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Review

Past and future impacts of land-use changes on ecosystem services in Austria

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ABSTRACT

Environmental and socio-economic developments induce land-use changes with potentially negative impacts on human well-being. To counteract undesired developments, a profound understanding of the complex relationships between drivers, land use, and ecosystem services is needed. Yet, national studies examining extended time periods are still rare. Based on the *Special Report on land use, land management and climate change* by the Austrian Panel on Climate Change (APCC), we use the Driver-Pressure-State-Impact-Response (DPSIR) framework to (1) identify the main drivers of land-use change, (2) describe past and future land-use changes in Austria between 1950 and 2100, (3) report related impacts on ecosystem services, and (4) discuss management responses. Our findings indicate that socio-economic drivers (e.g., economic growth, political systems, and technological developments) have influenced past land-use changes the most. The intensification of agricultural land use and urban sprawl have primarily led to declining ecosystem services in the lowlands. In mountain regions, the abandonment of mountain grassland has prompted a shift from provisioning to regulating services. However, simulations indicate that accelerating climate change will surpass socio-economic drivers in significance towards the end of this century, particularly in intensively used agricultural areas. Although climate change-induced impacts on ecosystem services remain uncertain, it can be expected that the range of land-use management options will be restricted in the future. Consequently, policymaking should prioritize the development of

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integrated land-use planning to safeguard ecosystem services, accounting for future environmental and socio-economic uncertainties.

1. Introduction

The planet's terrestrial surface is largely used for agriculture, forestry, and urban purposes, including infrastructure, industrial and residential buildings (IPCC et al., 2019). Land use is defined as "the total of arrangements, activities, and inputs that people undertake in a certain land cover type" (FAO, 1998), and it has always been adapted to the people's needs (Ellis et al., 2021). However, land-use changes have never been as dynamic as post the 1950ies, after the switch to fossil energies (Krausmann et al., 2003), transforming natural ecosystems towards intensively used agricultural land and built-up areas (Hansen et al., 2022; van Vliet et al., 2015). Socio-economic changes, including population growth, increased globalization, urbanization, changes in supply, demand and trade patterns, technological advances, dietary habits, or public opinion are considered to cause major changes in land use and farming practices (Beyer et al., 2022; Schaller et al., 2018; Schulp et al., 2019; Subedi et al., 2022). Yet, land-use changes can usually not be attributed to one single driver, but are a complex interaction of the climate, politics, and socio-economic conditions (Plieninger et al., 2016; Ustaoglu and Williams, 2017). In addition to significantly influencing the current and future climate of our planet (Tattoni et al., 2017), such transitions have major impacts on biodiversity (Powers and Jetz, 2019) and human well-being by altering crucial ecosystem services (García-Nieto et al., 2018; Gomes et al., 2021). For example, changes in living standards increase the demand for outdoor recreation (Buckley et al., 2015), while urbanization and agricultural intensification impact the provision of ecosystem services, such as climate regulation, flood mitigation, and erosion protection (Schirpke and Tasser, 2021; Stürck et al., 2015). Moreover, changes in land management practices are often introduced for short-term purposes, such as to increase agricultural productivity, but they can have long-term impacts on the provision of ecosystem services due to legacy effects, e.g., on disturbance of forest ecosystems (Munteanu et al., 2015; Weiss et al., 2020).

In Europe, policy measures and regulations at different governance levels directly and indirectly influence land use, for example, through public payments (Ustaoglu and Williams, 2017). However, spatial planning frameworks and instruments have proved largely ineffective in many European countries (e.g., Getzner and Kadi, 2020). A deeper understanding of land-use change processes and their impacts on ecosystem services is required to develop sustainable land-use management responses and policies as well as to effectively integrate ecosystem services into decision-making (Mandle et al., 2021). In recent years, progress has been made to embed ecosystem services in various European policies, e.g., the Green Infrastructure Strategy, the EU Biodiversity Strategy for 2030, the EU Forest Strategy, and the Regulation on the prevention and management of the introduction and spread of invasive alien species (IAS) (Bouwma et al., 2018). The future Common Agricultural Policy (CAP) also aims to explicitly support ecosystem services that are important to agricultural productivity, such as pollination, pest control, and soil fertility (Guy et al., 2021). However, the effectiveness of these policies still needs to be evaluated.

Land-use governance is organized in the individual countries, attributing different responsibility and power to national, regional and local authorities (Getzner and Kadi, 2020). In Austria, for example, land policy is organized within a federal policy system with nine federal states, resulting in nine regulations for spatial planning, nature protection, housing policy, flood risk management etc. with different or even contradictory goals and strategies. The Austrian spatial planning system also attributes strong power to local authorities, which have the right to determine local development and zoning plans, while regional planning remains 'weak' or (in some cases) inexistent (Getzner and Kadi, 2020). Consequently, the Austrian land policy is characterized by topographic restrictions in mountain regions, socio-economic and socio-demographic disparities and regional and local policy decisions. The lack of national regulations has resulted in high land conversion to permanent settlements, with Austria positioning itself as a leader in Europe (Getzner and Kadi, 2020; Umweltbundesamt, 2021). An analysis of the drivers, land-use changes, and impacts on ecosystem services at the national level can therefore reveal both general trends at a larger level (i.e., at national and European level) as well as the trends within the political boundaries of a country (i.e., at regional and local level). Such knowledge is key support for international negotiations addressing pressures from global change as well as for national and regional decision-making to scope with land-use changes resulting from environmental and socio-economic changes.

However, most studies examining the relationships between drivers of land-use changes and impacts on ecosystem services were conducted at continental or global scales (Hanaček and Rodríguez-Labajos, 2018; Polce et al., 2016; Schaller et al., 2018; Subedi et al., 2022) or at local or regional scales (e.g., García-Llamas et al., 2019; Schirpke et al., 2020). Studies combining empirical research of the past changes with future scenarios over several decades or centuries are still rare, despite their importance in capturing slow social-ecological processes and time lags between land-use changes, ecosystem state changes and related impacts on ecosystem services (Dearing et al., 2010; Requena-Mullor et al., 2018). For example, an intensive agricultural land use alters long-term ecological processes, affecting the provision of ecosystem services even after land abandonment (Bürgi et al., 2017), or natural reforestation of abandoned grassland in mountain areas can take several decades to centuries (Tasser et al., 2017). Another limitation of studies addressing relationships between land-use changes and ecosystem services is their focus on specific land-use types (Kirchner et al., 2015; Thom and Seidl, 2016) or a limited number of ecosystem services (Stürck et al., 2015).

This paper synthesizes past and future land-use changes and their impacts on ecosystem services in Austria using a long-term time horizon. It builds on the findings of a formal expert reporting to assess socio-economic and climatic drivers of land-use change in Austria as part of the *Special Report on land use, land management and climate change* by the Austrian Panel on Climate Change (APCC) [1]. This comprehensive report was written in German to provide a well-grounded knowledge basis for decision-making at country-level. We synthesize the main findings of Chapter 3 focusing on 'socioeconomic and climatic drivers of change of land use in Austria' to make the findings accessible to an international audience. We use a Driver-Pressure-State-Impact-Response (DPSIR) framework to (1) collect the main drivers of change for the three prevailing land use types, (2) describe major land-use changes in Austria reported for the past (1950–2022) and future (until 2100), (3) report the related impacts on ecosystem services, and (4) discuss responses by societal actors. Austria reflects socio-economic and political developments that are typical for Central Europe, while covering a variety of biogeographical regions, such as intensively used agricultural lowlands, forest-dominated areas, terrestrial and aquatic ecosystems of high ecological value, and high mountain regions. Austria became member of the European Union (EU) in 1995, and the implications of EU policies are relevant for other member states as well. Moreover, Austria has membership in several international institutions actively engaged in developing, monitoring and evaluating (agricultural) policies, such as

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[1] https://ccca.ac.at/en/climate-knowledge/apcc.

the World Trade Organization (WTO), the Organization for Security and Cooperation in Europe (OSCE), and the Food and Agriculture Organization of the United Nations (FAO). Therefore, our findings provide important insights into general relationships that are largely transferrable to other European countries, while also reporting on more specific impacts in different biogeographical contexts.

