Meynard et al., 2017), proves to be beneficial (*high confidence*), as noticed in Chapter 6 of the APCC Special Report on land use and climate change (Jäger et al., 2024) and the APCC Special Report on climate-friendly living (Penker et al., 2023). Adoption also depends on whether the envisaged measures are in line with the values and goals of the farmers, foresters and other entrepreneurs (de Sainte Marie, 2014; Schermer et al., 2018; Walder and Kantelhardt, 2018) and if schemes exist to compensate land users for their additional

expenses, since market compensation is often not given due to the public-good-character of ecosystem services.

Literature shows that substantial progress can be made when transformation pathways are developed together with the land users (Kraxner et al., 2017; Berthet et al., 2019; Meyfroidt et al., 2022). There is *high confidence* that stakeholder involvement in policy development is a prerequisite for effective implementation of climate policies (e.g., Renn, 2006; Newig et al., 2008; O'Faircheallaigh, 2010; Prutsch et al., 2018). For government policies to be effective in practice, their implementation by firms is a key precondition and thus needs a systemic design of government measures (requirements, processing, information, advice, documentation effort, conditions attached to subsidies) (Van Herzele et al., 2013; Darnhofer et al., 2017). Furthermore, it is important to note that many regulations that farmers or forest owners must adhere to are formulated not only by the government but also by private companies. Therefore, the establishment of a governance system that includes all participants in the value chain is essential, warranting a fair exchange of information and a balanced distribution of power within the chain.

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