2. Material and methods

2.1. Study area

Austria is located in Central Europe (Fig. 1) and has around 9 million inhabitants (Statistik Austria, 2023). It covers a surface of 84,000 km^2. About half of the Austrian territory is covered by forests, of which 82% belongs to private entities and 18% is owned by public bodies (BFW, 2016). One third of the Austrian territory is agricultural land, mostly comprising arable land (1.4 million ha) and permanent grassland (1.3 million ha) (EEA, 2018). The permanent grassland is almost equally divided between intensive grassland (high fertilization, more cuts) and low-intensity grassland (single-cut meadows, litter meadows, alpine pastures, and mountain meadows). Urban areas occupy almost 7% of the Austrian territory and about 10% is not used, i.e., mainly covered by rocks, glaciers, scree slopes, sparsely vegetated areas, and wetlands (EEA, 2018). Since the 1960s, the forests have increased by about 10%, resulting from afforestation or natural reforestation of abandoned agricultural land (BMK, 2022; Russ, 2019). In contrast, agricultural land has decreased due to abandonment in less favourable areas, or due to land requirements for settlements and infrastructure. The urban area has nearly doubled in the last 50 years, which is far above the European average (BMK, 2022).

The climate is characterized by pronounced seasonal variation and spatial heterogeneities due to Austria’s location in Central Europe and its topography (i.e., elevation ranges from about 100 m to 3800 m above sea level). The annual mean temperature ranges from 12 °C in warm lowland regions to −6 °C in the Central European Alps. As maritime air masses also influence the climate, precipitation patterns are complex, with mean annual precipitation varying from 450 mm in eastern Austria to more than 2500 mm in the Central European Alps (Matulla et al., 2003). Spring and summer temperatures have increased by about 2 °C over the last 40 years compared to the 1961–1990 mean, while there is no clear trend in precipitation patterns (Auer et al., 2007).

2.2. APCC Special Report

The *Special Report on land use, land management and climate change* (https://ccca.ac.at/wissenstransfer/apcc/special-reports/srland) by the APCC systematically collected, summarized and assessed the state of knowledge on land use and climate change in Austria to support the public with a well-founded basis for decision-making. The APCC adopted an open process facilitating and integrating contributions by the interdisciplinary community of Austrian researchers and experts in the field of land system science, such as agriculture, livestock management, forestry, economics, geography, hydrology, ecology, chemical and physical soil processes research, climate, spatial planning. The report was compiled following the established procedures and quality criteria of the International Panel on Climate Change (IPCC) as well as the APCC. The main quality criteria included (1) a comprehensive coverage of the topics, combining knowledge of grey and peer-reviewed literature from Austria and, where relevant, international research, (2) the inclusion of the interdisciplinary scientific community that is active on land use, land management and climate change, (3) the inclusion of relevant stakeholders in the process of report development, and (4) a rigorous, transparent, and fully documented review process.

The review process comprised four major stages, which were structured along the development of drafts (from the Zero-Order-Draft to the final draft) and reviewing processes, accompanied by author workshops, an open discussion platform, and stakeholder meetings (Fig. S1). During the scoping phase, in which the Zero-Order-Draft was developed, the content and structure of the report were defined and internally reviewed by the author team. After revising the Zero-Order-Draft, a First-Order-Draft was sent to external review conducted by recognized national and international scientific experts who are active in the field. The external review involved more than 50 Austrian stakeholders and experts from academia (e.g., universities and research institutes) and non-academic organizations (e.g., NGOs and public administration). The author team then integrated all comments of the external reviewers, recorded for each comment how it was taken into account, and prepared a Second-Order-Draft. The quality of the Second-Order-Draft was assessed by Review Editors, evaluating how the reviewer comments were incorporated. This second review included international experts from academia and non-academic organizations. The final report was prepared after all Review Editors and the APCC steering committee agreed that all comments had been incorporated appropriately. The writing and review process of the report took place between November 2019 and July 2022.

The literature for this report included peer-reviewed scientific

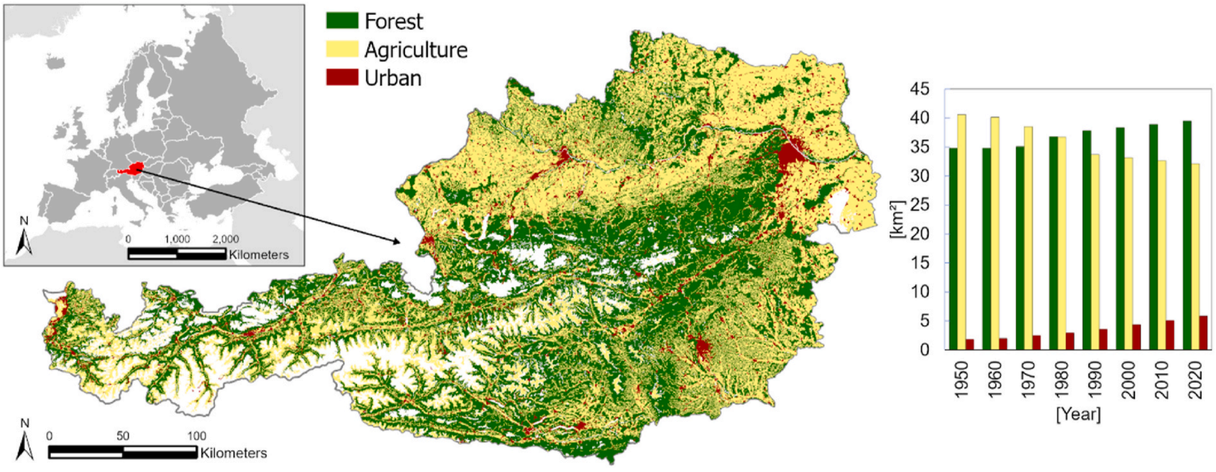

Fig. 1. Location of Austria in Europe (map inlet) and spatial distribution of the three land-use types in 2018 (i.e., forest, agriculture, urban) aggregated from CORINE Land Cover 2018; EEA, 2018; for aggregation of land-use types, see Table S1). White areas in the map include water and not used land cover types. Right: Changes over time in the spatial extent of forest, agriculture, and urban land. Data source: Statistik Austria (www.statistik.at).

papers, books, and grey literature published in English or German (see supplementary material). The inclusion of grey literature was necessary, as a lot of research based in Austria has not been published in scientific journals. The selection process of the literature was based on a) individual web-searches of each author in Scopus, Web of Science and Google Scholar, b) a forward/backward snowballing method (Wohlin, 2014), and c) internal and external suggestions by co-authors and external reviewers during the four reviewing stages. The findings were evaluated by the authors of the report based on the uncertainty language framework developed under the IPCC framework in terms of evidence and agreement (Fig. S2; Kause et al., 2022; Mastrandrea et al., 2010). According to the IPCC framework, evidence refers to the type, amount, quality and consistence of independent sources. To indicate the level of evidence, the authors of the report evaluated whether there were one or more case studies reporting changes/impacts based on a sound research approach and/or supported by qualitative/quantitative data. The level of agreement indicates whether different studies report the same or contradictory results. Evidence and agreement were indicated using three levels (low, medium, and high). To reduce subjectivity in the application of the uncertainty language, the evaluation was discussed among the authors who contributed to the same section of the report and reviewed during the four reviewing stages.

2.3. Conceptual approach and analysis

Chapter 3 of the report addresses socioeconomic and climatic drivers of land-use change in Austria, focusing on the three land-use types that cover most of the Austrian territory: agriculture, forestry, and urban (Fig. 1). All authors of this paper contributed to Chapter 3, which involved 27 authors for the report. To conceptualize the cause-effect relations regarding land-use changes and related impacts on ecosystem services, we restructured the contents of Chapter 3 along the DPSIR framework (Fig. 2). Based on approaches that integrate ecosystem services into a DPSIR framework (Balzan et al., 2019; Moss et al., 2021; Rounsevell et al., 2010), we define the DPSIR components as follows. **Drivers** refer to the highest level of causes for change resulting from anthropogenic activities. Key drivers include socio-economic developments, such as changes in demography and the global economy (Schaller et al., 2018) as well as human-induced climate change (Haque, 2023). These drivers create **pressures** on the biotic or abiotic characteristics of an ecosystem, e.g., increasing temperatures or changing precipitation patterns can cause desertification or reduce productivity (Stringer et al., 2021), or profit-oriented management of forests alters species composition (Johann, 2007). Consequently, these changes lead to **state** changes of land use types, which affect the capacity of ecosystems to provide benefits to people (Jones et al., 2016; La Notte et al., 2017). These state changes can result in positive and negative **impacts** on individual or multiple ecosystem services (Gomes et al., 2021; Polce et al., 2016). For example, the intensification of agricultural land use, primarily focusing on maximizing the net returns from agricultural production, may have negative effects on ecosystem services, such as climate regulation, erosion prevention, and flood mitigation, as well as opportunities for recreational and aesthetic experiences (Turkelboom et al., 2018). To counteract undesired impacts, **responses** are taken by societal actors or groups of actors relating to the drivers, pressures, state changes, and impacts through management practices, adaption and mitigation measures, and policies. For example, an increase in the frequency and magnitude of environmental hazards may require engineering measures (Bonazza et al., 2021), or certain management practices need to be adopted to reduce the risk of agricultural and forest insect pests (Jactel et al., 2019; Skendžić et al., 2021).

We identified the main drivers of change based on findings presented in the report. For this purpose, we screened the report and recorded the drivers for each land-use type. We grouped the drivers into the following five driver categories based on Balvanera et al. (2019):

(1) **Economic drivers** summarize all activities within the economic system, including international trade, and the transformation of the economic sectors during the past decades. Economic drivers were demonstrated to be strong for past decisions on land-use change, pushing deforestation, agricultural intensification, urbanization and even reforestation, e.g., the REDD + program (Malek et al., 2019).

(2) **Social changes** reflect the changes in individual standard of living and social prestige, such as habits of consumption for food, clothing, housing, and transport. Overall, social changes focus on the demand side of land-use changes (Antrop, 2004; Schulp et al., 2019) and are closely related to the economic drivers. For example, as people gain wealth, they can change their standard of living towards increasing their meat consumption, with

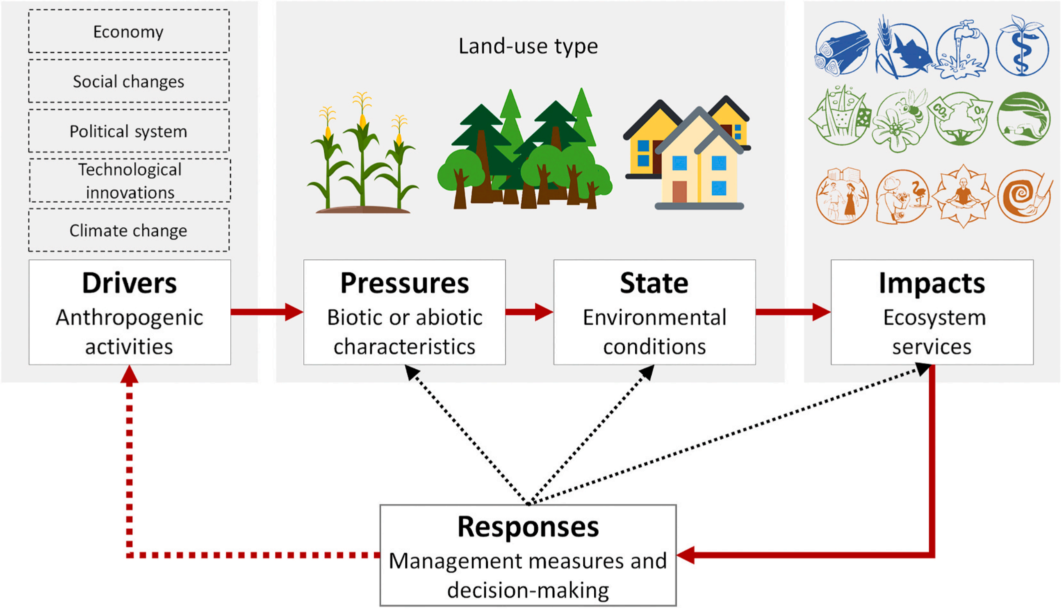

Fig. 2. Driver-Pressure-State-Impact-Response (DPSIR) framework used to assess the impacts of multiple drivers on three major land-use types (agriculture, forestry, and urban) and related ecosystem services from past to future (1950–2100). Icons for ecosystem services by Jan Sasse designed for TEEB.

tremendous impacts on land use (Luzzani, 2022). Furthermore, the demand for artificial surfaces used for housing, offices, or places for leisure increases (Antrop, 2004; Getzner and Kadi, 2020; Schulp et al., 2019) as well as for new infrastructure such as streets, railways, airports, canals and energy lines (Salvati et al., 2018; Zoomers et al., 2017). Here, we also include socio-cultural and socio-demographic changes such as population size and level of education.

(3) The **political system** (governance) summarizes the formal rules, policy strategies, and policy instruments within the different national, regional, and local authorities (Deslatte et al., 2022). Policy strategies can directly influence land use, such as natural hazard risk management or renaturation of wetlands (Ammann et al., 2006). Policy instruments, such as regulations, taxes, and financial subsidies, can have considerable impacts on land-use changes, as demonstrated by regulations that prevent the conversion of farmland to urban land (Ustaoglu and Williams, 2017) or public payments within the European Common Agricultural Policy (Primdahl et al., 2013).

(4) **Technological innovations** include a wide range of developments, such as digital farming and water-efficient irrigation systems, but also innovations in the transport or housing sectors (Seppelt et al., 2022). This allows, e.g., transforming agricultural land into highly productive croplands, like sugar beet, or maize. Innovations may lead to efficiency gains and reduce negative environmental impacts but may stimulate economic growth with corresponding rebound effects.

(5) **Climate change** (e.g., temperature increase and variations in precipitation patterns) influences land use. A warmer climate, for example, can encourage the expansion of agricultural areas into higher altitudes, but, at the same time, it may lead to the abandonment of agricultural land where precipitation is insufficient (Ramankutty et al., 2002; Stringer et al., 2021).

The pressures resulting from the main drivers and related state changes for the three land-use types agriculture, forestry, and urban were synthesized from the report adopting the following approach. We first screened the report for statements with a high level of evidence (Fig. S1) to focus on the most important drivers. This information was discussed among all authors to agree on the selection of relevant statements. Finally, the selected statements were ordered from past to future and along the driver categories.

Similarly, we summarized the impacts on ecosystem services caused by land-use changes, selecting the most relevant statements from the report, as indicated by a high level of evidence. Direct impacts on ecosystem services originating from climate change or changes in the demand for ecosystem services were not included. While pressures and state changes focused on each land-use type separately, impacts on ecosystem services also considered changes in spatial land-use patterns. Such changes are important to consider, as they can induce a shift in ecosystem services and reveal trade-offs and synergies (Egarter Vigl et al., 2016). For example, the expansion of cropland usually favours provisioning services, such as food and forage production, while an increase in forest area mostly leads to an increase in regulating services such as climate regulation and mitigation of hazards (Schirpke and Tasser, 2021). Responses are presented in the discussion section.

3. Results

3.1. Main drivers of land-use changes

Table 1
Main drivers identified for the three land-use types in Austria based on the assessed literature.

Driver category	Agriculture	Forestry	Urban
Economy	Globalization of markets Off-farm income Operating costs	Demand for forestry products and energy Operating costs	Economic growth Industrialization Living expenses
Social changes	Demand for (regional) food, feed and energy Labour markets	Interests of forest owners	Socio-demographic and lifestyle changes Demand for living space Demand for energy Demand for transportation Labour markets
Political system	Agricultural policies and reforms Transfer payments Nature conservation policies	Energy policy Nature conservation policies	Infrastructure and urban planning Urban sprawl Natural hazard planning
Technological innovations	Livestock breeding Irrigation Pesticides Fertilisers	Harvest technologies Biotechnology	(Renewable) energy production technologies
Climate change	Vegetation period Risk and damage potential	Forest disturbances (e.g., bark beetle, drought)	Temperature increase Risk of natural hazards

All driver categories were relevant for the three examined land-use types. However, main drivers partly differed among the three land-use types (Table 1). In terms of economy, for example, the globalization of markets was identified as major driver for agriculture, while industrialization was more relevant for urban areas. Changes in the labour market induced shifts or changes in agriculture and urban areas, while being less important for forestry. Moreover, the importance of individual drivers can differ regionally depending on biogeographical and socio-economic conditions, i.e., mountain areas vs. lowlands, rural vs. urban areas, or northern vs. southern regions of Austria. Land-use changes are generally influenced by multiple drivers, and interactions among different drivers may be cumulative or may prevent land-use changes (van Vliet et al., 2015). Moreover, recent drivers may have been neglected, if they do not yet appear in the literature pertaining to Austria, e.g., technological innovations enabling multiple land uses, such as double cropping or agri-photovoltaics (Gorjian et al., 2022).

3.2. Past and future land-use changes

3.2.1. Agriculture

After the Second World War, Austrian agricultural policy primarily focused on domestic food supply at reasonable consumer prices, and on securing the income of people working in agriculture through minimum agricultural commodity prices and public payments (Krausmann et al., 2003). In addition, technological progress based on fossil fuels was promoted to increase productivity, e.g., irrigation, breeding, synthetic fertilisers, and pesticides (Krausmann et al., 2003). These fundamental changes resulted in an intensification of agricultural land use during the 20th century (Erb et al., 2008). Increasing support for the second pillar of the Common Agricultural Policy (CAP) with a focus on rural development, starting in 1992, and for ÖPUL (Austria's subsidy program for environmentally friendly agriculture) slowed down the intensification of agricultural land and led to lower nitrogen inputs in agricultural cropping systems (Umweltbundesamt, 2019). When Austria joined the European Union in 1995, low commodity prices were replaced by direct payments (Eickhout et al., 2007). The reduction of trade barriers and the decoupling of agricultural subsidies, i.e., direct payments per hectare instead of transfer payments coupled to specific commodities (e.g., wheat, milk), led to greater integration into the world market, lower prices, and efficiency gains (i.e., efficient use of resources per labour unit). The structural change in the agricultural sector caused a decrease in the number of farms but increased average farm size and capital intensity, while marginal areas (e.g., pastures, steep cultivated areas) were less intensively used or abandoned (Flury et al., 2013). Consequently, the grassland area decreased from 4.3 million ha in 1926 to 1.3 million ha in 2000, while arable land declined from 3.4 million ha to 2.2 million ha over the same period (Erb et al., 2008). Especially the Southern Limestone Alps and the Western Alps were characterized by extensive land abandonment after 1960 (in some areas, only around 25% of the formerly cultivated areas are still managed as agricultural land), while the Central Alps and the Northern Limestone Alps were far less affected by structural change. Yet, agriculture has been intensified in easily accessible and climatically favourable locations in the lowlands and on the hillslopes of the Alps.

Changes in agricultural land use have been strongly influenced by changes in seasonal precipitation and temperature patterns as well as changes in the frequency and intensity of extreme weather events (Fig. 3; Eitzinger and Kersebaum, 2016; Thaler et al., 2012). The vegetation period has increased by 20–26 days since the mid-19th century to 212 days in 2010 (Tasser et al., 2013). The strongest increase was measured in the lowlands of northern and eastern Austria (up to 20 days) and in higher mountain and valley locations along the Italian border (Tasser et al., 2013). Between 1951 and 2018, phenological trends of leaf bursting and flowering in agricultural crops and wild plants occurred on average 2.24 days/decade earlier (Menzel et al., 2020), leading to changes in the plant and region-specific growth periods and altered sowing and harvest dates (Eitzinger and Kersebaum, 2016). Simulations for a range of climate scenarios indicate that dry conditions may have negative impacts on crop yields (Fig. 3), especially in semi-arid regions such as eastern Austria (Kirchner et al., 2015, 2016; Schönhart et al., 2018). Extreme weather events cause a high risk and damage potential for crop yields (Eitzinger, 2019). In humid regions, agricultural production may increase due to higher temperatures (Jäger et al., 2020; Schönhart et al., 2018) and create new possibilities, for example, expanding vineyards and orchards, or cash crop farming to higher elevations (Eitzinger and Kersebaum, 2016). Overall, uncertainty and multi-annual variability of crop yields increase with climate change (Balkovič et al., 2018).

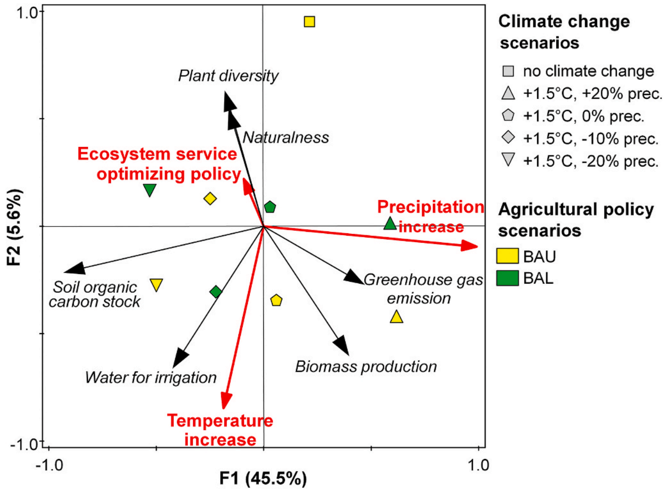

Fig. 3. Impacts of climate change scenarios (indicated in percentage change compared to 2008) on key ecosystem services under two agricultural policy scenarios until 2040. The business-as-usual scenario (BAU) depicts the CAP post-2013 reform, while the balanced ecosystem service scenario (BAL) aims at increasing the level of ecosystem services. The figure shows the triplot of the Redundancy analysis (RDA) illustrating the relationships (trade-offs and synergies) between different drivers (red vectors), state changes (symbols), and impacts on ecosystem services (black vectors). The length of the vectors indicates the degree of the factor loadings (i.e., the longer, the stronger) and the angle between the vectors represents the correlation among them. The x-axis (F1) is characterized by a precipitation gradient (from low to high precipitation). The y-axis (F2) is characterized by a gradient in intensity of use (from low to high intensity), indicating a trade-off within the agricultural intensification (biomass production is negatively correlated to ecosystem service optimizing policy). The statistical analyses were performed with the software package Canoco 5.0 (www.canoco5.com). Data source: Kirchner et al. (2015); see also Table S2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2.2. *Forestry*

During the 19th century, forests expanded again after a long period of deforestation due to the change from subsistence to an industrialized economy (Fig. 1) (Erb et al., 2008; Rudel et al., 2005). The replacement of firewood and charcoal with fossil fuels, the abandonment of (marginal) agricultural areas, fodder and food imports, and the reduction of secondary agricultural uses in forests reduced the use of forest resources and led to forest expansion (Flury et al., 2013; Gingrich et al., 2007), particularly at higher elevations on abandoned alpine pastures and meadows (Russ, 2019). Although forest expansion has decelerated since 2008, forest area increase has still been, on average, about 2300 ha per year. Standing timber stocks also increased over time. While the first National Forest Inventory in 1961–70 recorded a standing timber stock of 780 million solid cubic meters, the latest inventory in 2016–21 estimates standing timber stocks of 1180 million solid cubic meters (BFW, 2022; Gschwantner, 2019). The latter corresponds to average stocks per hectare in production forests of approximately 241–351 solid cubic meters. In particular, stocks close to former mines have strongly increased (Niedertscheider et al., 2017). Furthermore, social structural changes often caused a transition from “traditional” forest owners, who generated an (additional) income from the forest, to “forest-distant” forest owners, who sometimes have different or no interest in their forests with regard to wood supply (Hogl et al., 2003).

In addition to advances in harvesting technologies and improved access to forest areas due to better infrastructure, forest management has changed in Austria. In the 19th century, a profit-oriented forest management resulted in artificial forest regeneration, stand maintenance, and intensified cultivation of conifers to maximize yields (Johann, 2007). The occurrence of Norway spruce and Scots pine has been expanded beyond their natural distribution range, mainly in the lowlands and foothills of the Alps (Gschwantner and Prskawetz, 2005). This deliberate promotion of high-yielding tree species significantly boosted growth in the past century (Katzensteiner and Englisch, 2007), but it also led to a widespread increase in monocultures at the expense of mixed broadleaved forests. While the majority of Austrian forests has been managed with the primary goal of achieving economic benefits, only 0.8% of them is dedicated to securing natural forest dynamics including the conservation of biodiversity (Schwarzl and Aubrecht, 2004). In recent years, the demand for forest products has been rising and is expected to further grow, for instance, for construction wood and heating pellets (Strimitzer et al., 2021). Harvests on average account for almost 90% of the annual volume increment, but future productivity may decrease as the proportion of older stands and the proportion of slower-growing deciduous tree species has increased (BFW, 2022; Gschwantner, 2019). The former is a result of historical management practices, specifically the establishment of Norway spruce plantations after World War II, while the latter is driven by climate change and forest conversion aimed at enhancing forest adaptability.

Increases in atmospheric CO_2 concentration, nitrogen deposition, and temperatures have improved the growth and expansion of Austrian forests (Jandl et al., 2012). Yet, it is possible that forests acclimate towards increased CO_2 levels. Thus, CO_2 may only have a minor effect on growth in the longer term, and the high nitrogen deposition may no longer promote growth due to the lack of other soil nutrients (Klein et al., 2016). Moreover, decreasing water availability reduces tree growth, especially at low-elevation sites (Fig. 4; Ols et al., 2019). Climate change has increased disturbance activity of all agents with

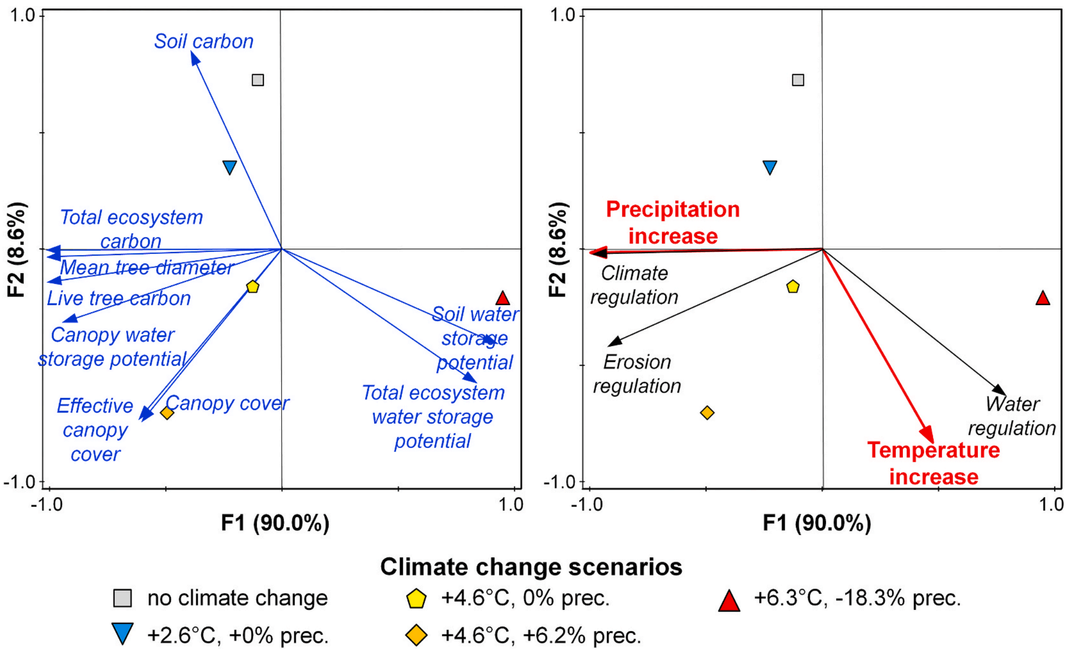

Fig. 4. Impacts of climate change scenarios on ecosystem functions (left) and the supply of key regulating ecosystem services (right) of forests over the next 200 years. Results pertain to landscape development implementing current management recommendations, with natural disturbances being dynamically simulated. The figure shows the triplot of the principal component analysis (PCA) illustrating the relationships (trade-offs and synergies) between drivers (red vectors), state changes (symbols), pressures (blue vectors), and impacts on ecosystem services (black vectors). The length of the vectors indicates the degree of the factor loadings (i.e., the longer, the stronger), and the angle between the vectors represents the correlation among them. The x-axis (F1) is characterized by a precipitation gradient (more precipitation is negatively correlated), while the y-axis (F2) is characterized by a temperature gradient (lower temperature increase is positively correlated). The biplots of the principal component analysis (PCA) were performed with the Canoco 5.0 software package (www.canoco5.com). Data source: Seidl et al. (2019); see also Table S3. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

global importance, except disturbances from snow and ice (Patacca et al., 2022). In Austria, significant climate change-induced increases in bark beetle disturbance are expected during the 21st century (Thom et al., 2017), but susceptibility varies strongly across the country. That is, warm regions with high proportions of spruce, such as southern Styria and Upper Austria, are more prone to bark beetles than other regions of Austria (Thom et al., 2013). An increasing frequency and intensity of droughts will reduce tree vigour, amplifying the impacts of bark beetles (Seidl et al., 2017). Norway spruce is the least resistant major tree species to drought in Central Europe (Thom et al., 2023). As water stress intensifies, the protective mechanisms of spruce trees against bark beetles or other disturbance agents become compromised (Netherer et al., 2015). Changes in the wind regime caused by climate change remain subject to high uncertainty (Matulla et al., 2008; McInnes et al., 2011), but even a small increase in wind gust speed may elevate disturbance amounts disproportionately strong (Thom et al., 2017). Combined with subsequent bark beetle calamities, increases in wind disturbance may greatly reduce the carbon sink or even turn forest landscapes into carbon sources (Albrich et al., 2022).

3.2.3. Urban

Between 1950 and 2021, socio-demographic structures changed considerably due to population growth, migration, and increased income (+23.2% inhabitants, and +44.8% households). In addition, the desire for a "house in the countryside", which was supported by housing subsidies, dense road networks and lower land prices in the outskirts of cities and rural areas, has driven a growing demand for residential building space in the communities around cities (Gaube and Remesch, 2013; Getzner and Kadi, 2020). Growing economic activities (production, services, especially logistics, storage, and trade) have also led to an expansion of industrial and commercial spaces, mostly in the outskirts of cities due to the large space requirements for buildings and parking lots, the better accessibility (motorway/railway connection) as well as the lower land prices for construction (Loibl et al., 2018). A total of 5729 km^2 of land was "consumed" for settlements and infrastructure by 2019, corresponding to 7% of the country's area and 18% of the permanent settlement area (Umweltbundesamt, 2021). The settlement area has almost doubled in the last 50 years, while the settlement growth is declining in peripheral regions since 2001 (Umweltbundesamt, 2021). Since 2009, the growth in settlement areas has been slowed down because of urbanization processes. The area used for road construction was between 4 and 14 km^2 per year in recent years with a declining trend (5.5 km^2 in 2019) (Umweltbundesamt, 2021).

In the future, the number of households is expected to continue to rise due to the increase of one- and two-person households, single parents, and childless couples as well as people with multiple residences (multi-local lifestyles) (www.statistik.at). As a result, the number of dwellings is expected to increase – from around 3.97 million (2020) to 4.47 million (2050) (www.statistik.at). In Vienna and in some of the regional capitals, the population is growing just as steadily as in the outskirts of the city due to the positive immigration balance. This agglomeration in urban regions may lead to a spatial redistribution of the population between urban agglomerations and (near-urban) rural areas in the future due to the different (tourist and landscape) attractiveness and development potential of rural regions (Arnberger et al., 2018). The growing energy demand (e.g., owing to increased and new mobility needs of new residents) as well as developments in information and communication technology, requires new infrastructures and leads to the exploitation and sealing of ecosystems. About 80 ha of land are sealed each year representing an average of about 8.5% of the annual land take over the past decade (EEA, 2022). Both conventional thermal power plants as well as wind and PV farms and hydroelectric power plants require large open spaces. While the possibilities for building large hydroelectric power plants in Austria have largely been exhausted, wind energy and photovoltaics are key renewable energy technologies with great growth potential. Even if photovoltaic systems are mainly installed in built-up areas (roofs, facades, etc.), agricultural areas or grassland are increasingly being considered (Fina et al., 2020). Increasing temperatures are expected to further influence settlement development. In the case of Vienna, the trend of summer days (SU: $T_{max} \geq 25$ °C) increased from 52.1 SU y^{-1} for the period 1961–1990 to 64.1 SU y^{-1} for the period 1981–2010, with strong indications to increase over the next decades (Žuvela-Aloise et al., 2016). Furthermore, an increase in multi-localities (i.e., second home residential buildings) as well as in tourism infrastructure for the summer retreat due to higher temperatures can be expected in the rural communities (Pröbstl-Haider et al., 2021). Climate change will also lead to an increase in intensity and regularity of natural hazards in urban areas, such as heavy rainfall and flood events (Fig. 5), which are intensified by increasing soil sealing, storms, avalanches and mass movements (IPCC, 2022). In mountain regions, this results in considerable risks for settlements and infrastructures.

3.3. Impacts of land-use changes on ecosystem services

Land-use changes induced shifts in ecosystem services (Kirchner et al., 2015; Schirpke et al., 2020). For example, the large-scale abandonment of mountain grassland led to the reduction or even loss of ecosystem services that are typically associated with grasslands, such as fodder production and aesthetic values (Lavorel et al., 2017). In contrast, reforestation increased forest ecosystem services such as timber production, wild food production (e.g., mushrooms, berries), and climate regulation (Egarter Vigl et al., 2016; Schirpke et al., 2020). Less intensive agricultural land use increased landscape multifunctionality, which had positive effects on the touristic use, local identity and quality of life as well as ecological functions (Huber et al., 2020; Schirpke et al., 2020). However, the decrease in landscape diversity and complexity along with the increase in forest area led to reduced aesthetic values (Getzner, 2020). Despite efforts to maintain the traditional landscape's authenticity and to avoid undesired landscape changes (Penker, 2009), the cultural landscape has been strongly urbanized with negative impacts on landscape scenery (Sklenicka et al., 2014). The decline in agricultural land, the increase in forest areas and urban sprawl in Austria during the past 20 years induced large-scale trends in ecosystem services – a decline across all ecosystem service categories, in particular in provisioning ecosystem services in the northern hillslopes and highlands, in the Southern Alps with the Klagenfurt Basin as well as in the Central Alps (Fig. 6). Some positive changes occurred for single ecosystem services; mostly for agricultural food production in almost all biogeographical regions, for some regulating services (e.g., provision of habitats, maintaining biodiversity, and providing habitats for pollinating insects) in the Pannonian plains and hills and Southern Alpine foothills, as well as for cultural heritage in many regions (Table S2).

In the future, a spatial shift of dominating ecosystem services can be expected. Regulating ecosystem services will continue to gain importance due to progressing climate and land-use change leading to an expansion of forest areas at higher elevations (Getzner et al., 2017; Tasser et al., 2017). However, ecosystem services provision of non-adapted forests may be limited in the next decades due to the increase in disturbances (Fig. 4; Albrich et al., 2022; Seidl et al., 2019), reducing the positive effects of forest on climate regulation (Seidl et al., 2017; Thom et al., 2020). In contrast, lowland areas will likely focus on provisioning ecosystem services to increase food and forage production, which however, depends on water availability (Fig. 3; Jäger et al., 2020). Cultural ecosystem services that greatly depend on the type of land use and the composition and diversity of the landscape, such as aesthetic or symbolic values, are likely to further decline due to increasing forest cover and intensification of land use (Schirpke et al., 2016; Tasser et al., 2020; Zoderer et al., 2019).

Ongoing urbanization may reduce the quality of the living space if the sealing of near-natural ecosystems in permanent settlement areas and severe urban sprawl coincide (Fig. 5; Sauter et al., 2019). At the same time, the demand for ecosystem services is increasing in urban areas, for example, for drinking water (Meisch et al., 2019) or recreational opportunities (Sauter et al., 2019). This also requires the transport of goods from rural to urban areas, or vice versa, for those seeking relaxation in nature (Schirpke et al., 2019). Urban green spaces as well as the nearby rural surroundings are therefore gaining importance for a balanced provision of ecosystem services (Breuste and Artmann, 2015). Such developments are to be expected above all in economically prosperous regions with migration gains (Tappeiner et al., 2008). In contrast, economically weaker regions will show less settlement growth, with a general expansion of the settlement area in the central and northern Alps (Schirpke et al., 2020).

Socio-economic drivers will still have greater impacts on ecosystem services than climate-related drivers until 2050 (Kirchner et al., 2015;

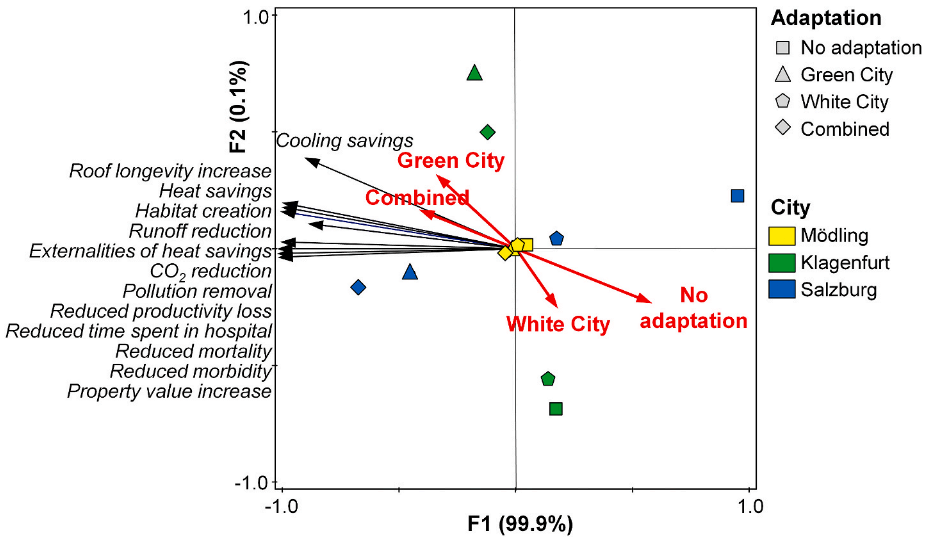

Fig. 5. Effects of adaptation strategies to climate change in three Austrian cities on key ecosystem services over a time horizon of 50 years. White City: increasing the reflectivity of sealed surfaces; Green City: increasing the greening measures; Combined: combination of measures for Green and White City. The figure shows the triplot of the principal component analysis (PCA) illustrating the relationships (trade-offs and synergies) between different adaptation measures (responses; red vectors), consequences on the state presented as the net present value (NPV; symbols) and changes in benefits from ecosystem services (impacts; black vectors). The NPV in is the present value of the cost benefits subtracted from the value of all installation and maintenance costs over the years. The length of the vectors indicates the degree of the factor loadings (i.e., the longer, the stronger), and the angle between the vectors represents the correlation among them. The x-axis (F1) is characterized by an adaptation gradient (loading in a positive direction means no adaptations), while the y-axis (F2) is characterized by a gradient between White city and Green city adaptation. All the statistical analyses were performed with the software package Canoco 5.0 (www.canoco5.com). Data source: Johnson et al. (2020); see also Table S4. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

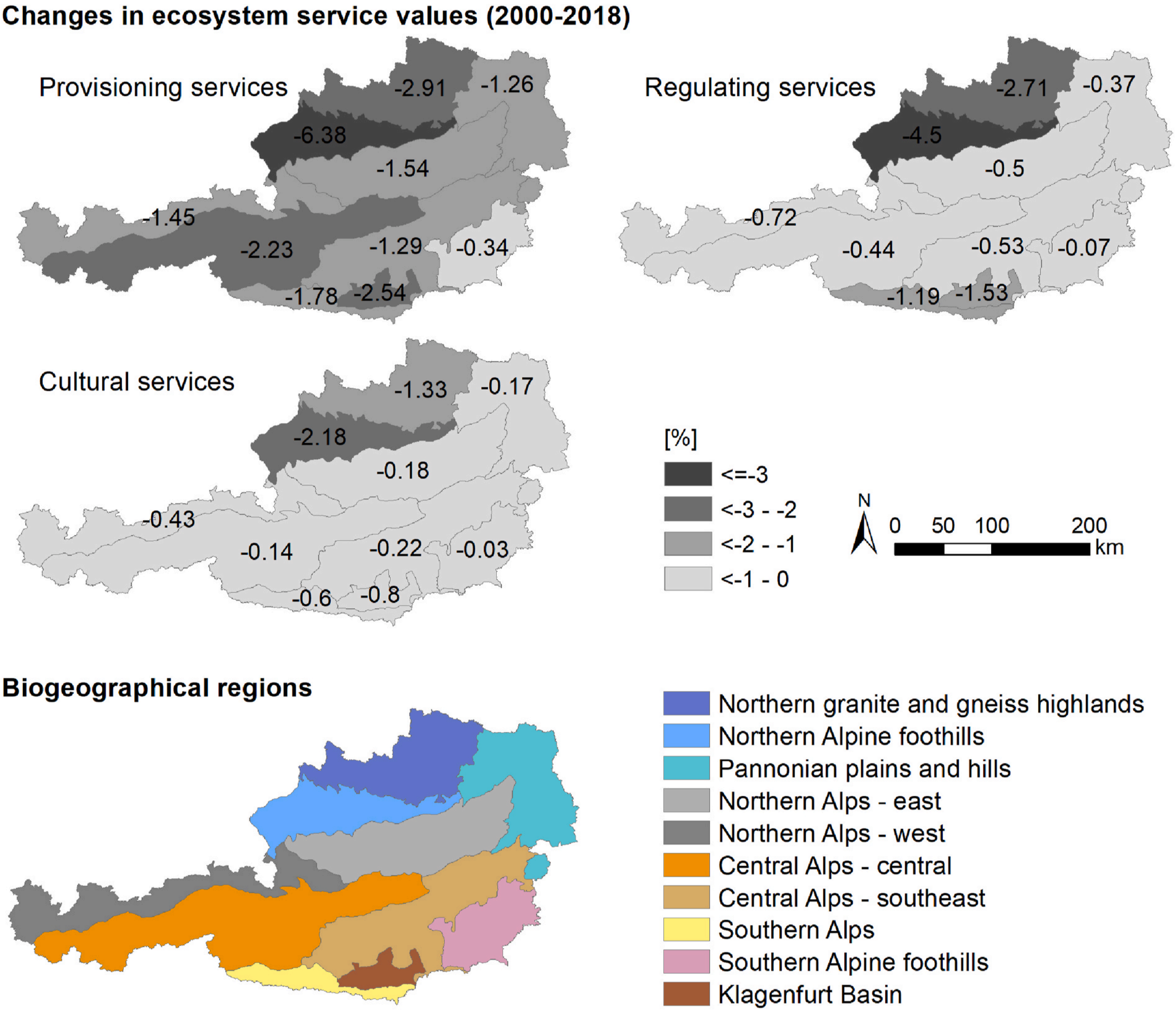

Fig. 6. Past impacts on ecosystem services in ten biogeographical regions in Austria. Ecosystem service values were calculated based on CORINE land cover 2000 and 2018 according to Schirpke and Tasser (2021) and summarized for biogeographical regions (from https://www.data.gv.at/katalog/dataset/naturraumzonen). For changes of individual ecosystem services, see Table S5.

Schirpke et al., 2017). For the second half of the 21st century, climate change is expected to become the dominant driver for changes in ecosystem services at the ecosystem level (Schirpke et al., 2017; Schürz et al., 2019; Seidl et al., 2019). In addition to an increased future suitability of currently open lands for forest development due to climate warming, the time lag in reforestation following open land abandonment continues to drive the shift towards forest-related ecosystem services (Tasser et al., 2017). Consequently, the replacement of subalpine grassland to forest may affect the water balance of the entire landscape (Strasser et al., 2019) and may lead to a decline in biodiversity (Dirnböck et al., 2003). In the long term, climate change may also increase tree species diversity of forests and a compositional shift towards deciduous forests (Tasser et al., 2017), potentially causing changes in ecosystem services, especially in cultural ecosystem services (Zoderer et al., 2019).

4. Discussion

4.1. Austria in the European context

Similar to many other European countries, land-use changes in Austria can be largely related to land abandonment and de-intensification of agricultural land use (Kuemmerle et al., 2016; Levers et al., 2016; Plieninger et al., 2016). However, abandonment mostly occurred in the mountainous and hilly areas of Austria, while an intensification of agricultural and forestry land use took place predominantly in the lowlands and flat Alpine valleys. These developments are also typical in regions of other countries within the European Alps (Egarter Vigl et al., 2016; Locatelli et al., 2017). In mountain areas, abandonment and intensification trends are greatly influenced by topography, which in turn determines climatic conditions, accessibility, and thus, the type and intensity of use (Marini et al., 2011). As a consequence of land abandonment, natural reforestation induces a shift of ecosystem services towards forest-related services, especially improving regulating services, such as climate regulation, which also occurs in many European mountain regions (Schirpke and Tasser, 2021). This development is even more pronounced in the Southern part of the Alps (Egarter Vigl et al., 2016), while the western part of Austria is characterized by a higher stability of land use due to livestock farming and large important tourism centres, compared to other Alpine regions (Schirpke et al., 2022). In contrast, provisioning and cultural ecosystem services in the Austrian Eastern lowlands are affected by urban sprawls and an intensification of land use. This trend also dominates many countries in Central and Eastern Europe, which are characterized by agricultural mixed systems (Schirpke and Tasser, 2021; van Vliet et al., 2015). Even more than other European countries, Austria undergoes strong urbanization processes, which mostly occur in already urbanized regions, especially around the capital and other larger cities. The extraordinary high land consumption in the countryside compared to other European countries (Getzner and Kadi, 2020) is related to the Austrian housing policy, which promotes the building of single-family detached homes leading to the expansion of the road infrastructure. To limit land conversion, spatial planning is underway to introduce measures, such as restrictive reallocation of building land, development plans with a higher building density, and building land mobilization (e.g., unused industrial areas or railway lines), but the effectiveness of these measures remains low (Getzner and Kadi, 2020).

4.2. Responses and implications for decision-making

Our findings highlight the general tendencies as well as regional differences in land-use changes and the level of impact on ecosystem services. These differences can be explained by different topographic and climatic conditions (i.e., mountain regions vs. lowlands), socio-economic and socio-demographic disparities, as well as different regional and local decisions due to the Austrian federal policy system. To counteract undesired impacts on ecosystem services due to land-use changes, land managers and decision-makers need to develop effective management responses. With respect to climate change impacts on agricultural production, adaption measures may include changes in crop rotations (to allow for more drought resistant varieties, for example), the shift from summer to winter crops (for a better use of winter soil moisture), the use of water-efficient irrigation technologies, as well as changes in farm size and structure (Jäger et al., 2020; Pröbstl-Haider et al., 2016). In forestry, concepts for the long-term improvement of the resistance (i.e., the ability to withstand a disturbance) and/or resilience (i.e., the ability to maintain and recover ecosystem functions) of forests have gained in popularity in Austria (Jandl et al., 2018). These concepts simultaneously can provide climate change mitigation effects, such as “Climate-Smart Forestry” (Verkerk et al., 2020). A future challenge for forestry will also be the low level of cohesion and integration of forest owners with the timber industry (Huber et al., 2013). Although facing the same challenges regarding forest resources, forest owners often consider themselves members of different industries competitors, making it difficult to adapt a shared and coordinated approach in both the management and the adaption to external influences. Furthermore, most forest owners recognize climate change as a challenge, but they are unsure about the necessary actions (Pröbstl-Haider et al., 2017). To mitigate health impacts of urban heat island effects, the importance of green and blue spaces in the urban areas is gradually becoming an important criterion for preventive and adaptation measures in climate-sensitive spatial planning (Vuckovic et al., 2020; Žuvela-Aloise et al., 2016). For example, scenarios of implementing different adaptation measures to reduce urban heat island effects in three Austrian cities in their cost-benefit analysis indicate that the Green City (i.e., green roofs, trees, low vegetation, and the unsealing of surfaces) had particularly positive effects on human well-being, while the White City (i.e., measures for an increase of the reflectivity (or albedo) of all roofs, building facades, and streets) had significantly lower positive effects (Fig. 5; Johnson et al., 2020). A combination of both strategies had the highest positive effect.

With more severe pressures from global change, spatial planning is expected to get a more crucial role to deal with ecosystem service trade-offs (Gerber et al., 2018; Steinhäußer et al., 2015), as the different political and societal needs and interests on how to use a specific area can create notable land-use conflicts (Mann and Jeanneaux, 2009; Steinhäußer et al., 2015). Such conflicts are aggravated in Austria due to the scarcity of land as well as the increasing competition of political and societal goals, e.g., to improve biodiversity, provide affordable housing, ensure the implementation of nature-based solutions (NbS), and economic growth. This opens the question how to use the limited resources and how to integrate these different goals and needs into the decision-making process (Steinhäußer et al., 2015). At the same time, the traditional regulatory planning instruments (e.g., regional plans, local development plans, and zoning plans) are often inadequate to integrate ecosystem services in the decision-making process. For example, existing planning instruments are mainly designed for the monitoring of NbS in urban areas instead of integrating them into the decision-making process (Abuseif et al., 2023; Mok et al., 2021). Due to many similarities among European countries and common policies, our findings provide important insights for decision-making at the European level, for example, the need to integrate more explicitly ecosystem services in European-wide policies (Bouwma et al., 2018). In particular, transnational efforts are needed across the countries within the European Alps to assure the provision of ecosystem services in these areas, which is indispensable not only for the local populations but also for the surrounding, densely populated areas (Schirpke et al., 2019).

4.3. Limitations

Despite a concerted effort to present the current state of knowledge on land-use changes and impacts on ecosystem services, our study has some limitations. One major challenge was related to the assessment approach, which did not allow to conduct a systematic quantitative review due to the high number of authors from different disciplines. Indeed, multi-faceted approaches including qualitative, quantitative and mixed methods are most effective for interdisciplinary systematic reviews (Drake et al., 2021; Nowell et al., 2022). To streamline terminology and to reach a shared understanding of concepts, it was necessary to create a glossary providing definitions for the most common terms. Nevertheless, there may still be differences in understanding across different disciplines. Experts from different disciplines may also assign a different level of evidence and agreement, depending on quantitative and qualitative research approaches (Kause et al., 2022). Thus, the indicated level of evidence in the report and consequently our selection of statements may have been biased.

Another main limitation represents the limited number of publications focusing on Austria, which are published in international scientific journals. Indeed, European-wide reviews rarely include case studies from Austria (Plieninger et al., 2016; van Vliet et al., 2015). To overcome this limitation, we included grey literature, often published only in German, but the quality of such publications is difficult to evaluate. Although a complex selection process of the literature was adopted, combining keyword-based literature search, the snowball method, and suggestions from the entire author team as well as external Austrian and international reviewers, some relevant studies may still have been missed in the selection process. Moreover, the findings may be biased by the available literature, as the number of research institutions is limited, which are not equally distributed across Austria. For example, research on agricultural land use is dominated by several research groups in Eastern Austria, whereas research on ecosystem services in mountain regions is mostly carried out by a smaller group of researchers located in Western Austria (Liu et al., 2022). Furthermore, publication activities often differ among institutions and research groups.

5. Conclusions

In Austria, past land-use changes were mostly driven by socio-economic factors, greatly impacting ecosystem services. While the intensification of agricultural land use and urban sprawl mostly have led to a decline in most ecosystem services in the lowlands, forest expansion due to the abandonment of mountain grassland has induced a shift towards forest-related services (i.e., increasing regulating services on the expense of various provisioning and cultural services) in mountain regions. Without more effective policies to curb unsustainable land-use changes, socio-economic determinants will continue to have negative effects on ecosystem services in the future. Especially, the consequences of land abandonment will be relevant in the long term, mostly in mountain regions due to the slow natural reforestation processes. However, scenarios up to the year 2100 indicate that progressive climate change could become the dominant driver for land-use changes in the second half of the century, especially on intensively used agricultural land. Although future impacts on ecosystem services from climate change remain highly unclear, it seems that management options will be reduced.

The main implications for policymaking are to develop more integrative and effective regional planning concepts and decisions. In particular, the revival of spatial planning frameworks and instruments at the local, regional and national scale will be needed to address these challenges. In tandem with agricultural policies and rural development programs, climate policies need to be developed, e.g., by placing a stronger focus on agri-environmental payments on greenhouse gas mitigation and ecosystem services or defining more stringent requirements for receiving direct payments. Additionally, the spatial planning processes need a substantially improved integration of ecosystem services in concrete land use decision-making. The consideration of ecosystem services in decision-making allows to shift from single-goal oriented approaches to a comprehensive evaluation of human well-being benefits related to the use of natural resources, which also can improve the chances of achieving the Sustainable Development Goals.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Literature base is provided in the supplementary material.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118728.

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